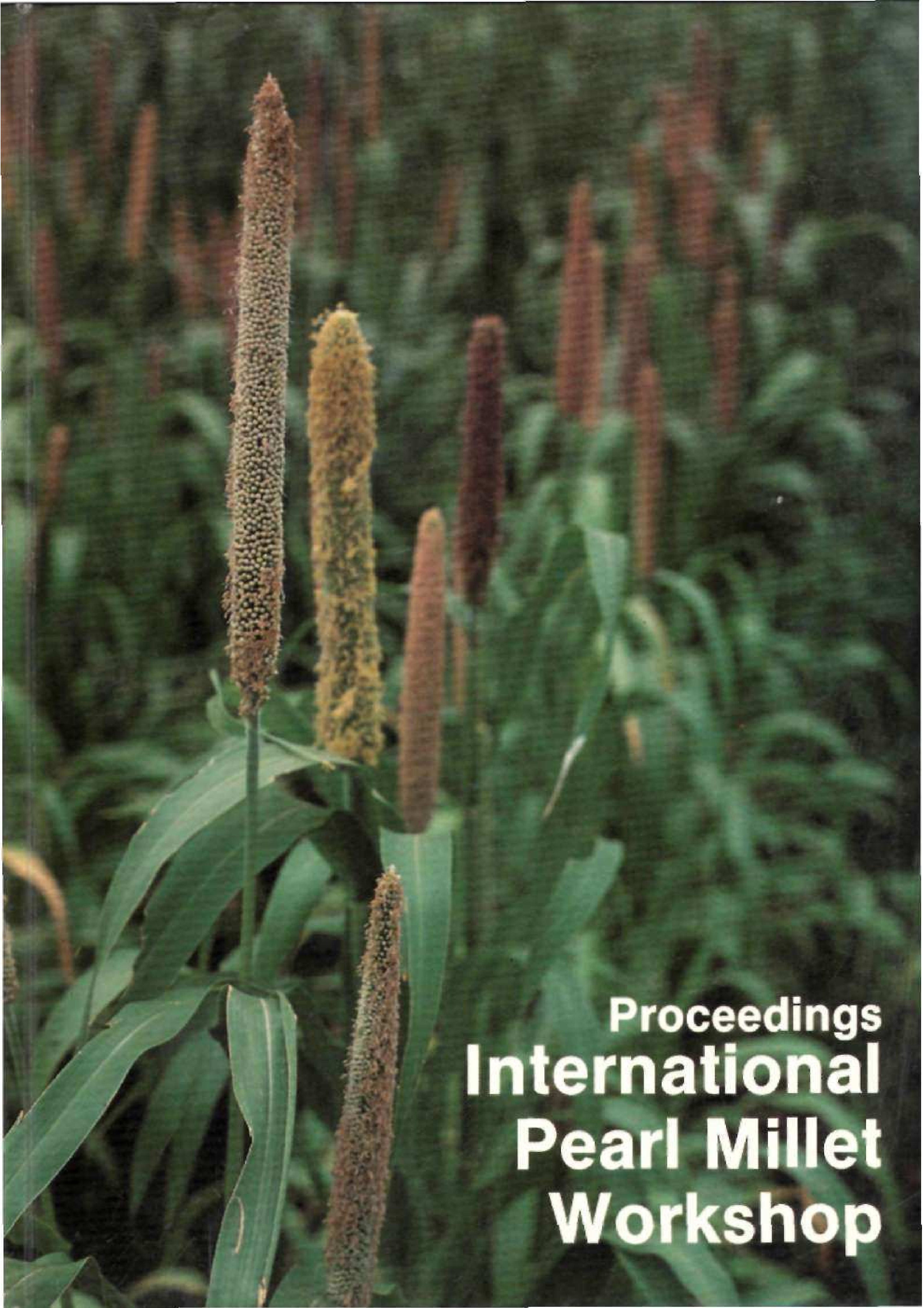

# Proceedings
# International Pearl Millet Workshop

**Cover:** Ex-Bornu, an important landracc population from the Bornu region of northeast Nigeria, which is extensively used as parental material in breeding programs in India.

# Proceedings of the

# International Pearl Millet Workshop

7-11 April 1986
ICRISAT Center, India

Sponsored by

USAID Title XII Collaborative Research Support Program
on Sorghum and Pearl Millet (INTSORMIL)

and

International Crops Research Institute for the Semi-Arid Tropics
(ICRISAT)

ICRISAT

International Crops Research Institute for the Semi-Arid Tropics
Patancheru, Andhra Pradesh 502 324, India

1987

***Correct citation:*** ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

*Scientific Editor*

**J.R. Witcombe**

*Publication Editor*

**Seth R. Beckerman**

**ISBN 92-9066-134-8**

The International Crops Research Institute for the Semi-Arid Tropics is a nonprofit scientific educational institute receiving support from donors through the Consultative Group on International Agricultural Research. Donors to ICRISAT include governments and agencies of Australia, Belgium, Canada, Federal Republic of Germany, Finland, France, India, Italy, Japan, Mexico, Netherlands, Nigeria, Norway, People's Republic of China, Sweden, Switzerland, United Kingdom, United States of America, and the following international and private organizations: Asian Development Bank, Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ), Global 2000 Inc., International Development Research Centre, International Fertilizer Development Center, International Fund for Agricultural Development, The European Economic Community, The Ford Foundation, The Leverhulme Trust, The Opec Fund for International Development, The Rockefeller Foundation, The World Bank, United Nations Development Programme, and the University of Hohenheim. Information and conclusions in this publication do not necessarily reflect the position of the aforementioned governments, agencies, and international and private organizations.

# Contents

**Pearl Millet Entomology**



**Pearl Millet for Fodder and Forage Production**



**Pearl Millet Microbiology**

# Welcome and Inaugural Address

**L.D. Swindale**[1]

It is my pleasure to welcome you all to ICRISAT and to this first session of the International Pearl Millet Workshop. This is the dry and hot season for us here at Hyderabad; the season between the end of winter and the coming of rains late in June. A time when we are reminded of the tropical nature and even sometimes the nearly arid nature of our environments, but when we also have the hope and promise of better days ahead once the rains begin to fall. You will see little experimental work in the fields right now for obvious reasons, but our pearl millet program has worked diligently to provide you with a series of demonstration plots in order to show you various aspects of our work. Although there is little experimental work going on in the field, there is a great deal going on in preparing for the season. It is indeed a very busy time in ICRISAT as it must be in your own institutes as well.

I hope you will take the opportunities that come to you during the week to look around ICRISAT to familiarize yourself with what we have here, meet your colleagues and talk about pearl millet and how we may work together on this crop. It is the fifth most important cereal. It is particularly important in Africa, and again most particularly in West Africa. These rather dry statements of fact do not indicate its true importance, its critical nature, which is due to the fact that it is really the last important cereal crop in arable farming. Beyond pearl millet we move from arable farming into pasture activities and even less intensive forms of agriculture. For the millet is the staple cereal, there is no serious alternative. When the millet fails, nothing else can be substituted, and that is why it is such a critical crop and why it is so important that a great deal of research time should be given to it. It deserves attention there beyond what the statistics of millet in the world or even in the developing world might indicate.

Furthermore as you know, I'm talking largely about the subsistence economy; of people who provide most of their own foods. They use traditional types of varieties and change is relatively slow both in the varieties they use and the products they make from them. We are aware of the importance of producing new and better cultivars which fit into the traditional way of doing things and which can be converted into the traditional food products that are made from pearl millet. Millet has played a greater role or place in the world of cereals, for many rural people in the past in eastern and southern Africa, but it has declined in importance over the last 30-50 years because of a preference for maize. The decline has been compounded by increased research on maize leading to greater productivity of the crop and by the incentives given to maize production through government policies. Maize has been grown, as a result, in dry conditions to which it is not adapted and it has failed too often in these conditions. Governments have come to realize this as well as the people themselves. So it is now necessary to re-establish the importance of sorghum and millet in these drier areas and to do so we must make the production of these crops attractive enough so that they can compete with maize, not only in the worst and most severe droughts but in at least a majority of years. Here is work for the scientists in millet. But in the long run, even in Africa, maize is not the problem at all. The problem is wheat, or more correctly, bread. Politicians are going to give the people bread. They have been saying this for a long, long time, and they mean it. Technocrats may decry this trend, particularly in tropical areas where wheat cannot be grown satisfactorily, but I can assure you that the protestations will be to little avail. They may slow the process down but they will not stop it. The people of the cities want bread, and elected officials will ensure that they get it. They are already exposed to bread and they will ask for it, they will insist upon it, and they will get it. In many

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tropical countries it will be very expensive to satisfy this demand unless millet can become bread. And this, too, the politicians recognize, and they will support whether efforts can be made to decrease the cost of giving people the food that they demand. So here is something else for the millet scientists to do. Don't ask me how you do it. You know far better than I do. I am just telling you it's got to be done.

Now let me say a few words about ICRISAT. Most of you know ICRISAT. Most of you have been here before. Some of you come here everyday. ICRISAT was created in 1972, specifically to deal with some issues that had arisen from the success of the so-called green revolution. ICRISAT was created to try to provide significant improvements in the livelihoods of the people who were not able to benefit from those increases in the production of irrigated rice and wheat; for the people in the dry lands, and particularly the dry lands of the semi-arid tropics, where vast number of people occupy 11 % of the earth surface and depend to a large extent upon the food products that they produce for themselves. ICRISAT has been charged with the responsibility to develop technologies for improving the major food cereals and legume crops of the semi-arid tropics. Over the years ICRISAT has developed into a sizeable research institute with its headquarters in Hyderabad where a great deal of our work is done, but with significant programs in other parts of the world, particularly in Africa. With pearl millet over the years, we have generated diverse breeding material largely resistant to downy mildew. We have developed and released open-pollinated varieties with resistance to two or more diseases. We have not done much yet with insect resistance. We have developed and transferred to scientists of the national programs field screening methodologies for stress tolerence and resistance; we have shown the possibilities of connecting high yield to improved protein in the crop. We have developed an understanding of how pearl millet tolerates environmental stresses, and perhaps most importantly we are working with the scientists of the national programs in an effective network of international cooperation.

The successes I have mentioned have been taken from statements in our 10-year plan which also will tell you some of the things that we hope to do in the future. We hope to improve upon what we have done to complete some of those tasks which are incomplete and to serve the world better. Recently we have decided to reorganize the management in ICRISAT. The present Director of Research, Dr. J.S. Kanwar, who will be with us later in the week will become the Deputy Director General of the Institute. We will establish three Program Directorates for cereals, legumes and resource management. I am pleased, at this time, to inform you that the Chairman of this session Dr. J.M.J. de Wet will be joining ICRISAT in June to become the Program Director for Cereals at ICRISAT Center. R.W. Gibbons who is sitting here quietly learning about pearl millet as fast as he can, is going to become Executive Director of ICRISAT for West Africa located at the ICRISAT Sahelian Center in Niamey, Niger and L.R. House, who is not here today, will hold a similar Executive Director's post for southern Africa. These changes will help us strengthen the relationship between the various parts of ICRISAT but also provide to our programs in West and southern Africa greater autonomy and greater opportunities to cooperate effectively with the national programs of the regions in which they are working.

ICRISAT Center research on pearl millet will in the future move away from its present applied character, towards more strategic research, but the applied research in Africa will be strengthened and will be given more opportunities to produce improved genetic materials in partnership with the national agricultural research scientists. I hope that this workshop will work out a global program of research for pearl millet in which ICRISAT will fulfil its role and the national agricultural research programs will fulfil theirs in effective partnership relations. The International Agricultural Research Centers are searching for better ways to participate with national programs and any suggestions that you have as to how this can be done will be greatly welcomed.

Finally it is my pleasure to inaugurate this pearl millet workshop. I hope that all of you will contribute fully to the discussions, think hard about what needs to be done, about how we can work together to better benefit those many, many millions of people who depend upon this important crop. Thank you very much.

# Welcome Address


## D.J. Andrews[1]


On behalf of Dr. Glenn Vollmar, director of INTSORMIL, I welcome you to this joint International Pearl Millet Workshop with ICRISAT. On a personal note, it is a pleasure for me to be back among the pearl millet scientists.

While the name ICRISAT is well known to most of you, I should take a moment to explain INTSORMIL: the International Sorghum and Pearl Millet Collaborative Research Support Program, it is one of a number of CRSPs, all funded by USAID through Title XII of the Higher Education Assistance Act of the U.S. Congress. This act aims to mobilize the research and teaching capacities of U.S. land-grant universities in collaborative research and training projects with developing countries.

INTSORMIL began in 1979, and includes some 35 scientists in the disciplines of breeding, pathology, entomology, physiology, plant nutrition, food quality and nutritive value, and socioeconomics in six universities: Kansas, Kentucky, Mississippi, Nebraska, Purdue, and Texas A & M. While INTSORMIL has collaborative research projects in a number of countries, it has staff in Botswana, Colombia, the Dominican Republic, Niger, and Sudan. Over 100 students have received graduate training. While pearl millet is not yet a commercial grain crop in the U.S. (although we believe it can be developed into one), it is receiving considerable attention in INTSORMIL. This builds on the previous USAID initiative of funding pearl millet breeding at Kansas State University, begun in 1971.

ICRISAT and INTSORMIL obviously have common interests and seek to develop complementary research, for example, the proposed collaborative research on the problems of sorghum and millet production on the acid soils in the SADCC region. This workshop is the most recent in a number of workshops jointly sponsored by ICRISAT and INTSORMIL.

Workshops like this are fundamental to the progress of research on the crop. We need to plan future joint research. I am sure you will go home from this meeting not only with renewed enthusiasm knowing what is possible with this very interesting plant with new ideas for your own research, but also with the ultimate aim we all have: to find ways for farmers to reliably produce more food from this important crop.

Without further preamble, let me once again welcome you to this Workshop.


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# Opening Session

## Moderator's Overview

# Pearl Millet *(Pennisetum glaucum)* in Africa and India

**J.M.J. de Wet**[1]

The genus *Pennisetum* is distributed throughout the tropics and subtropics of the world. It includes about 140 species. One African species, *P. glaucum* (L.) R. Br. was domesticated as the cereal pearl millet, and another African species, *P. purpureum* Schumach. became widely distributed as a tropical forage grass (Brunken et al. 1977). *Pennisetum glaucum* is widely distributed south of the Sahara in the semi-arid Sahel and bush from Senegal to Eritrea in Ethiopia. It was domesticated along the southern margins of the Saharan central highlands at the onset of the present dry phase some 4000-5000 years ago (Clark 1962, Davies 1968, Munson 1975).

Pearl millet is the most drought tolerant of all domesticated cereals, and soon after its domestication it became widely distributed across the semi-arid tropics of Africa and Asia. It is the principal food crop across sub-Saharan Africa and northwestern India, but in terms of world production, pearl millet is not a major cereal. It is planted on some 15 million ha in Africa, and 10 million ha in Asia, yielding approximately 10 million t of grain. Pearl millet is grown where no other cereal will yield grain, in regions with 200-800 mm of annual rainfall. It extends into the higher rainfall areas of the semi-arid tropics, but when rainfall is above 800 mm during the growing season, sorghum *[Sorghum bicolor* (L.) Moench] becomes the principal cereal. Nevertheless, average pearl millet yields compare favorably with those of sorghum. Average sorghum yields were 580 kg $ha^{-1}$ in Africa and 715 kg $ha^{-1}$ in India during the 1984 growing season, while for the same period average pearl millet yields were about 600 kg $ha^{-1}$ in both Africa and India.

Pearl millet yields vary extensively between a low of 71 kg $ha^{-1}$ in Botswana during the 1984 drought, and a high of 1818 kg $ha^{-1}$ in Sierra Leone during the same year. Inflorescences range in size and shape from globose, less than 10 cm long, to candle-shaped, over 150 cm long (Clement 1985). Spikelets are arranged in involucres surrounding a central axis. Each involucre has 1-9 spikelets. The potential large number of spikelets per inflorescence allows for a possible yield in pearl millet at least equal to the maximum yield in sorghum.

Stapf and Hubbard (1934) recognized 13 cultivated, 15 weedy, and 6 wild annual species in section Pennicillaria of Pennisetum. Clayton (1972) reduced these taxa to one cultivated species *[P. americanum* (L.) Leeke], two wild species *[P. fallax* (Fig. & de Not.) Stapf & Hubbard and *P. violaceum (Lam.)* L. Rich.], and two weedy species *[P. stenostachyum* (Klotzsch ex A. Br.) Stapf & Hubbard and *P. dalzielii* Stapf & Hubbard]. Brunken (1977) recognized the total variation of cultivated pearl millets as *P. americanum* spp. *americanum,* their closest wild relatives as spp. monodii (Maire) Brunken, and their weedy derivatives as spp. *stenostachyum* (Klotzsch ex A. Br. & Bouche) Brunken.

The specific name *P. americanum* (L.) Leeke is not taxonomically valid. The oldest name for cultivated pearl millet is *Pennisetum glaucum* (L.) R. Br., Prodr. Fl. Nov. Holl. 1:195. 1810. This species is based on *Panicum glaucum* L., Sp. PI. ed. 1:56 1753 (Type: Herman specimen from Ceylon in the British Museum, which is a typical cultivated pearl millet). The original diagnosis of *Panicum glaucum* by Linnaeus included two species of *Setaria as* well as the cultivated pearl millet. In the second edition of his species plantarum, Linnaeus transferred *Panicum glaucum* to Setaria. Modern rules of nomenclature, however, do not allow such a change, and the name *Panicum glaucum* therefore applies to cultivated Pennisetum. Variation within cultivated pearl millet is recognized as races *typhoides, nigritarum, globosum,* and *leonis.*

Race *typhoides* has obovate caryopses, and inflorescences are cylindrical, usually less than five times as long as wide. This race is grown across the arid savanna from Senegal to Egypt and South Africa. It is the principal pearl millet grown in Asia. Race *nigritarum* has obovate, but angular caryopses. Inflorescences are candle-shaped. It is extensively grown from northern Nigeria to the Sudan. Race

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*globusum* has globose caryopses, and inflorescences are candle-shaped. It is widely distributed in West Africa. Race *leonis* is characterized by oblanceolate and acute caryopses. Inflorescences are candle-shaped. This race is the principal pearl millet in Sierra Leone, and extends north to Mauritania.

Hybrids between pearl millet and its spontaneous close relatives cross readily to produce fertile hybrids (Marchais and Tostain 1985), allowing for extensive modification of the genome of the cereal (Belliard et al. 1980). Transfer of the cultivated genotype into wild cytoplasm is a source of nucleo-cytoplasmic male sterility (Marchais and Pernes 1985), and resistance to diseases and pests. Pearl millet also crosses with *Cenchrus ciliaris* L. (Read and Bashaw 1974), and more distantly-related species within Pennisetum.

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# Pearl Millet in Indian Agriculture

G. Harinarayana[1]


## Abstract

*Pearl millet is the fourth most important cereal food crop in India As a semi-arid and arid crop, it is traditionally a component of the dryland system, usually grown in soils with depleted fertility which receive 150-750 mm of rainfall per year.*

*Pearl millet was grown on 9.5% of the food-grain area and yielded 4.8% of Indian food-grain production during 1965-84. Rajasthan, Maharashtra, Gujarat, and Uttar Pradesh accounted for nearly 80% of 11.79 million ha and 70% of 5.25 million t of grain.*

*Traditional farming practices include the use of locally-adapted varieties with poor productivity, little application of manures and chemical fertilizers, minimum tillage, and limited intercropping operations. Nutritionally superior to rice and wheat, pearl millet is commonly used to make unleavened bread, thin or thick porridge, or may be cooked like rice.*

*The major factors that restrict the production potential of pearl millet are low hybrid coverage, slow varietal spread, poor plant establishment, no fertilization, weeds, and diseases. Some suggested remedial measures to increase production include: diversification of male-sterile lines, improvement of restorers, breeding heterogeneous and heterozygous single- and multicross hybrids for combating the twin problems of low yield and diseases, identification of sugary, yellow-, and white-grained pearl millets, and selection for drought resistance, efficient water use, efficient nitrogen utilization, salt and mineral tolerance, and disease resistance.*

*Millet is a staple food crop of India, a crop that has inherited the drought-prone, semi-arid, and arid areas of the world, but is also ideally adapted to irrigated farming, making it a potential world food grain. Pearl millet also stabilizes the food basket: increased production opens new possibilities of alternative food uses which can release rice and wheat for direct consumption through product substitution. The production potential of pearl millet has not been commercially exploited, and has so far been restricted to the use of improved seeds. Given quality seeds, small amounts of fertilizer, good cultural management, water harvesting, price support, and assured procurement, pearl millet production could increase many-fold and become stabilized at higher levels.*

## Résumé

**Rôle du mil dans l'agriculture indienne :** *Le mil se place en quatrième position parmi les céréales vivrières en Inde. Culture aridocole, le mil est exploité sur des sols lessivés des zones arides et semi-arides recevant entre 150 et 750 mm de pluies par an.*

*Entre 1965 et 1984, la superficie cultivée en mil représentait en moyenne 9,5% et sa production 4,8% de celles des cultures à grain en Inde. 80% de la superficie totale de 11,79 millions d'hectares dévolus au mil est situé dans les Etats de Rajasthan, de Maharashtra, de Gujarat et d'Uttar Pradesh qui fournissent 70% de la production totale de 5,25 millions de tonnes de grain du mil.*

*La culture traditionnelle se caractérise par l'utilisation de variétés locales peu productives, l'apport minime de fumier et d'engrais chimiques, une préparation médiocre du sol sans association poussée avec d'autres cultures. Le mil qui est supérieur au blé et au riz du point de vue nutritif, sert à faire des galettes ou une bouillie plus ou moins épaisse; il est parfois préparé comme le riz.*


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*La productivité du mil est limitée par plusieurs éléments dont la faible exploitation d'hybrides, la lente diffusion des nouvelles variétés, un mauvais établissement des plantules, un apport nul d'engrais, les mauvaises herbes et les maladies. Parmi les mesures proposées en vue d'augmenter la production, il faut noter les suivantes : la diversification de lignées mâles-stériles; l'amélioration des lignées restauratrices de la fertilité mâle (R); la sélection d'hybrides hétérogènes et hétérozygotes par croisement simple et multiple afin de résoudre le double problème des faibles rendements et des maladies; l'identification de mils à grain blancs ou jaunes ayant une saveur agréable et enfin; la sélection visant à la résistance à la sécheresse et aux maladies, à l'utilisation efficace de l'azote et de l'eau ainsi qu'à la tolérance au sel et aux éléments minéraux.*

*Quoique relégué aux zones arides et semi-arides souvent touchées par la sécheresse, le mil se comporte également très bien en culture irriguée démontrant son potentiel pour d'autres régions. Le mil, culture de base en Inde, permettra de stabiliser la situation vivrière : la diversification de l'emploi du mil suite à l'augmentation de sa production permettra de le substituer au blé et au riz pour la fabrication de certains produits; ceux-ci seront donc disponibles pour la consommation directe. L'exploitation commerciale du mil est peu développée et se limite à l'emploi de semences sélectionnées. Les semences de bonne qualité, l'apport d'engrais, un aménagement efficace de la culture et de l'eau, des prix favorables et la commercialisation assurée permettront d'augmenter sensiblement la production du mil et de la stabiliser à un niveau élevé.*

## Area, Production, and Productivity: Distribution Trends

### Contribution to National Food Basket

Pearl millet is the fourth most important food crop in India, after rice, wheat, and sorghum. It grew on 9.5% of the area under food grains in the following introduction of high-yielding varieties (post-HYV, 1965-84) as compared to 9.9% during the pre-HYV era (1954-65) (Table 1). The contribution to the food basket was 4.8% from 1965-84 as compared to 4.7% from 1954-65.

Compared to cereals, pearl millet contributed 12% of the area and 5.5% of the production in 1965-84 (Table 2), recording an increase of 0.8% in area, and a 0.1% decrease in production over 1954-65.

Among coarse grains, pearl millet occupies second place, following sorghum. Pearl millet grew on 27.2% of the area and yielded 18.9% of coarse grain production during 1965-84, an increase of 1.5% in area and 3.5% in production over 1954-65.

### Area

Pearl millet area as a percentage of coarse grains increased in Rajasthan, Gujarat, Haryana, Karnataka, and Madhya Pradesh during the post-HYV period (Table 2), but the contribution to total cereals increased only in Gujarat, Karnataka, and Madhya Pradesh.

In Rajasthan pearl millet is the principal grain crop, grown on 53.8% of the cereal area, and on 67% of the coarse grains area from 1965-84. The other two important states for pearl millet are Gujarat and Haryana, which accounted for more than 50% of the area under coarse grains, and over 30% of the cereal area.

Table 1. Contribution of cereal crops to food grains in India.

| Crop | Area (%) 1954-65 (Pre-HYV)[1] | Area (%) 1965-84 (Post-HYV)[2] | Production (%) 1954-65 (Pre-HYV) | Production (%) 1965-84 (Post-HYV) |
|---|---|---|---|---|
| Coarse grains | 38.8 | 35.1 | 30.6 | 25.2 |
| Sorghum | 15.6 | 13.5 | 11.7 | 9.0 |
| Pearl millet | 9.9 | 9.5 | 4.7 | 4.8 |
| Maize | 3.7 | 4.6 | 5.1 | 5.6 |
| Small millets | 4.1 | 3.5 | 2.7 | 1.5 |
| Finger millet | 2.1 | 2.0 | 2.6 | 2.1 |
| Barley | 2.8 | 1.9 | 3.6 | 2.2 |
| Cereals | 80.0 | 81.7 | 86.9 | 90.5 |
| Rice | 29.8 | 31.0 | 42.8 | 40.6 |
| Wheat | 11.4 | 15.6 | 13.7 | 24.7 |
| Food grains | 113.0[3] | 124.0[3] | 74.3[4] | 110.2[4] |

1. Pre-HYV = Pre-High Yielding Varieties era.
2. Post-HYV= Post-High Yielding Varieties era.
3. ha x $10^6$.
4. t x $10^6$.

Table 2. Area and production of pearl millet in India as percentage of coarse grains and cereals.

| State | Area | | | | Production | | | |
|---|---|---|---|---|---|---|---|---|
| | % of coarse grains | | % of cereals | | % of coarse grains | | % of cereals | |
| | 1954-65 (Pre-HYV)[1] | 1965-84 (Post-HYV)[2] | 1954-65 (Pre-HYV) | 1965-84 (Post-HYV) | 1954-65 (Pre-HYV) | 1965-84 (Post-HYV) | 1954-65 (Pre-HYV) | 1965-84 (Post-HYV) |
| Rajasthan | 66.0 | 67.0 | 58.8 | 53.8 | 40.4 | 42.5 | 26.5 | 22.6 |
| Maharashtra | 21.1 | 20.7 | 16.8 | 16.2 | 11.8 | 12.3 | 8.5 | 8.2 |
| Gujarat | 46.3 | 50.2 | 36.1 | 38.1 | 41.9 | 57.1 | 27.1 | 34.2 |
| Uttar Pradesh | 23.3 | 21.0 | 8.5 | 6.6 | 18.2 | 17.4 | 6.1 | 4.1 |
| Haryana | 62.1 | 67.9 | 36.3 | 31.0 | 53.9 | 60.0 | 16.7 | 11.5 |
| Andhra Pradesh | 13.1 | 12.9 | 7.9 | 7.4 | 12.7 | 12.3 | 5.0 | 3.9 |
| Karnataka | 10.7 | 12.3 | 8.4 | 9.3 | 5.4 | 6.5 | 3.3 | 4.0 |
| Tamil Nadu | 23.7 | 20.4 | 11.0 | 9.9 | 18.0 | 20.7 | 5.7 | 5.6 |
| Madhya Pradesh | 4.3 | 4.4 | 1.6 | 1.7 | 4.7 | *43* | 1.5 | 1.5 |
| Punjab | 48.2 | 18.6 | 20.3 | 3.5 | 23.3 | 13.7 | 7.1 | 1.5 |
| India | 26.1 | 27.2 | 13.2 | 12.0 | 16.2 | 18.9 | 6.1 | 5.5 |

1. Pre-HYV = Pre-High Yielding Varieties era.
2. Post-HYV = Post-High Yielding Varieties era.

## Production

The contribution of pearl millet to the national coarse grain basket increased during the post-HYV period. This increase was largely in Gujarat and Haryana, and partly in Rajasthan, Maharashtra, Karnataka, and Tamil Nadu. But the percentage contribution to total cereals decreased in most of the states except Gujarat and Karnataka.

Among coarse grains, pearl millet is an important food crop in Rajasthan, Gujarat, and Haryana and to some extent in Tamil Nadu, Uttar Pradesh, Punjab, Maharashtra, and Andhra Pradesh.

## Changes in Area, Production, and Productivity

The area under pearl millet remained nearly stable at about 11 million ha during 1954-1984 with a marginal compound growth rate of 0.3% (Table 3). The

Table 3. Changes in area, production, and productivity of pearl millet in India.

| State | Area (ha x $10^6$) | | | Production (t x $10^6$) | | | Productivity (kg $ha^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1954-65 (Pre-HYV)[1] | 1965-85 (Post-HYV)[2] | CGR[3] (%) | 1954-65 (Pre-HYV) | 1965-85 (Post-HYV) | CGR (%) | 1954-65 (Pre-HYV) | 1965-85 (Post-HYV) | CGR (%) |
| Rajasthan | 4.06 | 4.67 | 0.90 | 0.86 | 1.23 | 2.30 | 210 | 380 | 3.90 |
| Maharashtra | 1.74 | 1.63 | -0.40 | 0.48 | 0.56 | 1.00 | 276 | 342 | 1.40 |
| Gujarat | 1.59 | 1.58 | 0.00 | 0.57 | 1.22 | 5.10 | 361 | 770 | 5.00 |
| Uttar Pradesh | 1.07 | 1.02 | -0.30 | 0.57 | 0.68 | 1.10 | 528 | 664 | 1.50 |
| Haryana | 0.79 | 0.88 | 0.70 | 0.29 | 0.46 | 2.90 | 363 | 523 | 2.30 |
| Andhra Pradesh | 0.63 | 0.55 | -0.90 | 0.32 | 0.30 | -0.40 | 510 | 554 | 0.60 |
| Karnataka | 0.52 | 0.52 | 0.00 | 0.12 | 0.22 | 4.00 | 235 | 421 | 3.90 |
| Tamil Nadu | 0.51 | 0.41 | -1.40 | 0.30 | 0.32 | 0.40 | 593 | 787 | 1.80 |
| Madhya Pradesh | 0.18 | 0.21 | 1.00 | 0.11 | 0.13 | 1.10 | 574 | 613 | 0.40 |
| Punjab | 0.85 | 0.13 | -12.90 | 0.28 | 0.12 | -5.60 | 334 | 984 | 7.30 |
| India | 11.22 | 11.74 | 0.30 | 3.50 | 5.31 | 2.80 | 312 | 452 | 2.40 |

1. Pre-HYV = Pre-High Yielding Varieties era.
2. Post-HYV = Post-High Yielding Varieties era.
3. CGR = Compound growth rate.

area increased substantially in Rajasthan, Haryana, and Madhya Pradesh, was stable in Gujarat and Karnataka, and declined marginally in Maharashtra and Uttar Pradesh. The decline was rapid in Punjab. In Maharashtra, Uttar Pradesh, Andhra Pradesh, and Tamil Nadu, land was diverted to more profitable crops.

Pearl millet production increased from 3.5 million t in the pre-HYV period (1954-65) to 5.25 million t in the post-HYV period (1965-84), with an annual growth rate of 2.7%. All states except Andhra Pradesh and Punjab increased production. Gujarat (5%), Tamil Nadu (4.7%), Karnataka (3.9%), and Haryana (3.1%) recorded higher annual growth rates than the national compound growth rate. The production decline in Andhra Pradesh and Punjab could be attributed to decreased area, while the production increase in all other states is apparently from an increase in productivity. The national productivity increased from 312 kg $ha^{-1}$ in 1954-65 to 446 kg $ha^{-1}$ in 1965-84, an annual growth rate of 2.3%. Growth rates in Punjab (7.6%), Gujarat (5%), Karnataka (3.9%), and Haryana (2.4%) were higher than the national average. The remaining states also increased productivity by 0.3-1.8%.

## State and District Production

Rajasthan, Maharashtra, Gujarat, and Uttar Pradesh are the principal pearl millet growing states. They grew 68.8% of national production on 76.7% of the pearl millet area during 1965-84 (Table 3). Other important pearl millet growing states are Haryana (0.89 million ha), Andhra Pradesh (0.55 million ha), and Karnataka (0.52 million ha). Pearl millet is also grown in Tamil Nadu (0.41 million ha), Madhya Pradesh (0.21 million ha), and Punjab (0.13 million ha). There are 32 districts in India, each with more than 0.1 million ha growing pearl millet (Table 4).

Table 4. Principal pearl millet growing districts in India, 1976-81.

| State | Selected districts[1] | | Area (% of Indian total) State | Area (% of Indian total) Selected districts | Productivity (kg $ha^{-1}$) State | Productivity (kg $ha^{-1}$) Selected districts |
|---|---|---|---|---|---|---|
| Rajasthan | Barmer (0.89) | Jodhpur (0.56) | 39.0 | 36.7 | 224 | 286 |
| | Nagaur (0.49) | Churu (0.39) | | | | |
| | Jalore (0.26) | Bikaner (0.24) | | | | |
| | Jaipur (0.21) | Sikar (0.21) | | | | |
| | Jhunjhunu (0.20) | Jaisalmer (0.16) | | | | |
| | Alwar (0.15) | Bharatpur(0.15) | | | | |
| | Sawai Madhopur (0.14) | | | | | |
| Maharashtra | Nasik (0.35) | Ahmednagar (0.28) | 14.9 | 12.0 | 393 | 403 |
| | Aurangabad (0.18) | Pune (0.16) | | | | |
| | Dhule (0.13) | Bhir (0.11) | | | | |
| | Satara (0.11) | | | | | |
| Gujarat | Banaskantha (0.29) | Mehsana(0.21) | 12.7 | 8.0 | 909 | 1004 |
| | Kaira (0.16) | Bhavnagar(0.13) | | | | |
| | Kutch (0.I0) | | | | | |
| Uttar Pradesh | Agra (0.13) | Aligarh(0.11) | | | | |
| Haryana | Bhiwani (0.26) | Hisar(0.12) | 8.0 | 4.5 | 440 | 461 |
| | Mohindergarh (0.12) | | | | | |
| Karnataka | Bijapur (0.23) | Gulbarga (0.14) | 5.1 | 3.3 | 460 | 453 |
| India | | | 11.0 | - | 458 | |

1. Figures in brackets are area (ha x $10^6$).

# Environmental Parameters

## Geographic Distribution

Pearl millet is a short-day plant. It is adapted to warm, semi-arid to desert climates. It is found between 69-85°E longitudes and 8-31°N latitudes. It is grown at altitudes up to 600 m above sea level.

## Climate

Pearl millet is grown chiefly during the southwest monsoon or rainy season, but is also cultivated in the summer under irrigation, particularly in Gujarat and Tamil Nadu for food, and for fodder in Haryana and Punjab. The monsoon begins 5 Jun-15 Jul in the various pearl millet regions, and withdraws by 1 Sep-15 Oct (1895-1940 data). Climate data is extrapolated from I M D (1978).

**Rainfall and rainy days.** The annual rainfall in pearl millet growing areas ranges from 150-750 mm (1901 - 1950 data), most of which falls between Jun-Sep in 5-50 d (rainy day > 2.5 mm). The rainfall and rainy days increase from west to east and from south to north in Jun-Sep.

**Temperature.** Over a year the temperature varies between a minimum of-2.5 and a maximum of 50° C in the pearl millet growing areas. The mean daily temperature varies between 25-27.5°C in October, to 25-32.5°C in July. Normally the mean daily minimum temperature is 17.5-25°C in October, to 22.5-27.5°C in July, and the maximum from 30-35°C in October, to 30-40°C in July (1931-60 data).

The mean daily soil temperature recorded at 07:00 at 30 cm is 25-30°C in October to 27.5-30°C in July, and at 5 cm is 20-25°C in October to 25-30°C in July.

**Relative humidity.** The mean daily relative humidity at 08:30 is 50-80% in October to 70-90% in July and at 17:30 is 30-70% in October to 50-80% in July (1930-1961 data).

**Sunshine hours.** Over a 20-year period (1946-1965), mean annual sunshine hours varied from 6-8 h $d^{-1}$ but may reach as low as 3 h $d^{-1}$ in July (3-8 h $d^{-1}$), and as high as 10 h $d^{-1}$ during October (6-10 h $d^{-1}$).

**Evaporation.** On an annual basis the potential evapotranspiration ranges from 1400-2000 mm and varies from 5-10 mm $d^{-1}$ in July to 4-8 mm $d^{-1}$ in October.

Soils. Nine major soil zones are identified in India (UNESCO 1977). Pearl millet is grown on different soils. It is mostly grown on light-textured soils (Entisols) under a wide range of rainfall, from extreme dry to moderate, in Rajasthan and Gujarat. It is also grown in soils of light to medium texture (Aridosols and Alfisols) in Punjab, Haryana, Andhra Pradesh, Uttar Pradesh, Tamil Nadu, and Karnataka. On the heavy clay soils it is grown on deep soils (e.g., Vertisols) only in the lower rainfall areas like Karnataka and Maharashtra; under higher rainfall, its growth on heavy clay soils is confined to shallow well-drained soils, e.g., Vertic Inceptisols in Madhya Pradesh and Karnataka. Sivakumar et al. (1984) described at length the rainfall pattern and moisture- and nutrient-holding capacity of these soils.

# Traditional Farming Practices

Local farming practices vary widely depending on soil type, rainfall pattern, and availability of power (camels, cattle, or tractor) and implements (plow, blade harrow, and seed drill, made of either wood or iron).

**Varieties.** Local varieties are grown in Rajasthan (RSK and RSJ), Maharashtra (Avsari and Deothan), Gujarat (Bajra 207, Bajra 28-15, L 17 Baroda, and Babapuri), Uttar Pradesh (Mainpur), Haryana and Punjab (Jakharana, T 55, S 530, and A 1/3), Andhra Pradesh (AKP 1 and AKP 2), and Tamil Nadu (CO 1 to CO 5 and K 1). The traditional varieties are shy tillering, tall, late, and poor yielding, but tolerant to diseases.

**Preparatory cultivation.** Land is plowed once in summer followed by 1-2 harrowings before planting in Gujarat, Maharashtra, Tamil Nadu, and Madhya Pradesh, but land is plowed twice in Rajasthan and eastern Uttar Pradesh before the onset of the monsoon.

**Manures and chemical fertilizers.** Farmers may apply farmyard manure whenever available, every year or alternate years, but it is not a common practice. As a general rule, chemical fertilizers are rarely applied, but some farmers in Gujarat, Haryana, Tamil Nadu, Punjab, Maharashtra, and Karnataka apply complex fertilizer at 20-60 kg $ha^{-1}$ N, in single or split doses.

**Time of sowing.** Pearl millet is sown either by broadcast in Uttar Pradesh, by pora (drilling with a single tube behind the plow) in Rajasthan, or by kera (hand sowing behind a plow) in Andhra Pradesh. The crop is transplanted behind the plow in north coastal Andhra Pradesh.

**Plant populations.** Optimum plant populations are not common: undulating land resulting in dry and wet patches, uneven sowing depth, poor seeding emergence due to crusting, low seeding rates which do not permit thinning and transplanting, and seedling death due to early breaks in the monsoon all hamper plant establishment.

Farmers seed at a rate of 2.5 kg $ha^{-1}$, with typical spacing between rows varying from 30 cm in Maharashtra to 75 cm in Gujarat. The plant-to-plant distance also varies from 5-20 cm. Farmers barely maintain 50-75% of the recommended 180 000 plants $ha^{-1}$, and poor stands are primarily responsible for low harvests.

**Cropping pattern.** Pearl millet is grown in sole, mixed, or multiple cropping systems. It is grown in dry areas usually from kharif (rainy season) to kharif with no intervening crop. In the rainy season, it is grown mixed with a wide variety of pulses such as pigeonpea, greengram, blackgram, and horsegram (Maharashtra and Gujarat), cowpeas (Haryana and Punjab) and cluster beans (Rajasthan), and a variety of oilseeds such as groundnut (Gujarat, Andhra Pradesh, Karnataka, and Tamil Nadu) and sesame (Andhra Pradesh).

Rainy season pearl millet is followed by winter or postrainy cereals (wheat), pulses (chickpea), and oilseeds (mustard in Uttar Pradesh, Haryana, and Punjab), cereals (rice in Andhra Pradesh), and oilseeds (niger, *Guizotia abvssinica* [1.f.] Cass., in Maharashtra).

**Cultural practices.** Hand weeding is done in many states to the extent family labor permits. Hoeing is done in Gujarat, Maharashtra, Andhra Pradesh, Tamil Nadu, Karnataka, and Madhya Pradesh once or twice, depending on weed growth, 3-6 weeks after sowing.

**Diseases and pests.** Pests and diseases are not common on local varieties. Control measures are therefore not practiced by farmers.

**Harvesting and threshing.** After maturity, pearl millet plants are cut to ground level, sun dried, bundled, and stacked. Threshing is done manually or by animal power in most states, but tractors are used in Haryana and Punjab. The grain is cleaned of plant debris by winnowing, and stored in containers of earth, wood, jute, etc.

**Utilization.** Almost all the grain is used for local human consumption, but the excess is sold in local markets. Fodder is used to feed animals or occasionally for roofing, fencing, and fuel.

## Food Uses

Pearl millet is an indispensable food for millions inhabiting the semi-arid and arid tropics, and is more important in the diet of the poor.

Flour, grits, and whole grains of pearl millet are used to prepare staple foods like unleavened flat bread, cooked whole grains (called rice), and thin and thick porridge. Several other preparations use only pearl millet or blends with wheat, rice, or pulses. Differences in interstate preparations are discussed by Pushpamma and Chittemma Rao (1981).

Unleavened flat bread, called roti or chapati, is the most common preparation in millet growing areas. Finely ground millet flour is made into a firm dough with water, rolled into balls, flattened into a thin or thick bread between the hands or on a stone, and open baked on a shallow frying pan.

To make thin porridge, flour is mixed with water (1:4), boiled, and consumed with buttermilk and seasoned with jaggery (unrefined brown sugar) or salt. Sometimes pearl millet flour is mixed with finger millet flour. In thick porridge, the grits, obtained by dry or wet grinding, are first cooked in water (1:2 or 3), and the flour is later added to thicken the mixture. Sometimes the dehulled grain is cooked in water (1:3) like paddy rice.

Dry pearl millet grain can be popped in hot sand. The pops are sometimes eaten with powdered sugar or jaggery. Deep fried snacks can also be made from pearl millet. The grain is ground to a paste, flattened into rounds, and deep fried in oil to make puris. This paste is sometimes mixed with jaggery syrup, flattened into rounds, and deep fried to make sweet preparations. In another preparation, called hodge-podge, pearl millet grains are mixed with split pulses and cooked like rice. It is called kichri in north India.

## Production Constraints

**Low hybrid coverage.** Hybrid seeds need to be replaced each year. Hybrid seed production requires technical skills, off-season or off-location facilities, and financial investment. In spite of best efforts, in 1982-83 only about 40% of the pearl millet seed used in India was hybrid (Singh, G., no date), but the coverage varies from state to state. Gujarat, Andhra Pradesh, Tamil Nadu, and Punjab use more than 75%, Haryana 62%, Maharashtra and Karnataka approached 50%, while only 26% was used in the major millet growing state, Rajasthan.

**Slow varietal spread.** The spread of varieties has been slow. Unlike hybrids, varieties are heterogeneous, nonsynchronous, may be low tillering, and commercial seed is less uniform. The average productivity of varieties is lower than hybrids in AICMIP trials (Table 5). The certification of varietal seed has been a problem because varieties, with few exceptions, are less easily identified or described, but large quantities of certified seed of varieties have been produced in India.

**Limited cultivar choice.** The cultivation on a large scale of a single cultivar, such as HB 3, or now BJ 104, builds soil inoculum, resulting in varietal breakdown from increased disease pressure. Farmers should be encouraged to plant more than one cultivar to prevent the rapid spread of downy mildew, and to stabilize production under different agroclimatic conditions. The seed agencies should also be encouraged to produce diverse hybrids and varieties.

Table 5. Comparative performance of pearl millet hybrids and varieties in all India trials.

| | Hybrids (kg $ha^{-1}$) | | Varieties (kg $ha^{-1}$) | |
|---|---|---|---|---|
| Year | Initial trial | Advanced trial | Initial trial | Advanced trial |
| 1977 | 1954 | 2142 | 1318 | 1540 |
| 1978 | 1950 | 1883 | 1744 | 1945 |
| 1979 | 2215 | 2002 | 1831 | 1683 |
| 1980 | 2082 | 2109 | 1787 | 1727 |
| 1981 | 2104 | 2184 | 1893 | 1924 |
| 1982 | 2299 | 2328 | 1821 | 1784 |
| 1983 | 1764 | 2049 | 1272 | 1694 |
| 1984 | 1825 | 1863 | 1496 | 1577 |
| 1985 | 1908 | 2021 | 1594 | 1524 |

Source: Progress Reports of the All India Coordinated Millets Improvement Project, 1977-86.

**Low plant populations.** Grain yield is directly related to plant stand. Poor germination from low quality seed and low soil moisture leads to seedling death, reduced plant stands, and low grain yields. Plant stand establishment is critical to obtain higher grain yields.

Farmyard manure in seed furrows has helped to establish plant stands and produce higher grain yields (1834 kg $ha^{-1}$) than pora sowing (1083 kg $ha^{-1}$) or kera sowing (1094 kg ha"[1]) (AICMIP 1977-1982). Farmyard manure application also improves the soil.

**Chemical fertilizer.** Pearl millet usually receives no or low amounts of chemical fertilizer, but its response to fertilizer is tremendous. Even without fertilization, a high-yielding variety or a hybrid outyields local cultivars. Nitrogen application, however, widens this difference, indicating that the high-yielding varieties and hybrids use nitrogen more efficiently. Based on the response to nitrogen application, it is estimated that for every 1 kg N applied, the hybrids or improved varieties return 10-15 kg of grain at 30-60 kg $ha^{-1}$ N as compared to no application. However, 40 kg $ha^{-1}$ N was found to be profitable for most of the pearl millet growing regions, but higher nitrogen levels (60-80 kg $ha^{1}$) are recommended in areas with assured rainfall such as Gujarat and Uttar Pradesh. The response was also higher in hybrids than in synthetics and composites (AICMIP 1977-79).

**Weeds and weed control.** Because weeds compete with crops for water, nutrients, air, and space, it is imperative to keep fields weed-free. Hand weeding is superior to herbicidal application, but is more expensive and labor intensive, two elements which are limited under dry farming conditions. Preemergence application of Atrazine at 0.5 kg $ha^{-1}$ a.i. (active ingredient) reduced weeds from 1610 to 460 $nr^{2}$, and increased grain yield by 23% from 1870 kg $ha^{-1}$ (no weeding) to 2310 kg $ha^{-1}$, compared to repeated weedings (2670 kg $ha^{-1}$) (De and Gautam 1987).

**Transplanting.** Under normal conditions, direct sowing is superior to transplanting, but if sowing is delayed, transplanting is better than direct seeding. Transplanting should be done with 3-week-old seedlings, and could be extended up to mid-August where feasible. Transplanting offsets the rapid decline in grain yield from late seeding, helps cull diseased seedlings,and reduces the intensity of secondary infection.

**Diseases.** Diseases are endemic to pearl millet in India. Depending on weather conditions and genotype, downy mildew, ergot, and smut assume epidemic proportions. Downy mildew is a recurring threat, threatening high-yielding varieties since the 1970s. Ergot and smut lower only grain yield, but downy mildew also kills plants.

# Research Strategies

## Genetic Resources

The pearl millet germplasm collection at ICRISAT is 17 621 accessions from 42 countries as of September 1985. To be more useful, the morphological, physiological, and biochemical characteristics of the accessions should be published in a catalogue, which would stimulate use of the collection.

### Breeding Hybrids and Varieties

**Heterogeneous hybrids.** Phenotypically and genotypically homogeneous pearl millet hybrids are produced by crossing two inbred lines. This uniformity makes the hybrids vulnerable to diseases and pests. There is evidence that open-pollinated varieties are less susceptible to ergot and smut since they flower less synchronously, and pollination protects against these diseases. The use of partially inbred or open-pollinated restorers introduces phenotypic and genotypic heterogeneity into the hybrids, and may reduce disease incidence.

**Multicross hybrids.** The single-cross pearl millet hybrids are quickly becoming vulnerable to diseases, particularly downy mildew, because of genetic homogeneity. Triple- and double-cross hybrids may provide phenotypic and genetic heterogeneity to resist diseases.

**Bold-seeded hybrids and varieties.** Seed size is a significant component of grain yield. The commercial hybrids and varieties have small- to medium-bold grains, 4-6 g per 1000 grains, but grain size can vary from 2-14 g per 1000 grains. The private sector hybrids MBH 110 and MBH 118 are also bold seeded. It has become necessary to combine bold seed with higher effective tillering in male-sterile lines, restorers, and parents of open-pollinated varieties to produce higher-yielding, bold-grained hybrids and varieties.

**Sweet pearl millets.** The need for dual-purpose grain and fodder pearl millet hybrids and varieties requires the attention of research workers. Brix readings can vary from 3-16%. The value of pearl millet would rise substantially if sweet pearl millets for sugar extraction could be bred.

**White- and yellow-grained pearl millets.** White-grained pearl millets have an attractive color, high protein content, and are sweet. Yellow-grained pearl millets are rich in carotene, the precursor of vitamin A. The development of nutritionally superior white- and yellow-grained pearl millets would enhance the food value of the millet consumed by the poorest section of the population, and may find a place in irrigated farming.

# Manipulation of Production Processes

**Adaptation, tillering, and plant density.** High tillering potential appears to confer adaptive advantage to pearl millet in the semi-arid tropics. Low plant densities appear to promote tillering. Hybrids which have high tillering yielded more grain at low plant densities than composites and landraccs (Harinarayana 1980).

Tillers are produced at the base and nodal points. The ratio of effective to basal tillers (0.35) favors basal tillers in hybrids compared to varieties (0.59) indicating that all basal tillers are not productive (Harinarayana 1980), and hence the source of photosynthates is limiting. Tillering differences indicate the necessity to intensify studies on tillering potential of different millet genotypes in relation to plant densities.

**Dry matter production and distribution.** Hybrids and improved varieties produced more dry matter than local varieties. In spite of comparable harvest indices, hybrids produced higher grain yield than varieties, indicating high dry matter production and efficient distribution. Differences were also observed between early and late hybrids, and hybrids with common female and male parents. All these indicate the immense potential for breeding hybrids and varieties with higher harvest indices, or increased fodder production (AICMIP 1980).

**Effective water use.** Nearly 40% of the cultivated area in India is likely to be irrigated during the 1980s.

Pearl millet should find a place in irrigated dry areas, which could double and stabilize production with minimum inputs. Pearl millet can be successfully raised during the summer under irrigation.

In experiments under the All India Coordinated Millets Project, pearl millet hybrids produced 15-44% more grain under irrigation than under rainfed conditions (1400-1840 kg $ha^{-1}$) (Harinarayana 1980). Irrigated CJ 104 (5054 A x J 104) yielded 44% more than in the rainfed trial, while BJ 104(5141A x J 104) yielded only 30% more grain under irrigation, indicating female differences in water use. Similarly, differences due to males are discernible in the hybrids BD 111 (5141A x D 111) and BK 560 (5141 A x K 560), revealing selection potential for water input.

**Salt tolerance.** Uncontrolled and indiscriminate irrigation and poor drainage are increasing soil salinity. Understanding the physiology of salt tolerance and adaptation mechanisms will undoubtedly facilitate the development of management techniques for saline soil and water. The effects of salinity on germination, growth, and yield of pearl millet need critical investigation. Pearl millet hybrids appear to be more tolerant to salinity than populations (AICMIP 1979). Among the hybrids, the grain yield of CO 2 was 14 g $row^{-1}$ as against 161 g of PHB 14 and 28 g of BJ 104, indicating the existence of genetic variability for salt tolerance.

**Tolerance to micronutrients.** Alkaline soils occur in subhumid, semi-arid, and arid climates, and are well suited to small-grain agriculture. Plants grown in alkaline, acid, or saline soils accumulate unwanted minerals that limit root growth and nutrient uptake. Alkaline soils are deficient in iron and high in sodium and boron, while acid soils are high in aluminum. The development of wheat varieties well suited to very acid, high-aluminum soils in Brazil indicates varietal differences in tolerance to toxins.

**N, P, and K uptake.** Variations were observed in pearl millet fertilizer requirements, uptake, and utilization. Nitrogen utilization from applied fertilizer was highest in HB 4 when compared to HB 3 and HB 1. The utilization of soil N by HB 4 was intermediate between that of HB 3 and HB 1, while the N requirement to produce 100 kg grain was minimal. Since the female parent (Tift 23A) was common to all these hybrids, the N utilization differences are conceivably attributable to the male parents, K 560, J 104, and BIL 3B (B. Rama Moorty, Indian Agricultural Research Institute, New Delhi, personal communication).

These genotypes exhibit differential responses to fertilizer input, and different production potentials at different fertility levels indicates that the genotypes have different threshold responses. Germplasm and breeding material in advanced stages should be evaluated under different fertility levels.

## Input Management

**Biofertilization.** Bacterial fertilization has been found to affect consumption of recommended inorganic nitrogen. *Azospirillum* application alone increased grain yield from 1115 to 1434 kg $ha^{-1}$ (Harinarayana 1980). The effect varies depending on location, pH, C:N ratio, and supplemental nitrogen application. *Azospirillum* with 10 kg $ha^{-1}$ N has yielded as much grain as 20 kg $ha^{-1}$ N, indicating that 10 kg $ha^{-1}$ N could be saved. *Azospirillum* production should be commercialized on the lines of *Rhizobium* and applied extensively to increase pearl millet grain yield with or without the addition of inorganic nitrogen. More efficient strains better compatible with specific genotypes, and factors, both plant and bacterial, responsible for this specificity should be identified for large-scale screening.

The rhizosphere bacteria are influenced by mycorrhizae which increase the uptake of phosphorous, even in soils with threshold levels (Hubbell 1987). Studies to identify associative mycorrhizae beneficial to pearl millet in poor soils would be useful.

**Cropping systems approach.** The ever-increasing demand for food puts a premium on increasing food production per unit area. The traditional mixed farming systems have been scientifically transformed into intercropping systems which include pearl millet. The total system needs modifications based on selection of genotypes for plant habit, plant height, maturity, manipulation of ratio and proportion of component crops, and management of production components such as fertilizer, water, weeds, etc.

**Graded technology.** The adoption levels of improved technology vary depending on farm size, and farmer financial and technical resources. Field experience shows that technology based on low monetary inputs such as the introduction of high-yielding varieties and improved cultural practices has been widely adopted by all classes of farmers. However, graded technology is necessary to suit the varying levels of adoption. The relative contribution of each of the inputs to farmers of divergent resource bases operating at different levels of skills and management should be determined.

## Multiple Disease Resistance

Disease-induced crop losses are controlled through incorporation of resistant genes into host cultivars. The breeding of multiple disease-tolerant varieties should form the basic strategy to manage diseases in the coming decades. This appears to be particularly true of pearl millet, so often threatened with several diseases. The breakdown of downy mildew resistance, and the low frequency of ergot- and smut-tolerant pearl millets should open new vistas in biochemical pathology.

**Downy mildew.** Genetic studies have revealed strong cytoplasmic differences between F,s and reciprocal $F_1$s (Harinarayana 1980). The $F_1$s have been similarly ranked as their parents, confirming the cytoplasmic differences. Pooling resistant genes in a chosen cytoplasm appears worthwhile to stabilize downy mildew resistance.

The Indian parents were less susceptible than their African counterparts, revealing differential vulnerability due to different genes or races. The differential reaction combined with the reversal of cytoplasmic effects suggested the potential of Indian x African crosses for India, and African x Indian crosses for Africa.

**Ergot.** Pollination prior to ergot infection appears to prevent invasion of the stigma through a postpollination stigmatic constriction (Willingale and Mantle 1985). Ergot resistance based on selection for minimizing the time period between stigma emergence and anthesis has been successful (Willingale et al. 1986). Alternatively, apomictic genes from related species could be incorporated into cultivated *Pennisetums.* Heterogeneous hybrids, hybrid mixtures, and genocropping systems could conceivably match the need for high grain yield and temporal pollen provision (Thakur et al. 1983).

**Disease control.** Metalaxyl compounds appear to control downy mildew infection, prevent its secondary infection, and reduce the spore load in the soil. Seed treatment, sprays, and soil formulations are very effective but expensive. Cheaper, but effective chemical formulations to contain downy mildew and other diseases need to be identified.

## Policy Needs

**Pearl millet in the food security system.** The global food security system should build up national food grain buffer stocks. Pearl millet accounts for 12% of the area and 5.5% of the cereal production, and is a stabilizing force in the buffer stocks of India. Pearl millet is practically devoid of stored grain pests, and has a long storage life and keeping quality, minimizing storage costs. Pumping pearl millet into the food economy during low production years, even in preference to wheat and rice available at reasonable rates, provides nutritious food and reduces dependence on imported food grains. Price supports for millets should be coupled with guaranteed markets. The concomitant changes in food habits and demand would accelerate pearl millet development and production.

**Crop of poor resource base.** Pearl millet efficiently uses soil moisture and nutrients. It has the ability to produce some grain even under the most adverse weather conditions. It is preferred by farmers as a low cost, low risk option, not by choice, but by necessity. Hence it is relegated to marginal areas—areas with low soil fertility and low soil moisture, those permanently deprived of a more productive resource base. This adversely affects pearl millet production. It is a partner in the management of marginal areas, and marginal productivity contributes to differential resource allocation not only at the farmers' level, but also by national planners and policy makers.

**Transfer of technology—a must.** New technology has a key role to play in increasing the productivity of pearl millet. Specific technologies to suit small, medium, and large farmers as well as moisture and fertility gradients, have been developed by two All India Coordinated Projects, Millets and Dryland. These national research efforts are supplemented by international efforts through ICRISAT. These technologies have been tested on farmers' fields through Minikits, National Demonstrations, and Operational Research Projects.

**Doorstep technology delivery system.** Small and marginal farmers have yet to benefit from newly developed production technologies. Small and marginal farmers are often concerned with earning their daily bread and do not have time enough to spare for information transfer at a fixed time and place. It is necessary to reach them where they are. It would be worthwhile to develop a system for delivering technologies at the doorstep of these farmers.

## Management

Hybrids versus varieties. All the released and recommended hybrids have a grain-yield potential of around 2000 kg ha*[1] under rainfed conditions with little or no fertilization (Harinarayana 1985). However, hybrids have a higher grain-yield potential than varieties. On the basis of AICMIP yield data on released varieties and hybrids, hybrids should be preferred to improved varieties in the states of Maharashtra, Uttar Pradesh, Haryana, Andhra Pradesh, Madhya Pradesh, and Punjab.

The first varieties had lower grain-yield potential than the hybrids, but newly-released varieties and varieties not yet released are approaching or exceeding the grain yield of popular hybrids. Unlike hybrids, the varieties are self-perpetuating, more diverse, and less vulnerable to ergot, smut, and downy mildew.

As a rule, hybrids and improved varieties should be grown on equal areas to insure high and stable returns, and reduce the risks from drought and diseases.

Nitrogen application. Next to quality seed of high-yielding varieties, nitrogen becomes critical, particularly under drought conditions. Rajasthan, Maharashtra, Gujarat, and Uttar Pradesh together account for 76.7% of the area and 68.8% of pearl millet production in the country. However, the total N, P, and K consumption of Rajasthan does not exceed 10 kg $ha^{-1}$ with a total food grain production of less than 500 kg ha' (AICMIP 1983). Although Maharashtra (21.2 kg $ha^{-1}$), Gujarat (34.4 kg $ha^{-1}$), and Uttar Pradesh (49.4 kg $ha^{-1}$) consume more N, P, and K, the total food-grain productivity is less than 1 t $ha^{-1}$, indicating inequitable distribution of fertilizers between food grains and other crops. As a no- or low-energy input crop, pearl millet is fertilizer-starved and fertilizer-hungry, but its response to fertilizer is tremendous and the grain yield increases many-fold. Fertilizers should be allocated to rainfed pearl millet, subsidized to cover any risks, and preferably applied on a community basis. This is a necessary "minimum" of dry farming technology if pearl millet is expected to contribute significantly to the national food basket.

**Managing soil moisture.** Rainfed pearl millet faces a soil-moisture deficit during grain formation and seed development. Soil moisture conservation through grading, land shaping, drainage, erosion control, etc., is pivotal for the success of any technology. This often transcends individual boundaries and involves community and group action. Large scale adoption requires huge capital investments for equipment and technical expertise. The necessary infrastructure and institutional support is often missing in the rainfed areas.

**Collateral hosts for ergot.** Natural incidence of ergot has been observed on *Cenchrus ciliaris* and *Panicum antidotaJe* (Thakur and Chahal 1987). Cross inoculation studies confirmed their role. Eradication or deflowering of these graminaceous weeds requires urgent community action to reduce the incidence of downy mildew and ergot.

**Varietal rotation.** Currently a large number of hybrids and varieties are available for commercial exploitation. It would be advisable to rotate hybrids and / or varieties in order to discourage a single genotype and/or biotype of a particular disease. Varietal rotation similar to sequence cropping but limited to the varieties of the same crop prevents the outbreak of diseases.

**Hybrid mixtures.** Heterogeneous populations have a low incidence of disease infection. F, hybrids with and without disease resistance have been mixed to combine the twin advantages of high productivity with low disease incidence. Compared to downy mildew, ergot, and smut in pure stands, hybrid mixtures have recorded less infection than either of the parental hybrids. NHB 3 in pure stand has 44% downy mildew as against 6, 8, and 11% in combination with BK 560, CJ 104, and BJ 104. CJ 104 + BK 560 had 1.3% smut as compared to 1.9% in BK 560. BJ 104 + CJ 104 had comparable ergot incidence as the parents, but the mixture yielded more grain (Harinarayana 1982). Early and late hybrids should be mixed and cultivated widely to elevate grain yields and minimize disease infection.

**Genocropping systems.** Hybrid mixtures could adversely affect the seed industry. Genocropping, which is intercropping varieties of the same crop in order to maintain their identity and insure purity, has been advocated. A genocropping system functions on the principle of horizontal resistance to contain disease spread.

## Socioeconomic Factors

Management. There are significant managerial differences in the dryland farming villages of India. Farmers born in traditional farming households and farmers who receive hands-on farming training proved to be better managers.

Farm prices. The cost of inputs, particularly fertilizer and labor, have increased sharply in recent years, but prices for farm produce have not kept up. Fertilizer prices increased by 60% from 1980-81 to 1981-82. While large and efficient farmers can rapidly adjust to fluctuations, the small farmers are caught. Farm prices should be tied to industrial prices.

Credit and insurance. Farmers may not necessarily strive to maximize yields, particularly in a subsistence economy based on diversified farming. Small and marginal farmers do not have the ability to mobilize resources and cannot afford to take risks. For example, next to improved seed, fertilizer brings about the most visible changes in productivity. Large farmers readily adopt recommended practices, but even though small and marginal farmers are convinced of the utility of fertilizer application, they do not fully adopt the recommended levels because of the financial risk. Farmers are sensitive to price increases, lack of credit, and should be provided with cheap credit covered by insurance to insulate against bad weather.

Transport. Small and marginal farmers have limited marketable surpluses, and middlemen are the ultimate beneficiaries if the produce is taken to regulated markets.

Rural warehouses. It is necessary to develop a network of rural godowns (warehouses) to stockpile surplus production, and provide credit or advance payment that would partly ease the financial limitations of small and marginal farmers (Dwarakinath 1980).

## Future Outlook

India has 143 million ha of arable land. Nearly 50% is to be irrigated by 1990. The area under pearl millet has remained relatively stable, about 11 million ha over the past 30 years (10.58-13.93 million ha from 1954-1985). It is unlikely that a substantial pearl millet area would be lost to irrigation and other crops. Pearl millet production could be stabilized at over 5 million t during the 1980s. Productivity crossed the 500 kg $ha^{-1}$ mark in 1980-84, and could be elevated to 2000 kg $ha^{-1}$. Pearl millet continues to play a significant role in Indian food production as well as the economy.

Given the will and improved seed, and some fertilizer and irrigation where feasible, the productivity and production of pearl millet could be increased two- to four-fold. Substitution for rice and wheat by millets in food products, identification of new uses for pearl millet, development of white pearl millets and pearl millets with defined uses, price supports assured by firm procurement, distribution of millets during low production years, and utilization in food for work and nutritional networks, all would accelerate the growth, development, and utilization of pearl millet, an indispensable cereal of the semi-arid and arid tropics.

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# Pearl Millet in African Agriculture


## D.S.C. Spencer[1] and M.V.K. Sivakumar[2]



### Abstract

*A bout one-third of the world's millet is grown in Africa, about 70% of which is grown in West Africa. Pearl millet is the major millet grown in Africa. In relative terms pearl millet is more important to the agricultural systems and economies of Africa than in other regions of the world.*

*Millet production has increased at only 0.7% $a^{-1}$ during the last two decades, the slowest growth rate among food crops. Furthermore, the growth has been primarily due to increases in cultivated areas, indicating that technological innovations have not had much impact on aggregate millet productivity.*

*Pearl millet is used mainly as a grain-like flour (couscous), a dough (t6), and a porridge (fura, boule).*

*Abiotic constraints to increased millet production include the low and erratic rainfall in a short growing season, sand storms, high intensity rains, high air and soil temperatures, poor soils with low levels of natural fertility, traditional management practices such as low crop densities, and no fertilization.*

*Biotic constraints include the low genetic yield potential of local landraces, the effects of diseases such as downy mildew, the parasitic weed* Striga, *and grain-eating birds.*

*Pearl millet is traditionally grown as an intercrop with a legume such as cowpea or groundnut. In such situations economic returns are much higher than for a pure crop millet.*

*Prospects for millet production are increasing as research on the crop expands.*



### Résumé

**Rôle du mil dans l'agriculture africaine :** *Près d'un tiers de la production mondiale du mil provient de l'Afrique, en particulier l'Afrique de l'Ouest qui fournit 70% de la production du continent. La principale espèce cultivée est* Pennisetum americanum. *Le mil joue un rôle plus important dans l'agriculture et les économies africaines que dans d'autres parties du monde.*

*La production de mil s'est accrue de seulement 0,7% par an au cours de ces deux dernières décennies, soit le plus faible taux de croissance parmi les cultures vivrières. Cette croissance est plutôt due à l'expansion de la superficie cultivée, ce qui signifie que les innovations technologiques n'ont pas eu d'impact significatif sur la productivité.*

*Le mil est consommé sous forme de semoule (couscous), de pâte (tô) et de bouillie (fura, boule).*

*Les contraintes abiotiques à l'augmentation de la production sont : la pluviométrie faible et imprévisible pendant une courte saison de culture, les vents de sable, des pluies très intenses, des températures atmosphériques et du sol élevées, des sols peu fertiles, des pratiques traditionnelles, notamment une faible densité de semis et aucun apport d'engrais.*

*Parmi les contraintes biotiques, il faut signaler le faible potentiel de rendement génétique des variétés traditionnelles ainsi que les effets des maladies telles que le mildiou, de la mauvaise herbe* striga *et des oiseaux granivores.*



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Submitted as CP 380 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

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***En culture traditionnelle, le mil est cultivé en association avec une légumineuse telle que le niébé et l'arachide. Dans ce cas le rendement est plus élevé par rapport à une culture pure de mil.***

***L'intensification de la recherche sur le mil permettra d'améliorer les perspectives de production de cette espèce.***

# Area, Production, and Use of Millet

## Importance of the Crop

World production of all millets is about 29 million t, of which about 35% is produced in Africa (Table 1). The major African producers are Nigeria (about 31% of the African production) and Niger (about 12%), both in West Africa. Other major producers are Burkina Faso, Chad, Mali, and Senegal in West Africa, and Sudan and Uganda in East Africa.

Pearl millet *(Pennisetum americanum)* is the major millet grown in Africa. Apart from Uganda, which grows mainly finger millet, *Elusine corocana* (ICRISAT 1980), all the major African producers listed in Table 1 produce primarily pearl millet.

In all the major African millet-producing countries, the crop is of considerable importance in the agricultural system, and accounts for over one-third of total cereal output (Table 1). This contrasts with other areas of the world where large quantities of millets are produced, but in which they usually account for less than 10% of total cereal output. For example, India grows one-third of the world's millet, but the crop only represents about 7% of total cereal production. About 65% of Indian millet production is pearl millet. In relative terms pearl millet is more important to the agricultural systems and economies of Africa than in other regions of the world.

## Aggregate Production and Growth Rates

Sub-Saharan Africa (SSA) is the only part of the developing world in which the index of per capita food production has declined during the last two decades (World Bank 1984). Of all the subregions of SSA, West Africa has shown the slowest growth rate for total food production. Per capita production of all crops in West Africa has declined, except for rice, which is a minor staple in the region.

Table 1. Average annual area, production, and yield of millets and percentage of total cereal production by major producing countries in Africa as well as major regions of the world, in 1974-76 and 1980-82.

| Region/ country | Area (000 ha) | | Cereal Production (%) | | Production (000 mt) | | Yield (kg ha$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | 74-76 | 80-82 | 74-76 | 80-82 | 74-76 | 80-82 | 74-76 | 80-32 |
| Africa | 15218 | 16247 | 13.9 | 13.8 | 9630 | 10249 | 633 | 619 |
| Burkina Faso | 857 | 870 | 31.7 | 32.1 | 364 | 387 | 425 | 441 |
| Chad[1] | 959 | 1160 | 87.8 | 88.0 | 520 | 593 | 542 | 510 |
| Mali[1] | 1212 | 1425 | 70.1 | 76.9 | 852 | 868 | 702 | 615 |
| Niger | 2150 | 3060 | 74.0 | 76.5 | 828 | 1321 | 385 | 432 |
| Nigeria | 4800 | 5230 | 34.5 | 32.4 | 2843 | 3220 | 592 | 636 |
| Senegal[1] | 1004 | 938 | 79.7 | 80.7 | 658 | 642 | 655 | 705 |
| Sudan | 1126 | 1120 | 15.8 | 12.3 | 416 | 393 | 370 | 345 |
| Uganda | 498 | 303 | 38.2 | 42.1 | 613 | 489 | 1232 | 1615 |
| Asia | 25212 | 23450 | 3.0 | 2.5 | 16718 | 16445 | 663 | 701 |
| India | 18338 | 18096 | 7.6 | 6.7 | 9042 | 9426 | 493 | 521 |
| South America | 211 | 167 | 0.4 | 0.3 | 241 | 193 | 1141 | 1157 |
| USSR | 2914 | 2807 | 1.4 | 1.1 | 2410 | 1791 | 827 | 637 |
| World | 43610 | 43050 | 2.1 | 1.8 | 29062 | 28733 | 666 | 668 |

1. Includes sorghum.
Source: FAO Production Yearbook 1982.

The poor performance in food production is due in large measure to the very low and sometimes negative rates of growth for the major staples, i.e., millet and sorghum *(Sorghum bicolor L.)* as well as groundnut *(Arachis hypogea* L.) (Table 2).

Millet recorded the lowest growth rate of all food crops, except for groundnuts, during the past two decades. Its growth rate of only 0.7% $a^{-1}$ was substantially lower than the population growth rate of about 2.5% $a^{-1}$ during the same period.

### Crop Use

Pearl millet grain in Africa is grown primarily for human consumption. There are three primary methods of using the grain: as a grain-like flour (couscous), a dough (to), or a gruel (fura, boule, etc.). In West Africa, millet couscous is eaten mainly by the Peuhl, and is thus common in the regions where they live in Senegal, Gambia, and northern Nigeria. After decortication the grain is pounded into flour. Couscous is made by steaming the flour on a mat over an open pot, then sun drying. At mealtimes the couscous is boiled and served with a vegetable, fish, or meat sauce.

Among the other major ethnic groups in the Sahel (Bambara, Germa, Mossi, etc.) millet is more often consumed as *to.* Millet flour is cooked with water and an alkaline solution to make a thick paste or dough. The alkaline solution is made from burned millet straw. This is eaten by dipping into a meat or vegetable sauce.

To prepare the gruel or porridge (fura, boule, etc.,) millet flour is boiled with water. Milk, sugar, pepper, or salt may or may not be added. Fura is usually eaten as a secondary meal in the mornings or midday, although in times of scarcity it may be the only meal eaten.

At the onset of harvest immature millet heads are occassionally roasted and eaten as a snack. Millet cakes (slightly fermented millet flour deep fried in vegetable oil) are often sold in markets and urban areas. Another minor use of millet is in beer making.

Pearl millet straw has a number of important traditional uses in Africa. In areas where millet is the staple food, the straw is the most important building material for granaries and as a fencing material. It is also used to feed cattle and is sometimes harvested and stored for use as livestock feed during the dry season.

Table 2. Annual growth of major agricultural commodities in sub-Saharan Africa.

| | Growth rate $a^{-1}$ (%) | | |
|---|---|---|---|
| Commodity | 1969-71 to 1977-79 | 1977-79 to 1980-82 | 1969-71 to 1980-82 |
| Cereals | 1.3 | 1.9 | 1.5 |
| Maize | 1.3 | 0.8 | 1.2 |
| Millet | 0.4 | 1.6 | 0.7 |
| Rice (paddy) | 2.9 | 1.7 | 2.5 |
| Sorghum | 1.6 | 3.5 | 2.1 |
| Wheat | -0.2 | 3.9 | 0.9 |
| Oil & Oilseeds | | | |
| Coconuts | 0.9 | -0.8 | 0.5 |
| Groundnuts | -0.9 | -3.6 | -1.7 |
| Palm oil | 2.2 | 1.3 | 2.0 |
| Others | | | |
| Pulses | 1.1 | 3.8 | 1.8 |
| Roots and tubers | 1.8 | 1.7 | 1.8 |

Source: World Bank 1984, Table 22.

## Environmental Resources of the Area

Because of its adaptability to drought, pearl millet is grown in the regions of sub-Saharan Africa which have an alternately wet and dry climate. Since 70% of pearl millet in Africa is grown in West Africa, a major emphasis will be placed on West Africa in this section.

The low productivity of pearl millet in Africa is largely due to the harsh environment in which it is grown. Rainfall and soils are the major environmental resources that merit detailed analysis in the efforts to increase millet production.

### Rainfall

The bulk of African pearl millet is grown in the regions with annual rainfall ranging from 200-800 mm (Fig. 1). In West Africa, the rainfall gradient is very steep. Rains are usually limited to the summer months of May-Oct, and aridity prevails during the rest of the year.

Rainfall in the millet growing regions of Africa is not only low, but erratic. Large variations in time and space occur. The coefficient of variation of annual rainfall ranges from 20-30%. For example, mean annual rainfall in Niamey in Niger is 560 mm

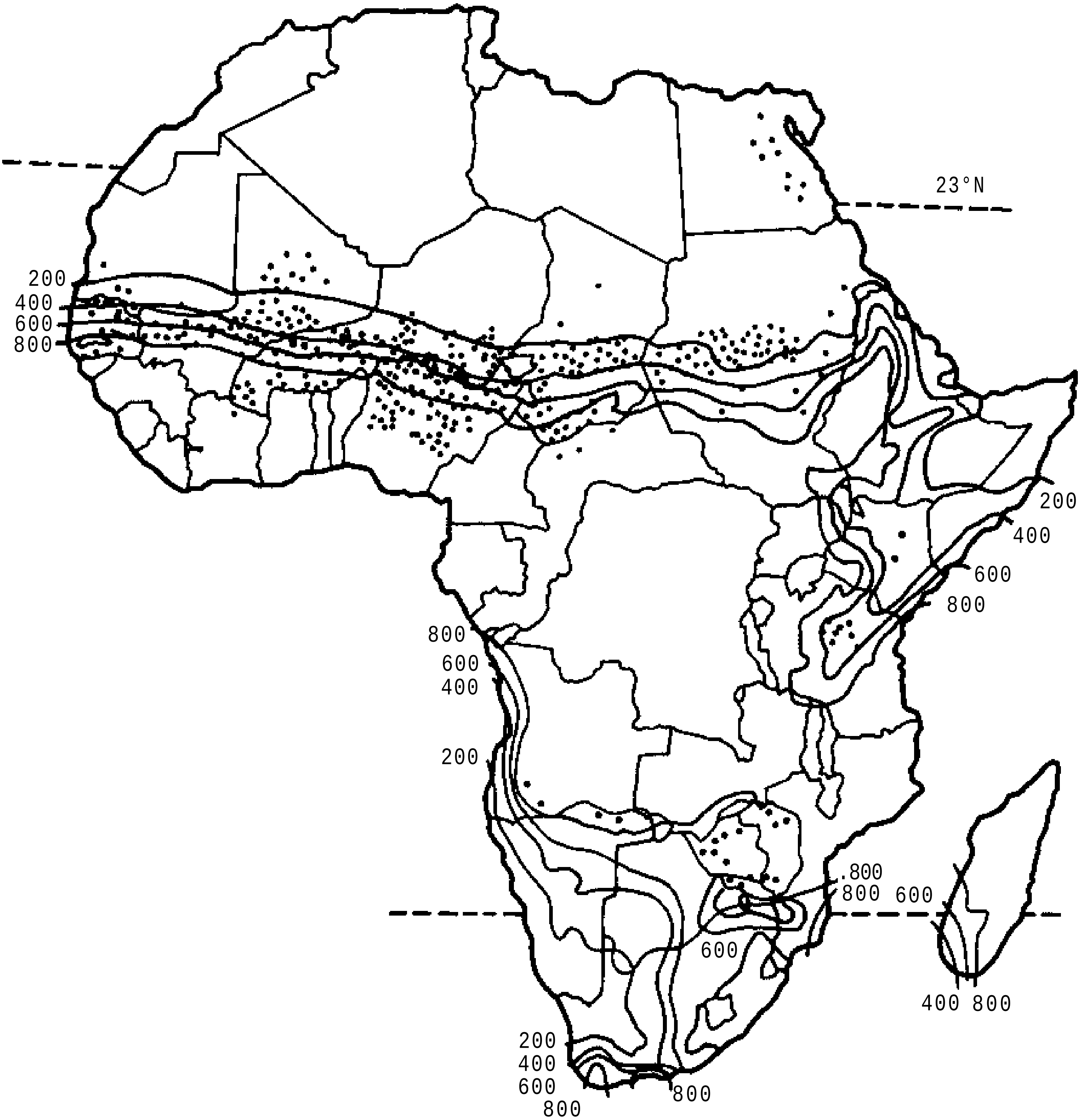


**Figure 1. Area planted to pearl millet in 1978 in relation to mean annual rainfall (mm) in Africa. Each dot equals 20 000 ha (Bidinger et al. 1982).**

over the last 80 years (Fig. 2), with a coefficient of variation of 26%.

Rainfall varies not only annually but also from month to month within the same year. Using the criterion of a mean annual rainfall of 560 mm, Niamey had an above-normal year in 1964, a normal year in 1968, and a below-normal year in 1972. However the rains terminated in early September in both 1964 and 1968 while in 1972 they continued until 18 Oct. These sorts of variations greatly affect crop production.

Furthermore, rain in West Africa often occurs in short but intense storms. Rainfall intensities usually range from 20-60 mm $h^{-1}$ with high values reaching 120-160 mm $h^{-1}$. On soils with lower infiltration rates, much of the water from such intense rains could run off, leading to low effective rainfall and heavy soil loss.

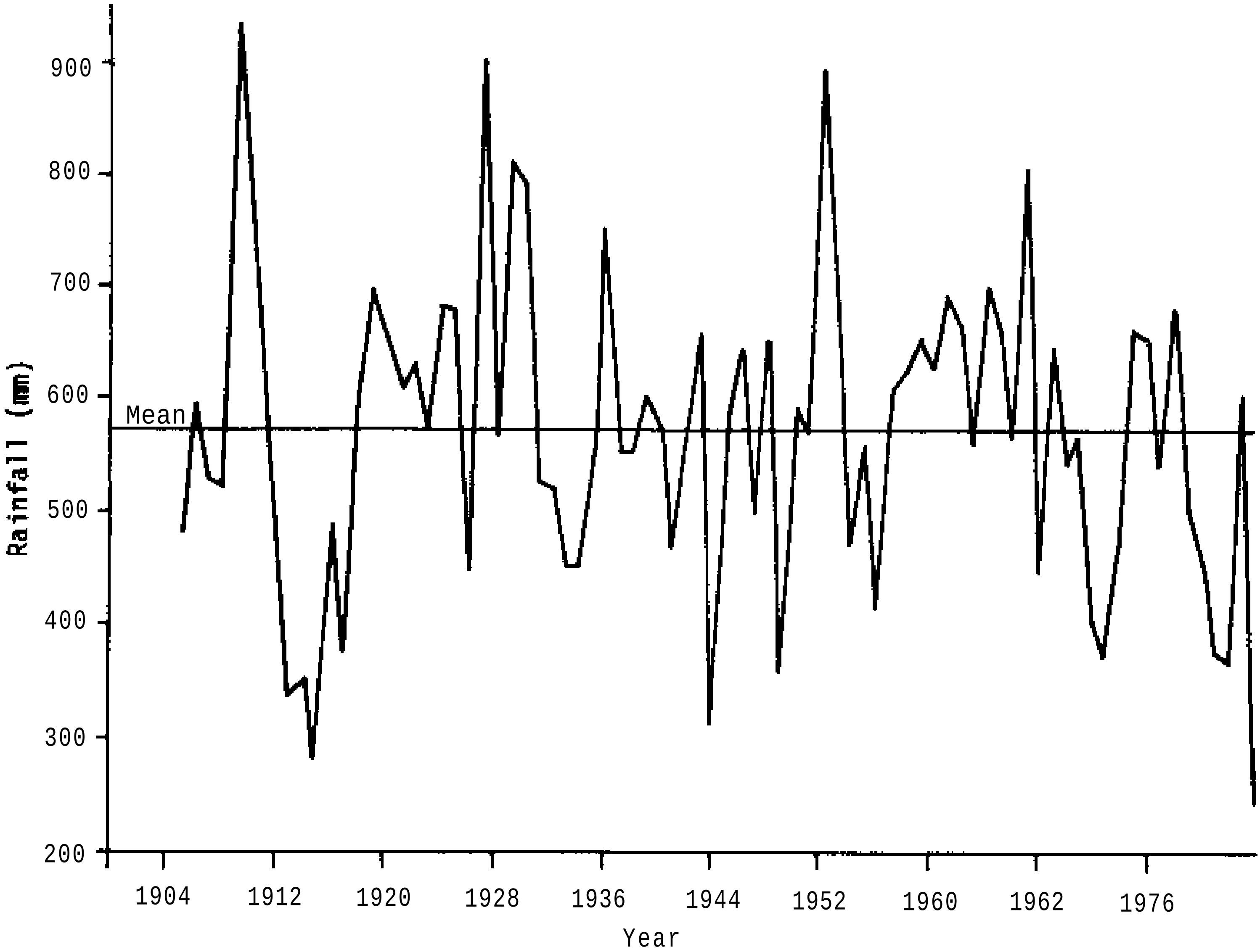


Figure 2. Annual rainfall variability of Niamey

## Growing Season

The variability in the annual and monthly rainfall opens to question the utility of the traditional practice of describing a crop-growing region using these figures. Average length of the growing season in the millet-growing regions of West Africa ranges from 60 d on the edge of Sahara to 150 d in the south. Of course, in drought years such as 1984, the growing season could be much shorter and lead to crop failure. Long-term daily rainfall data could be analyzed to provide meaningful information on the environmental risks to cropping. For example, the dates of beginning and ending of the rainy season and the length of the growing season have been used to highlight the differences in cropping potential between Kaolack (Senegal), and Ouagadougou (Burkina Faso), two locations with approximately the same mean annual rainfall (Table 3). The growing season at Kaolack is shorter than that at Ouagadougou by

Table 3. Average dates of beginning and ending of rains and length of growing season at Kaolack and Ouagadougou.

| Location (Rainfall) | Beginning of rains | | Ending of rains | | Length of the growing season | |
|---|---|---|---|---|---|---|
| | Date | s.d.[1] | Date | s.d. | Days | s.d. |
| Kaolack (800 mm) | 23 Jun | 14 | 27 Sep | 12 | 97 | 18 |
| Ouagadougou (830 mm) | 31 May | 16 | 24 Sep | 12 | 117 | 21 |

1. s.d. = standard deviation.

20 d. Obviously, crop breeders should pay more attention to the average length of the growing season than to mean annual rainfall.

## Drought Probabilities

Although millet is grown in drought-prone environments, precise information does not exist on the nature of climatic droughts in West Africa during its growth cycle. Assuming that the sowing date coincides with the calculated beginning date of the rainy season (Table 3, for example), the average length of dry periods at 10-day intervals during the crop growth cycle can be computed. Such calculations show that in the millet-growing regions of West Africa, the probabilities of drought are high during the crop-establishment and grain-filling phases.

## Temperature

Ong and Monteith (1985) have shown that temperature has a major effect on the rate at which crops grow. Germination, leaf and spikelet initiation, tillering, and grain filling have been shown to have pronounced differences in their responses to optimum and maximum temperatures.

Maximum temperatures vary from 28-42°C during the millet-growing season in West Africa. In the central and southern regions of West Africa, maximum temperatures are generally less than 35°C and sometimes as low as 30°C, whereas in the north they are almost always higher than 35°C. The minimum temperatures range from 15-28°C (Konate 1984). These data suggest that in the northern regions of West Africa maximum temperatures exceed optimum values, especially during germination and grain-filling periods. High air temperatures lead to high soil temperatures. In the sandy soil of Niger, surface soil temperatures (at 2 mm) in June were reported to reach 45-50°C after a rain, which led to low stand survival (ICRISAT 1984a).

## Soils

The major soil type on which millet is grown in the Sahelian zone of West Africa is the coarse-textured soils containing more than 65% sand and less than 18% clay (Swindale 1982). They occur extensively on flat to undulating topography developed under aeolian and alluvial sands. Low fertility, lack of water, and poor physical condition are important constraints to the use of these soils, which are low in organic matter, N, and P (Jones and Wild 1975, Ahn 1970). Soils in Niger for example, are very sandy with the sand fraction usually exceeding 92% (Table 4). The soils are acidic and average water-holding capacity varies, depending upon depth, from 75-150 mm.

Poor fertility is a major problem in the sandy soils of the Sahel. Organic matter content and cation exchange capacity of these soils are very low (Table 4). Nitrogen management can be difficult because the soil has a low buffering capacity (Swindale 1982). To produce stable yields, the low phosphorus content of these soils needs to be improved by application of phosphorus fertilizers. Allowing arable land to lie fallow to recover fertility without added fertilizers is a traditional practice followed by subsistence farmers. But the number of fallow years between crops has been reduced because of growing

Table 4. Some physical and chemical properties of soils at three locations in the millet growing areas of Niger.

| Soil characteristics | Locations: Sadore[1] | Gobery[2] | Gaya[3] |
|---|---|---|---|
| Soil texture (%) | | | |
| Sand | 94 | 95 | 66 |
| Silt | 1 | 3 | 23 |
| Clay | 5 | 2 | 11 |
| pH | | | |
| Water (1:1) | 5.3 | 5.2 | 5.4 |
| KCL | 4.3 | 4.3 | 4.9 |
| Organic matter (%) | 0.2 | 0.3 | 0.8 |
| Total N (%) | 0.01 | 0.02 | 0.03 |
| C:N ratio | 10 | 9 | 18 |
| Phosphorus | | | |
| Total (%) | 48 | - | 84 |
| Available P (Bray I) (ppm P) | 3.2 | 2.6 | 2.5 |
| Exchangeable cations (meq 100 $g^{-1}$) | | | |
| Ca | 0.60 | 1.00 | 2.40 |
| Mg | 0.30 | 0.20 | 1.00 |
| K | 0.06 | 0.08 | 0.13 |
| Na | 0.00 | - | 0.00 |
| CEC (meq 100 $g^{-1}$) | 0.96 | 1.28 | 3.53 |
| Base saturation (%) | 86 | - | 98 |

1. 13° 18'N 2° 21'E; 560 mm rainfall $a^{-1}$
2. 13° 5'N 2° 54'E; 600 mm rainfall $a^{-1}$
3. 11° 59'N 3° 30'E; 840 mm rainfall $a^{-1}$

population pressures in recent years, and has led to a decline in soil fertility. Jones and Wild (1975) comment that questions cannot yet be answered on the possibilities of continuous cropping on these soils.

Poor structural stability of the sandy soils is also a major constraint (Swindale 1982), since the soils are susceptible to wind erosion when they are dry. Early in the rainy season, sand is carried in the air at high wind speeds just before the rains arrive, physically damages the emerging seedlings (sand blasting), and is deposited over them. The weight of the sand coupled with high soil temperatures often causes high seedling mortality, with resultant poor crop establishment. As the soil dries there is a tendency for the surface horizon to harden, which causes a permeability problem.

Soils with higher clay content and greater water-holding capacity occur in the Sudanian and Northern Guinean Zones of West Africa and elsewhere in eastern and southern Africa. These soils with higher fertility and better physical condition are rarely used for sole crop millet. Millet is planted in association with sorghum or maize *(Zea mays* L.), the principal crops in these areas.

## Crop Production Systems

Pearl millet in Africa is grown largely by subsistence farmers and is usually intercropped with other cereals, especially sorghum, and/or a legume, usually cowpea (*Vigna unguiculata* L. Walp.). In the Northern Guinean Zone of West Africa where sorghum is a more important crop than millet, sole-crop millet is virtually unknown. Thus, in their surveys in the Nigerian savanna, Norman et al. (1982) found virtually no sole-crop millet, although millet mixtures occupied about one-third of the cultivated area. Moving northward through the Sudan to the Sahel zone, the proportion of sole cropping increases. For example Singh et al. (1984) report 0.4-5.0% in the Sudanian Zone of Burkina Faso, while Gbiriche and Schipprack (1985) report 17% from northern Ghana. The proportion rises to 30-50% in villages in the Sahelian Zone of Niger (ICRISAT 1986). Some of the common management practices under these two systems are described below.

### Millet as a Pure Crop

Most of the millet crop in West Africa is planted with virtually no prior land preparation. The use of animal traction for cultivation in West Africa decreases from the subhumid to the semi-arid zones. In a major part of the millet-growing region, use of animal traction for preparatory cultivation is not common and soils are seldom plowed.

As a rainfed crop, pearl millet is sown with the first rains during the growing season. In West Africa the crop is sown in Apr-May in the Southern Zone and May-Jun in the Northern Zone. In higher rainfall areas it is not uncommon to delay the sowing of millet. Photosensitive late millet varieties in Ghana are planted in Jun-Jul, mature on stored moisture, and are harvested in Nov-Dec (Gbiriche and Schipprack 1985). In the bimodal rainfall belt near the equator in East Africa, millet is planted with either the early or late rains, in either March or August (Rachie and Majmudar 1980).

Most millets grown in West Africa fall into two groups, early and late (Table 5). The choice of the appropriate variety in a given zone is dictated by the available length of the growing season, with the early millets grown in general in the low-rainfall northern regions and the late types in the more humid southern regions.

Millet is sown in hills 45 x 45 cm to 100 x 100 cm apart. Spacings of 100 x 200 cm or even 200 x 200 cm are sometimes used. A hand-held hoe or "dhaba" is used to open the holes, seeds are thrown in, and the hole is covered with the heel of the foot. The number of seeds sown in each hill varies enormously. In a stand-establishment study in three villages of Niger up to 400 seeds have been found in a single hill (P. Soman, ICRISAT Center, India, personal communication).

Traditionally farmers sow low populations, about 5000-7000 hills $ha^{1}$. Because of problems with wind erosion and crop establishment, or failure of early rains, farmers are often forced to repeat sowing, sometimes up to three times. The stand is progressively thinned during weedings once the plants have reached 15 cm.

Interculture and weeding are primarily done using hand tools. This places severe demands on available labor and limits the area that could be weeded. If more area is sown than the farmer and his family can cope with, some of the farm is abandoned to weeds, which lowers productivity (Bourke 1963).

Diseases and insect pests have been known to cause yield losses of up to 50%. Birds and *Striga,* a parasitic weed, also cause severe damage from time to time. Systematic use of insecticides or fungicides is not a common practice in traditional farming systems.

Table 5. Millet types and maturity durations reported from different countries in West Africa.

| Country | Millet type | Average duration (d) | Reference |
|---|---|---|---|
| Niger | Early | 75- 95 | Naino et al. (1985) |
| | Late | 120-130 | |
| Nigeria | Gero | 70-100 | Nwasike (1985) |
| | Maiwa | > 120 | |
| | Dauro | > 120 | |
| Senegal | Souna | 75- 90 | Gupta (1985) |
| | Sanio | 120-150 | |
| Burkina Faso | Iniadi | 75- 90 | Lohani (1985) |
| | Late | 130-170 | |
| Mali | Souna | 75- 90 | Niangado et al. (1985) |
| | Sanio | 110-120 | |
| Ghana | Early | 90-110 | Gbiriche and Schipprack(1985) |
| | Late | 120-140 | |
| Ivory Coast | Early | 90 | Beninga (1985) |
| | Late | 150 | |
| Gambia | Suno | 80- 90 | Cox (1985) |
| | Sanio | 140 | |
| Togo | Early | 80-100 | Kpodar (1985) |
| | Late | 140-160 | |

Under the subsistence-level millet farming in West Africa, yields are generally low even in regions with sufficient rainfall. Yields ranging from 100-600 kg $ha^{-1}$ under farmers' conditions are often reported. Fertilizer is rarely used except in special agricultural development projects.

## Millet in Intercropping

As indicated earlier, pearl millet in West Africa is more commonly grown in association with cowpea, groundnut, sorghum, maize, or sorrel *(Hibiscus sabdarifa).* Evidence for one or more of these systems in all West African countries is given by Moustapha and Adjahossou (1985), Beninga (1985), Niangado et al. (1985), Naino et al. (1985), Mabissoumi (1985), Sawadogo and Kabore (1985), Bbuyemusoke (1985), Gbiriche and Schipprack (1985), and Reddy and Gonda (1985).

The choice of component crops in the intercrop often depends on the farmers' past experience and objectives, food habits, availability of seed, soil type, and market demands (Mamane 1980). However millet/cowpea is the most prevalent intercropping system, especially in the Sahelian Zone of West Africa.

Plant density in the intercrop depends upon soil fertility and previous harvests (Reddy and Gonda 1985). Under farmers' conditions plant densities are usually low. In baseline studies in Burkina Faso, Matlon (1984) observed low densities of cowpea from 1000-8000 plants $ha^{-1}$, although optimum densities are much higher at 15000 plants $ha^{-1}$. In the millet/sorghum intercrop, sorghum densities are often low, and the variety choice is based on earliness and succulence of stems or grains since the sorghum is generally consumed soon after harvest (Sawadogo and Kabore 1985). In Mali, introduced varieties of millet and cowpea are not better adapted than the local varieties in the intercropping system (Simpara 1985). The same conclusions were drawn from farmers' tests in Burkina Faso (Sawadogo and Kabore 1985).

Component crops in the intercrop are often sown in separate rows, although sowing in the same row or hill is not uncommon. In certain regions triangular sowing is adopted (Reddy and Gonda 1985), with manure placed in the centre of the triangle. In the Maradi region of Niger, millet and cowpea in the millet/sorghum/cowpea intercrop are sown alternately in the same direction while sorghum is sown perpendicular to rows of the other two crops.

The sowing date depends upon the arrival of rains and labor availability. Millet, the primary crop in the intercrop system, is sown with the first rains at the end of May or early June, while the associated crop of sorghum or cowpea is sown 2-3 weeks later at the end of the first weeding (Sawadogo and Kabore 1985), or after an effective rainfall. Labor availability is recognized as a more important constraint than availability of land for intercropping in Niger (Reddy and Gonda 1985).

Millet yields have usually been reported to be higher under intercropping than under sole cropping. Data from ICRISAT's long-term village studies in western Niger show that intercropped millet yields were higher than pure crop millet yields. Swinton et al. (1985) also found that intercropped millet and sorghum yields were as good or better than monocropped millet or sorghum in other regions of Niger. In Burkina Faso, Sawadogo and Kabore (1985) reported that millet/cowpea yields were higher than millet yields in sole cropping.

## Economics of Millet Production

In 1975 Norman highlighted the economic advantage of intercropping in traditional African farming systems. He showed that in northern Nigeria, both average gross and net returns per unit area were about 60% higher from crop mixtures than sole crops, and increased with the number of crops. But Norman's data were from the Northern Guinean Zone, where millet is a subsidiary crop that is only grown in mixtures.

In 1982, ICRISAT began a long-term socioeconomic study in two villages in western Niger in the heart of the millet-growing zone of West Africa. Sole-crop millet is grown on 30-50% of the gross cropped area depending on season and rainfall. The 1982-83 data are from an area where long-term expected rainfall is 450-550 mm (Virmani et al. 1980), but in which actual rainfall in the 2 years was 50-80% of the total. Soils are uniformly sandy with irregular topography.

Under traditional farming conditions, average millet grain yields were very low, ranging from 130-285 kg $ha^{-1}$, while cowpea grain yields were virtually zero (Table 6). Millet yields were higher in intercrops than in pure crop stands. At the low plant densities used by farmers, and since cowpea is usually planted about 3 weeks after millet, the cowpea does not reduce the millet yield. Rather, it contributes hay which increases the gross income. Thus total output of millet/cowpea intercrops was usually at least double that of a sole-crop millet.

Intercrops containing sorghum also produced higher millet yields than sole-crop millet. But this was because such intercrops are generally planted in lower-lying areas where farmers expect that there will be adequate moisture to meet the higher needs of sorghum. Their expectations were not fulfilled in 1982 and 1983, and the sorghum produced no grain.

Labor use on millet/cowpea intercrops was at least one-third higher than for sole-crop millet because of the need to plant cowpea after millet, to weed between millet as well as cowpea rows, and to harvest cowpea. No more than 10% of the labor was hired, confirming that the farms are mainly traditional family farms.

Gross margins were calculated by deducting all variable costs (mainly the value of seed and hired labor), from gross output. Gross margins $ha^{-1}$ averaged 11 000 F CFA for sole-crop millet (about 350 F CFA = US$ 1 at present exchange rates). The gross margin $ha^{-1}$ was at least 20% higher for the millet/sorghum and millet/sorrel intercrops, and over 80% higher wherever there was cowpea in the intercrop. Returns to family labor, measured by gross margin per hour were also much higher for intercrops, than for sole-crop millet. It is clear that under traditional farming conditions in western Niger, economic returns are substantially higher for intercropped than sole-cropped millet.

## Constraints to Increased Millet Production

Constraints to increased millet production in Africa can be classified into abiotic and biotic constraints.

### Abiotic Constraints

- Low and erratic rainfall in a short season, leading to drought periods of varying lengths.
- Sand storms, high-intensity rains, and high soil temperatures cause poor seedling establishment.
- Poor soils with low levels of natural fertility and low water holding capacities.
- Traditional management practices such as low crop densities, nonuse of fertilizers, or poor or no tillage.
- Lack of household capital and poor credit and input delivery systems limit the scope to improve management practices.

### Biotic Constraints

- Low genetic yield potential of land races which respond poorly to improved management.
- Diseases such as downy mildew and smut.
- Insect pests such as stem borer and earhead caterpillar.
- Parasitism by *Striga*.
- Grain-eating birds.

The challenge facing millet researchers is to develop improved technology which could mitigate the adverse effects of these constraints, and that would be within the reach of small-scale, resource-poor farmers in Africa.

## Summary

Millet is grown in regions of Africa with rainfall ranging from 200-800 mm and with a growing sea-

Table 6. Productivity of alternative millet based cropping systems in western Niger, 1982/1983.

| | Cropping System[1] | | | | | | |
|---|---|---|---|---|---|---|---|
| | M | M/C | M/S | M/C/S | M/C/S/L | M/L | M/C/L |
| Ha Farm$^{-1}$ | 4.4 | 3.3 | 0.6 | 0.6 | 0.5 | 0.9 | 1.2 |
| Family Labor Use (man-hour equivalents ha$^{-1}$)[2] | | | | | | | |
| Male | 108.3 | 143.5 | 110.5 | 205.5 | 189.2 | 127.9 | 178.7 |
| Female | 5.4 | 8.9 | 6.8 | 11.5 | 14.0 | 7.3 | 8.0 |
| Child | 14.2 | 20.6 | 11.1 | 33.8 | 20.0 | 11.0 | 25.1 |
| Total | 120.8 | 162.7 | 122.9 | 233.9 | 213.2 | 140.7 | 199.3 |
| Hired Labor Use (man-hour equivalents ha$^{-1}$) | | | | | | | |
| Male | 11.9 | 15.2 | 8.9 | 9.7 | 21.5 | 7.3 | 11.9 |
| Female | 0.2 | 0.1 | 0.3 | 2.3 | 0.2 | 0.2 | 0.5 |
| Child | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Total | 12.1 | 15.3 | 9.3 | 12.0 | 21.7 | 7.5 | 12.4 |
| Fert.(kg ha$^{-1}$) | 1.2 | 5.9 | 0.0 | 0.7 | 0.0 | 3.7 | 2.2 |
| Seed (kg ha$^{-1}$) | | | | | | | |
| Millet | 4.8 | 5.4 | 5.3 | 7.1 | 6.4 | 4.7 | 11.3 |
| Cowpea | 0.0 | 0.8 | 0.0 | 1.2 | 0.6 | 0.0 | 0.7 |
| Sorghum | 0.0 | 0.0 | 0.5 | 1.5 | 0.6 | 0.0 | 0.0 |
| Sorreli | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.4 | 0.3 |
| Total Cost (F CFA) | 1707.3 | 2765.7 | 1519.3 | 2949.5 | 2936.9 | 1228.0 | 2414.8 |
| Grain yield (kg ha$^{-1}$) | | | | | | | |
| Millet | 128.5 | 215.4 | 155.0 | 283.9 | 240.8 | 143.5 | 224.7 |
| Cowpea | 0.0 | 2.7 | 0.0 | 7.7 | 1.0 | 0.0 | 0.8 |
| Sorghum | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Sorrell | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.4 | 0.7 |
| Harvested hay/straw output (kg ha$^{-1}$) | | | | | | | |
| Millet | 0.9 | 1.9 | 0.8 | 5.9 | 1.3 | 1.0 | 2.8 |
| Cowpea | 0.0 | 30.5 | 0.0 | 73.6 | 65.7 | 0.0 | 54.2 |
| Sorghum | 0.0 | 0.0 | 5.1 | 2.0 | 11.5 | 0.0 | 0.0 |
| Value of output (F CFA ha')[3] | | | | | | | |
| Grain | 12686 | 21007 | 16797 | 29499 | 25522 | 14328 | 21914 |
| Straw | 5 | 2823 | 38 | 6812 | 6164 | 10 | 5013 |
| Total | 12692 | 23830 | 16834 | 36311 | 31687 | 14337 | 26927 |
| Gross margin (F CFA) | | | | | | | |
| Per ha | 10985 | 21064 | 15315 | 33361 | 28750 | 13109 | 24513 |
| Per hour | 91 | 129 | 125 | 143 | 135 | 93 | 123 |

1. Crops in system : M = millet, C = cowpea, S = sorghum, L = sorreli.
2. 1 man-hour equivalent = 1 man-hour = 1 woman-hour = 0.5 child-hour.
3. FCFA = Unit of currency in West Africa.

son from 60-150 d. About 70% of African pearl millet crop is produced in West Africa.

Millet is primarily grown by subsistence farmers under harsh environmental conditions in intercrop systems with other cereals and legumes, on small-scale family farms. There are many abiotic and biotic constraints to increased millet production.

Millet is the staple food in some of the poorest countries and regions of Africa, but its production has increased at only 0.7% $a^{-1}$ during the last two decades. This is much less than the population growth rate, and is the lowest growth rate for food crops in the region. Furthermore, these increases have been due mainly to increases in cultivated area rather than to yield increases, showing that technological innovations have not yet had much impact on millet productivity. What are the prospects for the future?

After a survey of the evolving technical and social conditions of African agriculture and an evaluation of the stock of technological innovations, Matlon and Spencer (1984) concluded that with the exception of limited high potential zones, the set of new technologies is most often inappropriate. Their use could not bring about a substantial increase in aggregate supply. From a recent review of appropriate technologies for farmers in the semi-arid zones of West Africa (Ohm and Nagy 1985), it is evident that available technologies for millet are still inadequate.

But recent research results show that there is some promise for the future. For example, on-farm tests in Niger have shown that low to medium doses of phosphorus fertilizer can be profitable when applied to traditional varieties (ICRISAT 1984b, 1985, 1986). Improved millet varieties which perform as well as traditional varieties under traditional management, but perform significantly better under improved management, are being tested. These and other developments which auger well for the future are discussed by Fussell et al. (1987).

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# Utilization of Wild Relatives of Pearl Millet

**W. W. Hanna**[1]

***Abstract***

*The wild* Pennisetum *species offer diverse germplasm that can be used to improve pearl millet. In the primary gene pool, the wild, weedy pearl millet subspecies* monodii *and* stenostachyum *are the most readily and easily utilized. The germplasm in the secondary and tertiary gene pools is more difficult to manipulate and transfer to pearl millet. Useful characteristics in the wild species that could be used to improve pearl millet include disease and insect resistance, genes for fertility restoration of the $A_1$ cytoplasm, cytoplasmic diversity, yield genes, apomixis, maturity, and many inflorescence and plant morphological characteristics. Research with the wild species requires specific objectives, large populations, good screening methods, and a team effort. One of the greatest research needs in the* Pennisetum *genus is adequate and systematic collection and preservation of the wild species.*

**Résumé**

**Utilisation des formes sauvages du mil :** *Les espèces sauvages du genre* Pennisetum *offrent une diversité génétique qu'on peut exploiter en vue d'une amélioration culturale du mil. Dans le pool génique primaire se trouvent les sous-espèces sauvages et adventices, à savoir,* monodii *et* stenostachyum, *qui se prêtent facilement à cet usage. Il est plus difficile de manipuler et de transférer le matériel génétique à partir des pools secondaires et tertiaires. Les caractéristiques intéressantes chez les espèces sauvages sont : la résistance aux maladies et aux insectes ravageurs, les gènes permettant de restaurer la fécondité du cytoplasme $A_1$, la diversité cytoplasmique, les gènes associés au rendement, l'apomixie, le cycle et les caractéristiques liées à l'inflorescence et à la morphologie de la plante. La recherche sur les espèces sauvages demande une définition précise de l'objectif, de grandes populations végétales, des méthodes efficaces de criblage et le travail en équipe. La prospection adéquate et systématique ainsi que la conservation des espèces sauvages s'avèrent nécessaires en recherche sur le genre* Pennisetum.

## Introduction

Pearl millet *(Pennisetum americanum)* is an excellent research organism, an important world food and forage crop, and has abundant natural genetic diversity, but it has not received the attention it deserves. Its potential contribution to science as a research organism and its potential for meeting world food needs as a grain crop have not been fully recognized.

Pearl millet makes an excellent research organism because of many desirable characteristics. It is a diploid with 2n = 14 large chromosomes, and has a protogynous habit of flowering which allows it to be easily cross-pollinated and genetically manipulated. A single plant can be readily selfed and cross-pollinated as both male and female. Inbreds are usually vigorous and hybrid vigor is significant. An inflorescence can produce 1000 or more seeds and a single-spaced plant can produce 25 or more inflorescences. Some genotypes will naturally flower 35-40 d after planting, or can be induced to do so with short day length and high temperatures, thus

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ICRISAT (Internationa! Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986. ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

making it possible to grow a number of generations per year. Pearl millet plants can grow to maturity in a 5-cm pot and produce 100 or more seeds. In the opinion of the author, these and other characteristics make pearl millet the *"Drosophila"* of the plant kingdom.

Pearl millet is an important food grain in Africa and India. It is a high quality forage in the United States, Australia, and South America. However, there is new interest in growing pearl millet for grain in the USA because it is drought tolerant and produces high quality grain. Pearl millet tolerates low fertility and low soil pH, but responds positively to more favorable soil and water conditions.

## Evolutionary History and Domestication of Pearl Millet

Based on evidence of genetic diversity within the genus in Africa, it is generally accepted that pearl millet originated there. More specifically, the Sahelian Zone from western Sudan to Senegal appears to be the center of origin (Harlan 1975). Various reports indicate pearl millet has been grown for thousands of years (Brunken 1977, Burton and Powell 1968, Rachie and Majmudar 1980). In the last 200-300 years, pearl millet has been given a number of genera and species names such as *P. glaucum* L. and *P. typhoides* (Burm.) Stapf and Hubb. In 1976 it was renamed *P. americanum* (L.) Leeke (see Terrell 1976). Those interested in more detailed discussions on the taxonomy, origin, domestication, and evolutionary history of pearl millet should consult Brunken (1977), Jauhar (1981), Rachie and Majmudar (1980), and Stapf and Hubbard (1934).

## Gene Pools

*Pennisetum* is a genus with over 140 species (Brunken 1977) divided into five sections: *Gymnothrix, Eu-Pennisetum, Penicillaria, Heterostachya,* and *BrevivaJvuia* (Stapf and Hubbard 1934). Pearl millet belongs to the *Pcnicillaria* section. The literature and observations by the author at the Royal Botanic Gardens, Kew, UK, indicate that most of the wild *Pennisetum* species are found in Africa. However, there are a number of reports of *Pennisetum* species being collected in other countries. There are specimens of *Pennisetum* species on record at Kew from Israel, Japan, India, Australia, New Zealand, Polynesia, Mexico, Central and South America, and other countries, including many in Africa.

The *Pennisetum* genus has species with chromosome numbers in multiples of x = 5, 7, 8, and 9 (see Table 1, Hanna and Dujardin In press, and Jauhar 1981). In the x = 5 group is *P. ramosum* (2n = 10). The x = 7 group includes pearl millet and its wild weedy subspecies (2n = 14), *P. purpureum* (2n = 28), and *P. schweinfurthiii* (2n = 14). *Pennisetum massaicum* (2n = 16 and 32) is the only known species in the x - 8 group. The remainder of the species where chromosome numbers have been established belong to the x = 9 group. Ploidies reported range from diploid to octoploid (Jauhar 1981). Both sexual and apomictic species as well as annual and perennial species are included in the genus.

The diverse germplasm in *Pennisetum*, both within and between species, offers possibilities for use in improving pearl millet and to produce interspecific hybrids with forage potential. The ease with which the wild germplasm can be manipulated and used will vary both within and between species. One way of classifying the wild or exotic germplasm is by the ease with which it can be introgressed into the cultivated species. A system of primary, secondary, and tertiary gene pools has been suggested for dividing the wild germplasm (Harlan and de Wet 1971).

In *Pennisetum*, the primary gene pool includes the wild, grassy, and weedy *P. americanum* subspecies (2n = 14), *monodii* and *stenostachyum* that readily cross with pearl millet and produce fertile hybrids (Table 1). *Monodii* is the true weedy subspecies found mainly in the Sahelian Zone of Africa in an east-west line from Senegal to Ethiopia. It is found "as a natural colonizer on sandy soils in disturbed habitats such as seasonal stream beds and roadsides as well as a weed near human habitations'* (Brunken 1977). Inflorescences are 2-20 cm long with loosely arranged involucres that readily shatter (Brunken 1977). Inflorescence length in about 100 accessions that the author observed ranged from 2-12 cm. Involucral bristles are densely plumose. Stems are thinner and leaves are narrower than those of most pearl millet accessions. Most flower in response to short day length.

*Monodiiis* a rich source of germplasm that can be used to improve pearl millet. Data indicate that it is an excellent source of genetic diversity for new cytoplasms, stable cytoplasmic sterility, pest resistance (disease and insect), fertility restoration, hybrid vigor, etc. Based on intuition and five years of research with *monodii*, the author believes that this subspecies is an excellent source of genes for high resistance or immunity to every pest on pearl millet and for improved yield. *Monodii* identification is sometimes confused with *P. pedicellatum* and *P. polystachyon* (both 2n = 36 or 54), wild species which by causal observation look similar.

Based on its morphological characteristics, *stenostachyum* is an intermediate between wild *monodii* and pearl millet (Brunken 1977), and probably is a cross between the two. It is reported to have inflorescences 5-150 cm long (Brunken 1977), but the author observed inflorescence lengths range from 8-20 cm

Table 1. Chromosome number(s) and gene pool relationships of some *Pennisetum* species.[1]

| *Pennisetum* species | Chromosome number 2n | Gene pool[2] |
|---|---|---|
| *americanum* (L.) Leeke | 14 | Cultivated |
| subsp. *monodii* (Maire) Brunken (same as violaceum) | 14 | 1 |
| subsp. *stenostachyum* (Kloyzcsh ex. A.Br, and Bouche) Brunken (shibra or *monodii americanum* cross) | 14 | 1 |
| *schweinfurthii* Pilger | 14 | 3 |
| *purpureum* Schumach. | 28 | 2 |
| *ramosum* (Hochst.) Schmeinf. | 10 | 3 |
| *massaicum* Stapf. | 16,32 | 3 |
| *alopecuroides* (Linn.) Spreng. | 18 | 3 |
| *atrichum* Stapf & Hubb. | 36 | 3 |
| *bambusiforme* Hemsl. | 36 | 3 |
| *basedowii* Summerhayes & C.E. Hubbard | 54 | 3 |
| *cattabasis* Stapf and Hubb. | 18 | 3 |
| *clandestinum* Hochst. ex Chiov. | 36 | 3 |
| distachyum Rupr. | 36 | 3 |
| *divisum* (Forssk. ex Gmel.) Henr. | 36 | 3 |
| *flaccidum* Griseb. | 18,36 | 3 |
| *frutescens* Leeke | 63 | 3 |
| *hohenackeri* Hochst. ex Steud | 18 | 3 |
| *lanatum* Klotzsch | 18 | 3 |
| *latifolium* Spreng. | 36 | 3 |
| *macrostachyum* Trin. | 54 | 3 |
| *macrourum* Trin. | 36 | 3 |
| *nervosum* Trin. | 36 | 3 |
| *nodiflorum* Franch. | 18 | 3 |
| *notarisii* Th. Dur. & Schinz, L.C. | 36,54 | 3 |
| *orientale* L.C. Rich | 18, 36, 54 | 3 |
| *pedicellatum* Trin. | 36,54 | 3 |
| *polystachyon* (L.) Schult. | 36,54 | 3 |
| *pseudotrilicoides* | 18 | 3 |
| *setaceum* (Forsk.) Chiov.) | 27 | 3 |
| *schimpeii* Steud. | 18 | 3 |
| *setosum* (Swartz) L.C. Rich. | 54 | 3 |
| *squamulatum* Fresen. | 54 | 3 |
| *subangustum* (Schumacher) Stapf. & Hubb. | 36,54 | 3 |
| *tempisquense* | 72 | 3 |
| *thunbergii* Kunth. | 18 | 3 |
| *trisetum* Leeke | 36 | 3 |
| *villosum* R. Brown ex Fresen | 18, 36, 54 | 3 |

1. There are many more *Pennisetum* species but chromosome numbers and gene pool relationships have not been established.
2. Gene pool relationships based on Harlan and de Wet, 1971.

in about 30 accessions. Unlike *monodii,* the involucres are tightly arranged on the inflorescence as in pearl millet. Like *monodii,* the involucres readily shatter. The dominant species in the fields and roadsides of western Senegal is reported to be ssp. *monodii* (Brunken 1977). This intermediate type should theoretically be found wherever *monodii* and pearl millet are or have been growing in the same area.

*Stenostachyum* should be almost as good a source of genetic diversity for the same characteristics as *monodii,* but an exception may be cytoplasmic diversity, since it cannot be determined whether pearl millet or *monodii* was the female parent (and contributed cytoplasm) in the original cross. *Stenostachyum* germplasm may be somewhat easier to manipulate since it is partially domesticated. However, the author prefers beginning with *monodii in* a program to transfer germplasm from a wild to the cultivated species, based on general observations of genetic diversity in the two subspecies.

The secondary gene pool (Table 1) has only one known species, *P. purpureum* or napiergrass (2n = 4x = 28). It is a sexual species. Napiergrass (A'A'BB genomes) has the A genome in common with pearl millet. The author's research has shown that the B genome is dominant over the A' genome and masks genetic variability (consequently phenotypic variability) on the A' genome. Because of this relationship, mutations have accumulated on the A' genome since the beginning of the species with very little selection pressure on the A'. As such, the A'genome should be an excellent source of genetic variability. Napiergrass readily crosses with pearl millet and produces sterile triploid hybrids, but fertility can be induced by doubling the chromosome number of the triploid to produce a hexaploid. Napiergrass is a rhizomatous perennial, with desirable characteristics, e.g., resistance to most pests, vigorous growth, and outstanding forage yield potential. Most of these characteristics appear to be on the B genome. Interspecific hybrids with pearl millet have immediate forage potential but can also be used as bridges to transfer genes from napiergrass to pearl millet.

The tertiary gene pool includes the remainder of the wild *Pennisetum* species (Table 1). Examples of species in this group can be found in Jauhar (1981) and Stapf and Hubbard (1934). Crosses between these species and pearl millet are difficult, but are sometimes possible with special techniques. Interspecific crosses are usually highly male and female sterile, but fertility can be induced through chromosome manipulation. This group includes both sexual and apomictic species that are both diploids and polyploids with base chromosome numbers of x = 5, 7, 8, and 9. There are both annual and perennial as well as rhizomatous and nonrhizomatous species in this group. Most have a protogynous habit of flowering. Some useful characteristics of this group include apomictic reproduction, perennial growth habit, drought tolerance, cold tolerance, pest resistance, and cytoplasm diversity. In addition to agronomic characteristics, this tertiary group has excellent germplasm for basic scientific research. As an example, two species, *P. orientale* and *P. villosum* have reported chromosome numbers of 2n = 18, 27, 36, 45, and 54 each for studying polyploidy effects.

## Using the Wild Species

Germplasm from wild species is usually more difficult to manipulate than germplasm within the cultivated species. However, ease of manipulation and success in using germplasm from wild species will vary both within and between species, and can be affected by both genotype and ploidy level. More success can be expected when using wild species to improve a cultivated species if:

- objectives are specific (with some flexibility),
- a team approach is used,
- good screening or selection techniques are available for desired characteristics,
- alternative methods are tested,
- large populations are studied,
- highly heritable characteristic(s) are transferred, and
- multiple cycles per year are possible.

These factors have helped to make utilization of wild germplasm successful in the Grass Breeding Program at Tifton, Georgia, USA. They also usually become more important as breeding moves from using wild subspecies in the primary gene pool to using wild species in the tertiary gene pool. Until recently, the wild species have not been used to improve pearl millet.

In January 1980, the first crosses in the Grass Breeding Program were made in the greenhouse between pearl millet and three *monodii* (primary gene pool) accessions sent by M. and Mme. A. Lambert, French plant breeders in Senegal. *Monodii* was used as the female parent to transfer the *monodii* cytoplasm to pearl millet. The $F_1$ crosses planted in the field in 1980 segregated for both rust-free *(Puccinia substriata* var. *indica)* and leaf spot-free

*[PiricuIaria griesea (Cke.)* Sacc] plants, the only two major leaf diseases on pearl millet in the USA. Rust resistance is controlled by one major dominant gene (Hanna et al. 1985a), while *Piricularia* resistance appears to be controlled by a few dominant genes (author's unpublished data). This resistance was rapidly backcrossed into pearl millet by:

- producing up to four backcross cycles per year,
- screening for resistance in the field and greenhouse during the winter,
- manipulating temperature and daylength to induce flowering,
- treating seed in a water solution of 1% 2-chloroethanol and 0.5% sodium hypochlorite for 1 h to break seed dormancy (Burton 1969), and
- insuring a ready supply of the recurrent parent by storing its pollen (Hanna et al. 1983).

The dominant rust- and Piricularia-resistant genes have been incorporated in a cytoplasmic male-sterile line (similar to Tift 23DA), which makes it possible to produce disease-resistant hybrids using an array of pollinators that may not be disease resistant. In 1985, hybrids between the new male-sterile line crossed with inbred 186 produced 28% more dry matter than Tift 23DA x 186 hybrids, indicating the transfer of yield genes from *monodii* to the new inbred. In another test, some Tift 23A x *monodii* hybrids yielded up to 77% more dry matter than Gahi 3, one of the highest yielding commercial hybrids. This provides further evidence that genes for hybrid vigor are present in the *monodii* germplasm. Tests in the USA and Senegal with a number of *monodii* accessions have shown the accessions to have genes for resistance to rust, *Piricularia,* downy mildew *(Sclerospera graminicola),* and smut (*Tolyposporium penicillariae),* the only diseases present at the test sites (Hanna et al. 1985b). Research at Tifton has also shown that *monodii* has excellent fertility restoration genes for the $A_2$ cytoplasm and that stable A, male-sterile lines, without fertile revertants, can be derived by using *monodii* cytoplasm.

Pearl millet has probably been crossed more often with napiergrass *(P. purpureum)* in the secondary gene pool than with any other wild species. Crosses between these two species have been made mainly for investigating the forage potential of the interspecific cross and for studying chromosomal relationships. Crosses between diploid (AA) or tetraploid (AAAA) pearl millet and napiergrass (A'A'BB) produce male-sterile, AA'B (2n = 21), or female-sterile AAA'B (2n = 28), hybrids. Both sterile hybrids are vigorous, can be vegetatively propagated, and have forage potential (Hanna and Monson 1980). It has been suggested that the triploid (AA'B) interspecific hybrids could be commercially produced in a frost-free area if a cytoplasmic male-sterile diploid line is used as the seed parent (Powell and Burton 1966). Cooperative efforts with scientists in Hawaii have shown that the above techniques, with modifications, can be used to produce interspecific hybrid seed on a commercial level.

In addition to the immediate use of the napiergrass germplasm as interspecific forage hybrids, napiergrass could also be a source of excellent germplasm to improve pearl millet. Male and female fertility can be induced by doubling the chromosome number of the sterile triploid to produce a balanced chromosome hexaploid, 2n = 6x = 42 (AAA'A'BB). Most of the morphological characteristics of napiergrass indicate that the germplasm (except pest resistance) from this species would be more applicable to improving forage production in pearl millet.

One of the first efforts to cross pearl millet with hexaploid (pearl millet * napiergrass) plants produced 2n = 4x = 28 (AAA'B) sterile plants (Krishnaswamy and Raman 1956). A later backcross (BC) series of the same type produced chromosome numbers of 2n = 21-35 in $BC_1$ 2n = 18-33 in $BC_2$, and 2n = 14-17 in $BC_3$ (Gildenhuys and Brix 1969). The $BC_2$ generation was male-sterile and was pollinated with pearl millet pollen to produce $BC_3$ plants. All $BC_3$ plants had only the A genome while plants in $BC_1$ and $BC_2$ contained some B genome chromosomes (Fig. 1). The researchers in the latter study concluded that the $BC_3$ plants probably had the A genome complement of the original pearl millet parent used in the cross, and it was not possible to combine the desired characteristics of pearl millet with the perenniality of napiergrass (Gildenhuys and Brix 1969).

Each of the above studies used a single hexaploid plant in the crosses with pearl millet. Since 1978, over 50 hexaploids were produced at Tifton by using different pearl millet and napiergrass accessions (Gonzales and Hanna 1984, Hanna et al. 1984). The research has shown that sterile 2n = 28 to 46 chromosome (ca. AAAA'B) plants are produced when tetraploid pearl millet is crossed with hexaploid plants (Fig. 1). Most plants have 2n = 5x = 35 chromosomes. All plants have some B genome chromosomes. When diploid pearl millet male-sterile lines are pollinated with hexaploid pollen, most plants are highly sterile with 2n = 4x = 28 (AAA'B) chromosomes. However, a few AA genome, and AA' genome male-sterile lines, and A A' genome male-fertile plants are produced from certain crosses (Hanna 1983).

The latter group of A A' plants are of interest (Fig. 1). The production of diploid plants without B genome chromosomes with at least part of the A' genome from napiergrass has opened access to the vast storehouse of germplasm that has accumulated on the A' genome since the beginning of the species. The A A' plants apparently result from an occasional

Pearl millet (2n = 14, AA genome) X Napiergrass (2n = 4x = 28, A'A'BB genomes)

$F_1$ triploid
(2n = 3x = 21, AA'B)
Male and female sterile

Colchicine

Hexaploid
(2n = 6x = 42, AAA'A'BB)
Male and female fertile

X Pearl millet[1] (2n = 14, AA)

BC$_1$ X Pearl millet
(2n = 21 to 35) (2n = 14, AA)
A and B genomes

BC$_2$ X Pearl millet
(2n = 18 to 33) (2n = 14, AA)
A and B genomes

BC$_3$
1. 2n = 14, AA
Male and female fertile
2. 2n = 15, A and B genomes
High sterility
3. 2n = 16 or 17, A genomes
High sterility

X Pearl millet[2] (2n = 4x = 28, AAAA)

BC$_1$
(2n = 5x = 35, AAAA'B)
Range 2n = 28 to 46
Male and female sterile

X Cytoplasmic[3] male sterile pearl millet (2n = 14, AA)

BC$_1$
1. 2n = 4x = 28, AAA'B
Male and female sterile
2. 2n = 14, AA
Male sterile, female fertile
3. 2n = 14, AA'
Male sterile, female fertile
4. 2n = 14, AA'
Male and female fertile

1. Guildenhuys and Brix (1969)
2. Hanna (1984), Personal communication
3. Hanna (1983)

**Figure 1. Pearl millet x napiergrass hybrids and backcross progenies with pearl millet.**

N = 7 gamete with some A* chromosomes that unite with an N = 7 gamete from pearl millet. If the gamete from the hexaploid with the A' chromosomes has fertility restorer genes, the resultant BC plant is male fertile. The fertile AA' plants have been produced repeatedly, but not consistently at the same frequency, from the same hexaploid plants. There are apparently unknown factors (such as environmental) that could affect the production of N = 7 gametes from the hexaploids. The A' chromosomes from napiergrass have contributed excellent genetic variability for inflorescence and plant types, maturity, and fertility restoration of the A, cytoplasm. Those interested in more information on the triploid hybrids should consult Jauhar (1981) and Muldoon and Pearson (1979).

Most interspecific hybrids in the tertiary gene pool in *Pennisetum,* as in most genera, have been produced for studying species relationships and chromosome behavior. Wide crosses made in *Pennisetum* are summarized in Jauhar (1981) and Rachie and Majmudar(1980). In 1978 researchers at Tifton began a program to transfer genes controlling apomixis from the wild species in the tertiary gene pools to pearl millet, with the objective of producing true-breeding hybrids to fix hybrid vigor. Most of this research over the past 6 years is summarized in Hanna and Dujardin (1985). Briefly, apomictic but highly sterile interspecific hybrids were first produced between pearl millet and (1) apomictic triploid (2n = 3x = 27) *P. setaceum* (Hanna 1979), and (2) tetraploid (2n = 4x = 36) *P. orientate* (Dujardin and Hanna 1983a, Hanna and Dujardin 1982). Although, the interspecific hybrids were vigorous, these species as a source of genes for apomixis were not pursued because of the high sterility and poor expression of apomixis.

A hexaploid (2n = 6x = 54) species, *P. squamulatum,* was the third species which was tried in the germplasm transfer program. Logically, crosses between pearl millet and this species should be the least successful, because of the polyploid nature of *P. squamulatum,* and a previous report on a single pearl millet x *P. squamulatum* hybrid indicated the hybrid was highly male and female sterile. Research on *P. squamulatum* showed that this species was an obligate apomict (Dujardin and Hanna 1984) and that when tetraploid pearl millet was used in a crossing and backcrossing program, hundreds of partially male-fertile, obligate apomictic, interspecific hybrids and BC derivatives (Fig. 2) could be produced (Dujardin and Hanna 1983b, 1985a). Double-cross hybrids (Dujardin and Hanna 1984) and trispecific hybrids (Dujardin and Hanna 1985b) between pearl millet, napiergrass, and *P. squamulatum* have also been produced (Fig. 2) for use as 'bridges' to transfer germplasm.

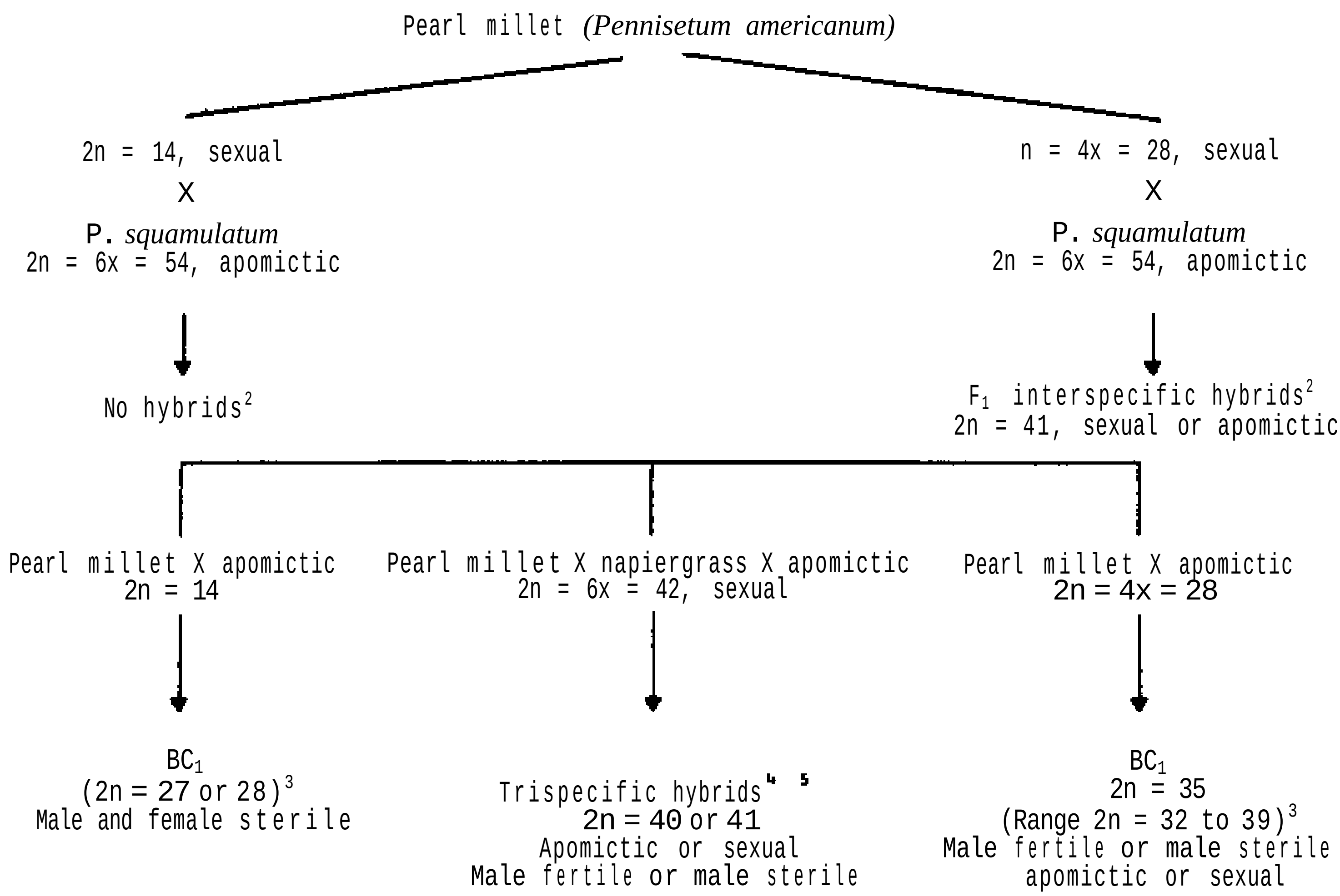
Up to this stage, the objective of producing an apomictic pearl millet has been accomplished primarily by manipulating entire genome sets. At this stage, it is necessary to transfer genes, pieces of chromosomes and/or single chromosomes of a genome to pearl millet. To accomplish this, cytological and genetic techniques, gamma radiation, and cell culture techniques are being used in cooperation with Dr. Peggy Ozias-Akins in Dr. Indra Vasil's laboratory at the University of Florida. The cytoplasm of *P. schweinfurthii has* also been transferred to pearl millet by pollinating *P. schweinfurthii x* pearl millet hybrids with pearl millet pollen (Hanna and Dujardin 1985). Studies are continuing on effects of the exotic cytoplasm on pearl millet.

The entire wild germplasm transfer program involves observing as well as discarding thousands of interesting plants. If every interesting plant or progeny were pursued, there would be no time to accomplish the main objective, which at Tifton is to produce an apomictic pearl millet. An alternative to discarding seed is its long-term storage when possible.

## Novel and Future Techniques for Germplasm Transfer

Biotechnology techniques could possibly have the greatest impact in the future transfer of traits from the secondary and tertiary gene pools or from other genera to pearl millet. These techniques will involve transferring pieces of DNA from a wild species source to protoplasts of pearl millet by using vectors or such techniques as electrophoration. These techniques are most effective when biochemical markers (not yet identified in *Pennisetum)* are linked to the gene being transferred and when subsequent transformed protoplasts can be regenerated into plants (not presently possible in *Penmsetum).* However, plants can be regenerated from suspension cultures of pearl millet (Vasil and Vasil 1981a) and pearl millet * napiergrass hybrids (Vasil and Vasil 1981b). It will only be a matter of time before the necessary techniques are developed. This time period will be greatly shortened if geneticists, cell biologists, and molecular biologists cooperate and work together.

In the meantime, development of efficient screening methods for desired traits and improved methods for speeding up the backcrossing process need to




1. Dujardin and Hanna (1984)
2. Dujardin and Hanna (1983b)
3. Dujardin and Hanna (1985)
4. Dujardin and Hanna (1983a)
5. Dujardin and Hanna (1985b)

**Figure 2. Interspecific hybrids between pearl millet and *Pennisetum squamulatum* and backcross derivatives.**

continue. Techniques and chemicals that will alter the genome structure and arrangement in pollen cultures or suspension cultures, or both, would be very helpful to manipulate germplasm of wild species to improve pearl millet.

## Future Research on Wild Relatives

Currently the greatest need in wild *Pennisetum* research is to adequately and systematically collect the wild species in the primary, secondary, and tertiary gene pools. The seeds of these accessions need to be increased, dried, and put in long-term storage as well as in working collections for evaluation and use. A partial collection has been assembled at Tifton over the past 3 or 4 years by obtaining a few accessions from various collections around the world. However, this collection does not represent all species nor the genetic diversity of the genus. Collecting, increasing, and storing the wild germplasm requires tremendous amounts of time, resources, and work. Working with some of the species can be quite difficult owing to, for example, short-day sensitivity, small seed size, and self-incompatibility. But the collection, increase, and evaluation must be done. To get it done, all scientists working directly or indirectly with pearl millet must cooperate.

In germlasm use and transfer research, the primary gene pool *(monodii and stenostachyum)* appears to have the greatest immediate potential to improve pearl millet with specific traits. Even though these wild, weedy subspecies readily cross with pearl millet and produce fertile progenies, the crossing and screening processes as well as the increase of the wild species are very time consuming. Because the process is so time consuming, there needs to be open and active cooperation at the laboratory, state, national, and international levels to get the most benefit from research with the wild species. More benefits from wild *Pennisetum* species research will result from cooperative work.

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# Food Quality and Consumer Acceptance of Pearl Millet[1]

**L.W. Rooney[2] and C M . McDonough[3]**

### *Abstract*

*The major classes of traditional foods from pearl millet are unfermented bread, (roti); fermented breads, e.g., galettes; thick and thin porridges; steam cooked products, e.g., couscous; nonalcoholic and alcoholic beverages; and snacks. Relatively little information on the specific types of pearl millet that have optimum properties for each of these food systems is currently available. Specific pearl millet cultivars with known good and poor quality attributes for major products are required.*

*The pearl millet caryopsis contains a high proportion of germ which in part explains the higher level of fat and protein in the grain. The germ is difficult to remove during milling because it is embedded inside the kernel. Dry milling of pearl millet by traditional hand decortication and pounding often produces low yields of flour with poor storage stability. Differences in dry milling properties among cultivars exist. Varieties with large, spherical, uniform, hard kernels produce the highest milling yields. The color, hardness, pericarp thickness, and other kernel characteristics vary, but have not been documented systematically. Standard terms to refer to kernel characteristics need to be defined to facilitate information exchange among pearl millet improvement programs. The breeding of pearl millet cultivars with improved dehulling properties is critically important to the crop's long-term utilization potential.*

*The starch of pearl millet is similar to sorghum and maize starches. The lipids of pearl millet have fatty acid contents similar to sorghum and maize. Pearl millet has a higher protein content with more desirable levels of essential amino acids than sorghum. In general, its digestibility is better than sorghum. Pearl millet contains less cross-linked prolamins and more salt-soluble proteins than sorghum. Overall its nutritional value is good, but removal of the germ during milling decreases the nutritional value.*

*Breeding pearl millet cultivars with better color, flavor and dry milling properties will increase the utilization of the crop. The lack of information on heritable kernel properties as they relate to end use quality is a major handicap. National and international millet research should emphasize the acquisition and documentation of critical factors affecting pearl millet quality. Considerable progress can be made using relatively simple procedures to characterize properties that affect grain quality. Continued expansion in national and international efforts to improve pearl millet should include a high priority for food quality research.*

### Résumé

**Qualités organoleptiques du mil et goûts des consommateurs :** ***Les plats traditionnels à base de mil sont divisés en pains non fermentés ("roti"), pains fermentés (galettes), bouillies liquides et épaisses, plats cuits à la vapeur (couscous), boissons alcooliques et non alcooliques et d'autres préparations. On ne dispose pas d'informations adéquates sur les qualités organoleptiques optimales des différents types de mil qui sont adaptées à la préparation de ces plats.***

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1. This research was done under existing Texas Agricultural Experiment Station project Hatch-6676 (Sorghum Quality Improvement). It is supported in part by the INTSORMIL Title XII Sorghum and Millet Research Program, which is sponsored in part by Grant AID/DSAN/XII/G-0149 from the Agency for International Development, Washington, DC 20253.

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*La teneur en graisse et en protéine du mil est supérieure à cause de la proportion élevée du germe dans le caryopse. Enfoncé dans le grain, le germe est difficile à dégager par la mouture. Le broyage à sec en décorticant ou pilant les grains à la main donne peu de farine qui ne se conserve pas très bien. Les qualités technologiques (pour le broyage à sec) sont variables; il existe des variétés à grain de grande taille uniforme, sphériques et dures qui produisent la plus grande quantité de farine. La couleur, la vitrosité, l'épaisseur du péricarpe ainsi que d'autres caractéristiques sont également variables; elles n'ont pas encore fait l'objet d'une analyse systématique. Il convient également de normaliser les termes décrivant ces caractéristiques afin de faciliter l'échange d'informations entre les différents programmes d'amélioration culturale. La sélection de cultivars faciles à décortiquer s'avère très importante pour l'utilisation à long terme de cette céréale.*

*L'amidon chez le mil est semblable à celui du sorgho et du maïs, ainsi que les acides gras renfermés dans les lipides. La teneur en protéine, en particulier celle des acides aminés essentiels, est plus élevée chez le mil par rapport au sorgho. En général, le mil est plus facile à digérer que le sorgho. Il y a moins de prolamines et plus de protéines solubles dans le sel chez le mil que le sorgho. La valeur nutritive du mil quoique satisfaisante en général, est réduite par l'enlèvement du germe au cours du mouturage.*

*La sélection de cultivars ayant de meilleures couleur, saveur et qualités technologiques (pour le broyage à sec) favorisera considérablement la consommation de cette céréale. Cependant, le manque de connaissances concernant les qualité héritées du grain qui sont liées à son usage, représente un désavantage important. La recherche nationale et internationale devrait s'efforcer à identifier et à documenter les éléments critiques affectant la qualité du grain en adoptant des systèmes simples de caractérisation de ces éléments. Toute expansion de la recherche au niveau national et international devrait donner une priorité élevée aux études sur la qualité organoleptique.*

## Introduction

Pearl millet *(Pennisetum americanum)* is a staple human food in both Asia and Africa. Rachie and Majmudar (1980), Hoseney et al. (1981), Hulse et al. (1980), and Hoseney and Varriano-Marston (1980) have presented reviews on the physical, chemical, and processing properties of pearl millet. The review by Hulse et al. (1980) is especially comprehensive.

The objectives of this paper are to review the traditional methods of preparing foods and to discuss the structural, physical, and chemical characteristics of pearl millet that affect food quality. An understanding of the food quality of pearl millet is improving, although progress is relatively slow.

## Traditional Millet Foods

The classification scheme (Table 1) for major classes of traditional foods is similar to that proposed in the 1981 Sorghum Food Quality Symposium (ICRISAT 1982), which was based on efforts by Vogel and Graham (1979) It has facilitated efforts to identify critical factors affecting pearl millet food quality. Other schemes for classifying traditional foods are based upon the viscosity of the foods (Dako 1985). Literally scores of dialectic names are used to refer to these traditional food products. Some are presented in Table 1. In general, pearl millet, sorghum, and other cereals are used to make these products. Steinkraus (1983) has presented considerable information on the major native foods produced by fermentation around the world.

### Milling of Pearl Millet

Food products are produced from whole, cracked, or ground pearl millet. Many consumers decorticate (dehull) the kernel before grinding it into various particle sizes for use in different products. Pushpamma and Rao (1981) found that two-thirds of the consumers in the Indian state of Andhra Pradesh decorticated grain. In most areas of Africa, a significant portion of the pearl millet is decorticated.

Pearl millet is generally decorticated by washing the clean grain in water. The water is removed and the grain is crushed using a stone mortar and wooden pestle. The bran is removed by washing or winnowing the sun-dried, crushed material. The endosperm chunks can be boiled like rice, or they can be ground into flour by additional pounding in the mortar, hand stone grinding, or grinding with a mechanical stone or plate mill. Decortication is sometimes accomplished by using rice dehullers or

Table 1. Traditional foods made with pearl millet.

| Type of food | Common names | Countries |
|---|---|---|
| Unfermented bread | *roti, rotti* | India |
| Fermented bread | *kisra, dosa, dosai, galletes, injera* | Africa, India |
| Thick porridge | *ugali, tuwo, Saino, Dalaki, aceda, map, bogobe, ting, tutu, kalo, karo, kwon, nshimba, nuchu, td, tuo, zaafi, asidah, mato, sadza, sangati* | Africa, India |
| Thin porridge | *uji, ambali, edi, eko, kamo, nasha, bwa kal, obushera* | Africa, India |
| | *ogi, oko, akamu, kafa, koko, akasa* | Nigeria, Ghana |
| Steam cooked products | *couscous, degue* | West Africa |
| Boiled, rice-like | *annam, acha* | Africa, India |
| Snack foods | | Africa, Asia |
| Alcoholic beverages, sweet/ sour opaque beers | *burukutu, dolo, pito, talla* | West Africa |
| Sour/opaque beers | *marisa, busaa, merissa, urwaga, mwenge, munkoyo. utshwala, utywala, ikigage* | Sudan, Southern Africa |
| Nonalcoholic beverages | *mehewu, amaheu, marewa, magou, leting, abrey, huswa* | Africa |

other abrasive dehullers (Reichert 1982). In rural Africa, a wooden mortar and pestle is used to thresh, decorticate, and grind flour or meals. Sieves are used to produce flour or meal with acceptable particle size for specific products.

Pearl millet is usually milled daily in quantities of 2-3 kg. Water is added to moisten the pericarp and facilitate bran removal. The moisture often promotes fermentation and microorganism growth, both of which affect the keeping properties of the products. In addition, the higher oil content of pearl millet can lead to rancidity problems during storage.

Decortication of 2.5 kg of pearl millet takes two women about 1.5 h, including winnowing (Chinsman 1985). Processing into flour with a mortar and pestle requires an additional 2.0-2.5 h. Size, shape, and hardness of the kernel and thickness of the pericarp affect milling yields and time. The extraction rate is lower for pearl millet (74%) than for sorghum (79%).

## Unfermented Breads

Rotis are unleavened, flat breads made from wheat, sorghum, or pearl millet in India (Pushpamma and Rao 1981, Subramanian and Jambunathan 1980). The grain is often milled on small electrical or diesel-powered stone attrition mills to produce a fine flour. The ground grain is sifted to remove coarse pieces of pericarp, leaving flour of about 95-99% of the initial grain mass. Usually warm or boiling water is added in increments and the flour and water are kneaded into a dough. When the proper amount of water has been added, the dough can be hand pressed into a thin circle and baked. If properly made, the roti should puff during the final baking. A good roti has a creamy white color with a few slightly darker spots, flexible texture, and a bland flavor.

Although many variations in these procedures exist, a general scheme is shown in Figure 1. In some households, part of the flour is cooked in water or soaked in water overnight. These modifications improve cohesiveness when dry flour is added to partially cooked flour to produce the dough. Rotis made from pearl millet have acceptable texture, taste, and color.

Roti can be a major food depending upon the socioeconomic status of the consumer. It is eaten with vegetables, dhal, meat, milk, curd, pickles, chutneys, other sauces of various kinds, and in many other ways. Rotis are softened with milk or buttermilk and sometimes mixed with malted or germinated cereals to produce special weaning foods.

Several standardized laboratory procedures have been proposed for use in evaluating sorghum and millet cultivars for roti quality (Murty and Subramanian 1982, Desikachar and Chandrashekar 1982, Clean sorghum or millet

↓

Grind on a disc or plate mill (Chakki)

↓

Sieve (through a U.S. #20 mesh)

↓

Flour (95-99% of original grain)

↓

1:1 mixture of flour:water (boiling)

↓

Hand-kneading

↓

Dough formed into circular pieces
(1.0-3.0 mm thick, 12-25 cm diameter)

↓

Bake 30-40 s

↓

Roti is turned, bake 60 s

↓

Moisten roti surface

↓

Place roti on hot stones or coals to puff

↓

Roti stored in covered baskets

**Figure 1. Traditional procedure for the preparation of roti.**

Olewnik et al. 1984, Lindell and Walker 1984). The gelatinization of part of the flour improves the elasticity and cohesiveness of the dough and produces better roti (Desikachar and Chandrashekar 1982).

## Fermented Breads

Galettes of West Africa, kisra of the Sudan (Ejeta 1982), and dosai of India are breads made from fermented sorghum, pearl millet, and other flours. Kisra, a major food in the Sudan, is produced from whole flour obtained by grinding pearl millet with stone attrition mills. The kisra process (Fig. 2) varies, but generally a thick paste is made with flour and water. The paste is inoculated with a starter from a previous batch of kisra. Fermentation time (12-16 h) depends on the starter, the temperature, cooking utensils, and the millet flour utilized. Once the dough is fermented, it is diluted with water to form a thin batter which is baked on a lightly oiled metal or clay sheet. The batter is added at one end of the hot sheet, swiftly distributed over the surface of the pan with a small spatula and baked 30-40 s on one side only. Good kisra peels off as a single piece without breaking, yielding a soft, flexible, paper-thin pancake which is eaten with stews and other side dishes. A white color is desired, with a soft, moist, but not spongy, texture. It should remain soft for 1 d. Pearl millet is used for kisra in some areas of the Sudan, but information on its quality is not available.

Galettes are produced from fermented pearl millet flour in West Africa. The flour is mixed with water (other ingredients may be added) and the batter is fermented overnight. The batter is placed on a greased pan and fried on both sides. Alternatively, the batter is deep-fat fried to produce snacks. Galettes are often consumed for breakfast.

Dosai is a slightly crisp, yet flexible, thin pancake

Sorghum or millet grain

↓

Dry mill

↓

Sieving
(overs are reground)

↓

Add water, starter and mix
(3 volumes water:2 volumes flour)

↓

Ferment dough
(22-24 h)

↓

Dilute to a batter with water

↓

Pour onto greased pan

↓

Spread into thin sheet

↓

Bake on one side (30-40 s)

↓

Kisra

**Figure 2. Traditional procedure for the preparation of Sudanese kisra. Adapted from Steinkraus (1983).**

which is consumed with curd, vegetables, chilies, and other sauces. Dosai is made from a 1:2 mixture of fermented cereals and fermented black gram (Fig. 3). It is widely consumed in South India and Sri Lanka. Rice is the preferred cereal but pearl millet and other cereals are used in some areas. Idli is similar to dosai except it has a coarser particle size and is steamed into small, white, acid-leavened cakes. Idli is soft, moist, and spongy with a slightly sour taste. Pearl millet with a light color that more closely resembles rice give the best dosai and idli (Desikachar 1977).

## Porridges

The major difference between thick and thin porridges is the concentration of flour in the porridge. Generally, thick porridges are solid and can be eaten with the fingers, while thin porridges are consumed by drinking or by using a utensil. In this discussion, thick porridges will be emphasized since they have the most critical characteristics relating to millet quality. Thick porridge may be made by souring and fermenting flour prior to cooking or by cooking the flour or meal in acid, alkali, or water (Fig. 4). In general, alkaline, thick porridge products are more sensitive to changes in millet and sorghum properties than are other porridges (Scheuring et al. 1982, Da et al. 1982). Alkaline porridges are popular in areas of West Africa. In Mali, a thick porridge, *to,* is generally made using 'potash' (Scheuring et al. 1983), while in neighboring Burkina Faso, it is usually made by cooking the flour in tamarind extract (Da et al. 1982). Potash is obtained by leaching ashes with water to produce alkali. Porridges made with alkali often produce very dark, undesirable colors. In Niger and Tanzania, thick porridges are prepared by cooking flour in water while in southern Africa, Niger, and Sudan, sour, fermented porridges are preferred.

Typical procedures for producing thick porridges are presented in Figure 4. The pearl millet is usually decorticated by hand-pounding in a mortar and pestle followed by crushing the decorticated grain into flour. Part of the flour, suspended in cool water, is then added to boiling water, or boiling water containing potash or tamarind extract, and cooked to produce a thin porridge. Part of the thin porridge is set aside and flour is added to the remainder of the thin porridge with vigorous stirring. Portions of the thin porridge may be added to the cooking pot with the flour. When all the flour and thin porridge is stirred into the cooking pot, the mixture is cooked for a few more minutes. The vigorous stirring during cooking produces a thoroughly gelatinized, smooth paste. The thick porridge is consumed after cooling by tearing off a handful and dipping it into sauce made with chilies, onions, tomatoes, okra, garlic, or other vegetables, including amaranthus leaves, cow-

Black gram dhal → Wash and soak 5-10 h → Fine grind in mortar

Decorticated millet → Soak in water 5-10 h → Coarse grind in mortar

↓

Combine slurries into a thick batter
Mix well

↓

Add salt for seasoning
(approximately 1% w.v)

↓

Incubate 12-24 h in warm place (30-32°C)

↓

Pour batter onto a hot greased pan

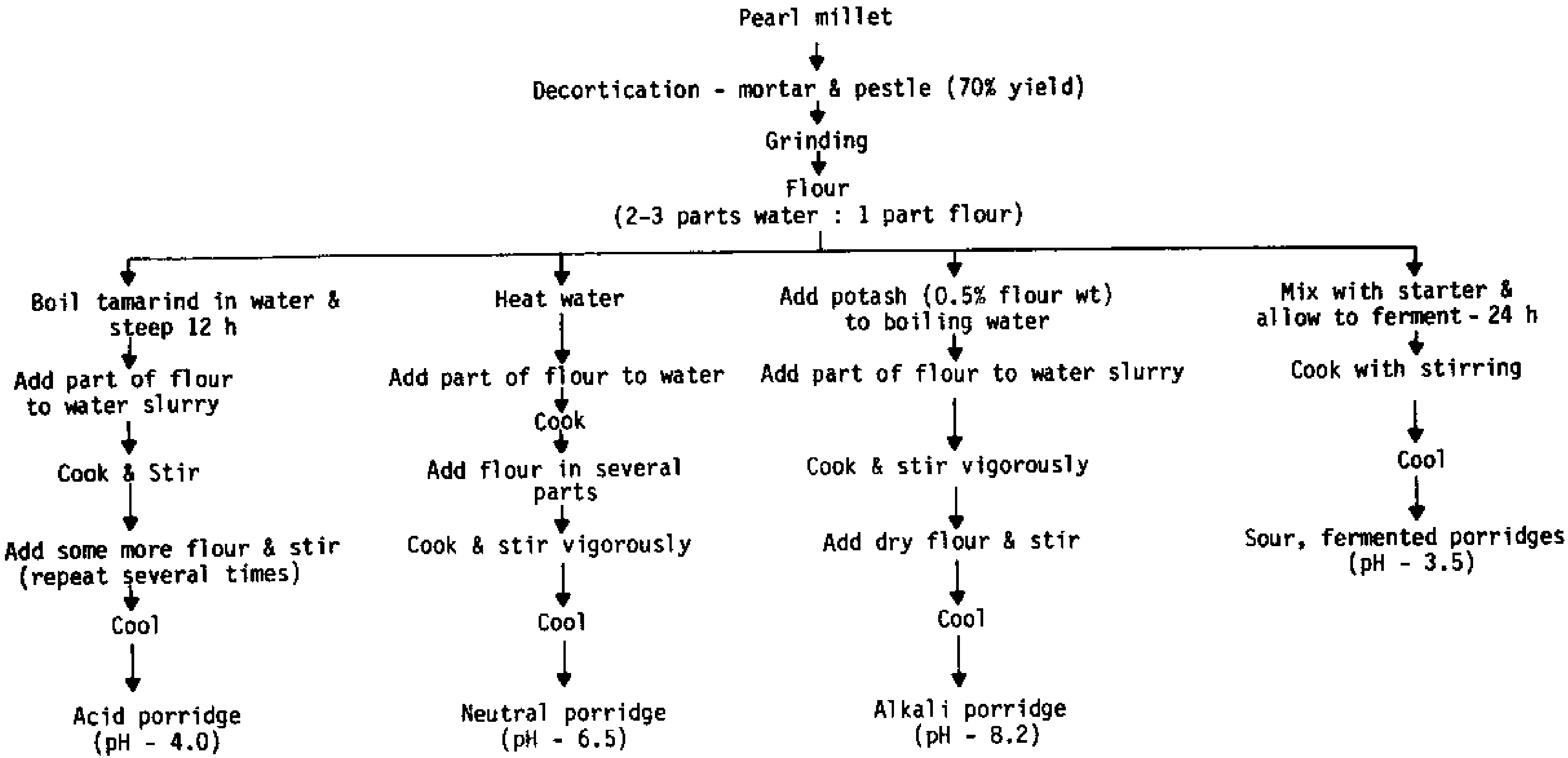
↓

Fry on both sides

↓

Dosai

**Figure 3. Traditional method of Indian Dosai preparation. Adapted from Steinkraus (1983).**




To cook 2 kg of flour cooking time varies but may require up to 30 min after water is boiling and the process starts. Part of the thin porridge formed in the initial cooking phase is retained and mixed into the porridge along with dry flour to produce a smooth texture.

**Figure 4. Traditional processes of thick porridge preparation.**

peas, peanuts, or baobab leaves. When available, meat or fish go into the sauce. Okra in the sauce significantly adds to the palatability of the porridge.

Good thick porridges have a texture that permits consumption without sticking to fingers, teeth, or mouth. Some varieties of pearl millet produce sticky, thick porridge. Consumers complain that the "taste" of some porridges is poor and are reluctant to grow those varieties, when, in fact, they are really reacting to inadequate texture. Keeping-quality of porridges is of major importance because the porridge is stored overnight, reheated, and consumed. Porridges with poor keeping quality become mushy, sticky, and lose water. In general, the actual taste of the porridge is not very important because it is masked by the sauces. Porridge made with tamarind extract (acid) is generally firmer and lighter in color than that made with alkali (Da et al. 1982). In general, a white or yellow colored porridge is preferred. Pearl millets are often soaked overnight in sour milk or fermented, which improves the color and palatability.

### Thin Fermented Porridges

A fermented porridge, ogi, is produced in Nigeria and Ghana (Obilana 1982). It is prepared by soaking whole grain in water at room temperature for 2-3 d (Fig. 5). The steeped grain is crushed in a slurry of water and sieved to remove the bran. The remainder, mostly endosperm chunks and starch granules, is allowed to ferment longer. Most of the water is decanted from the solids, which are then cooked to produce ogi. Solids can be stored under water for several hours. Sometimes the solids are wrapped in leaves and sold. Ogi, because it is highly refined, is a preferred food for the elderly and sick, and is also preferred for young children, especially when it is cooked with milk.

Ogi is a free-flowing porridge with a creamy consistency and smooth texture. Light-colored ogi with a slightly sour taste is preferred. When the solids level is higher, thick porridges are produced and are consumed with sauces, stews, etc., as described previously.

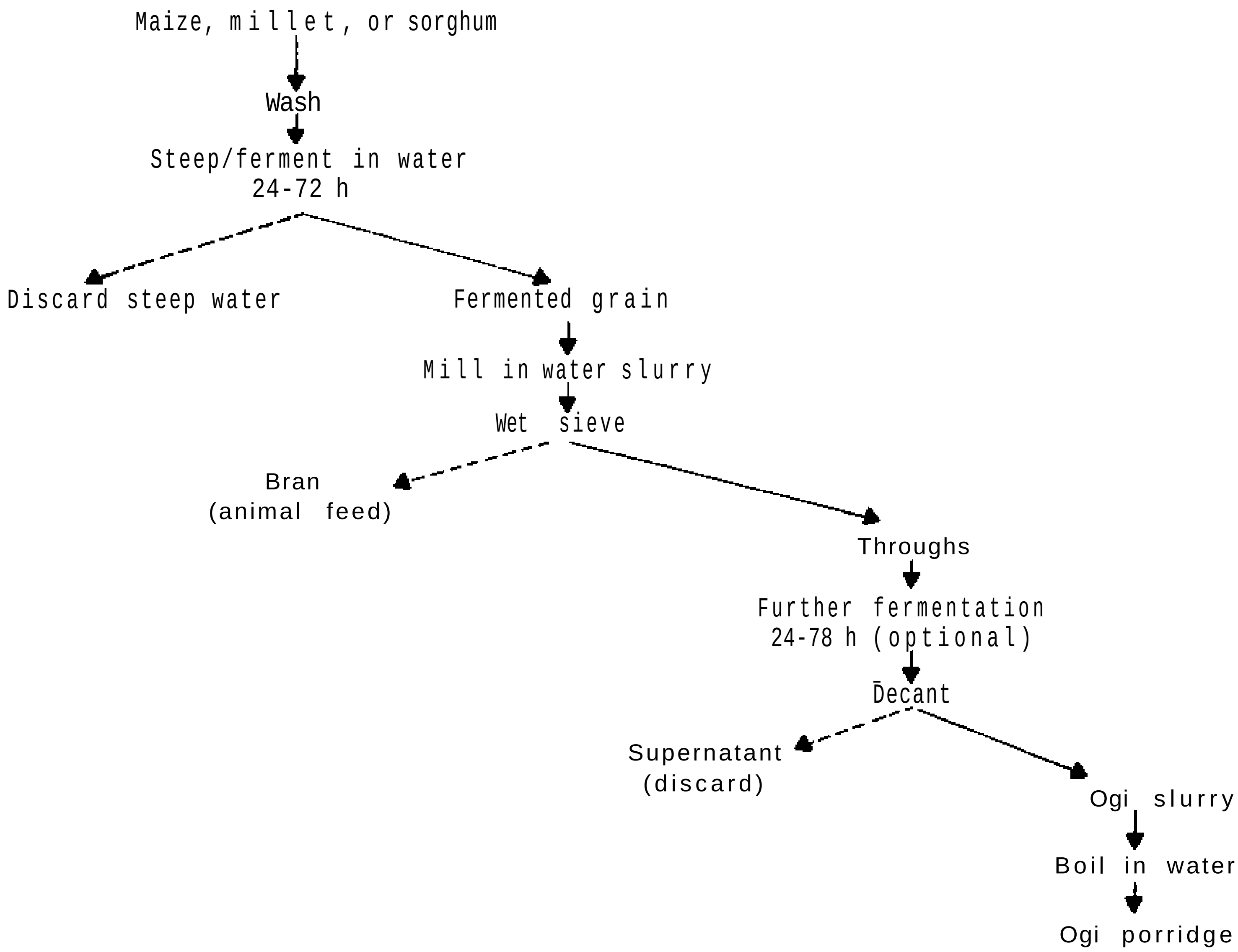



**Figure 5. Traditional procedure for the preparation of Nigerian ogi. (Banigo et al. 1974).**

## Steamed Products

Couscous is the preferred food staple in many areas of West Africa, especially Senegal. A traditional process for producing couscous is presented (Fig. 6). Pearl millet is generally decorticated and milled by hand-pounding in a mortar and pestle to produce couscous flour. The flour is agglomerated and steamed. Gums and mucilages from several species are added to the couscous to improve palatability. In Mali, ground okra and baobab leaves are used. Fresh couscous is consumed with a sauce containing vegetables, especially legumes, and other foods. Dried couscous is one of the few traditional, cereal-based convenience foods of the Sahel. Sun-dried couscous can be stored and reconstituted in milk or be rehydrated by steaming prior to serving with a sauce.

Whole pearl millet kernels
↓
Wash in water
↓
Decortication (mortar & pestle)
↓
Dry and winnow - remove bran
↓
Pound decorticated grain again and sift through 1-mm sieve
↓
Discard overs or recycle
↓
Flour
↓
Add 40% water to flour and force through 1.5-mm sieve
↓
First steaming
→ break up particles
↓
Second steaming
↓
Break up partially steamed couscous, add powdered baobab leaf, okra or other source of gums
↓
force through 2.5-mm sieve
→ discard overs
↓
Third steaming
↓
Couscous

**Figure 6. Traditional procedure for the preparation of couscous.**

Sorghum and millet couscous is an excellent product when consumed with the typical sauces used in West Africa. The disadvantage of couscous is the laborious, time-consuming process, and the skill required to make the product. Small- scale, mechanized production of couscous in urban centers might be an economical way to enhance the acceptability of sorghum and millet.

In Mali, sanio pearl millet produced lower yields of couscous than keninke sorghum (Sidibe et al. 1982). Galiba et al. (1985) found that sanio and souna pearl millets produced couscous with a higher moisture content than sorghum couscous. The taste and color were different, but were quite acceptable. The milling yields were lower for souna and sanio pearl millets compared to sorghums with hard or intermediate kernels.

Degue (steamed, fermented millet dumplings) is consumed in West Africa. The flour is made into a stiff dough which is formed into large dough balls and steamed. The degue is broken into small pieces, covered with sour milk and eaten. The large dough balls may be stored overnight or longer. In Niger and Nigeria this product is referred to as fura.

## Boiled Rice-Like Foods

Pearl millet is substituted for rice in many areas. Usually, decorticated pearl millets are used, but sometimes the whole kernel is cracked and cooked. The decorticated grain is cooked in a 1:3 ratio of grain to water. Sometimes the grain is soaked overnight in water to facilitate cooking (Subramanian and Jambunathan 1980). The grains are cooked until soft, and the excess water is removed. In general, the cooked product should not be sticky, although the desired texture varies among consumers, and should be light colored. Pushpamma and Rao (1981) indicated that in some areas of India, the lighter-colored pearl millets were preferred. In some areas of Africa, slate grey pearl millets are soaked overnight, which lightens the color.

## Beer

Two major kinds of beer are produced in millet consuming areas: (1) a soured, alcoholic, effervescent, brown, viscous, opaque beverage which is consumed while undergoing active fermentation (Novellie 1982), and (2) a sweet, relatively non-sour type of beer (Rooney and Kirleis 1980). The soured beer is made from malted sorghum or millet or both, and several different starchy materials, e.g., corn grits and sorghum flours, are used as adjuncts (Fig. 7). Malted sorghum and millet provide the source of enzymes. The traditional production of beer is an art usually practiced by women who arc known by the quality of beer they produce. During malting, pearl millet requires a warm temperature and must be kept moist and aerated by turning. The germinated pearl millet is then sun-dried and can be ground as needed for brewing. The final composition of the beer varies drastically because in traditional brewing, conditions are extremely variable. Opaque sorghum or millet beers contain alcohol, 2-4% m/v (mass/volume), 0.3-0.6% lactic acid, and 4-10% total solids with a pH of 3.3-3.5. They are an important source of nutrients in many areas because they contain vitamins, minerals, proteins, and carbohydrates that have been solubilized during malting and brewing (Novellie 1982, 1984).

Dolo, a light brown, alcoholic, slightly bitter, sweet-sour, fruity beer, is made by fermentation of malted millet or sorghum in some areas of West Africa. Dolo has relatively low levels of solids and does not have the strong sour taste of Kaffir beer. The pH of Kaffir beer is lower than that of dolo because of higher levels of lactic acid and acetic acids. Sometimes, the nonfermented beer, the wort, is given to children as a nutritious drink or food (Rooney and Kirleis 1980).

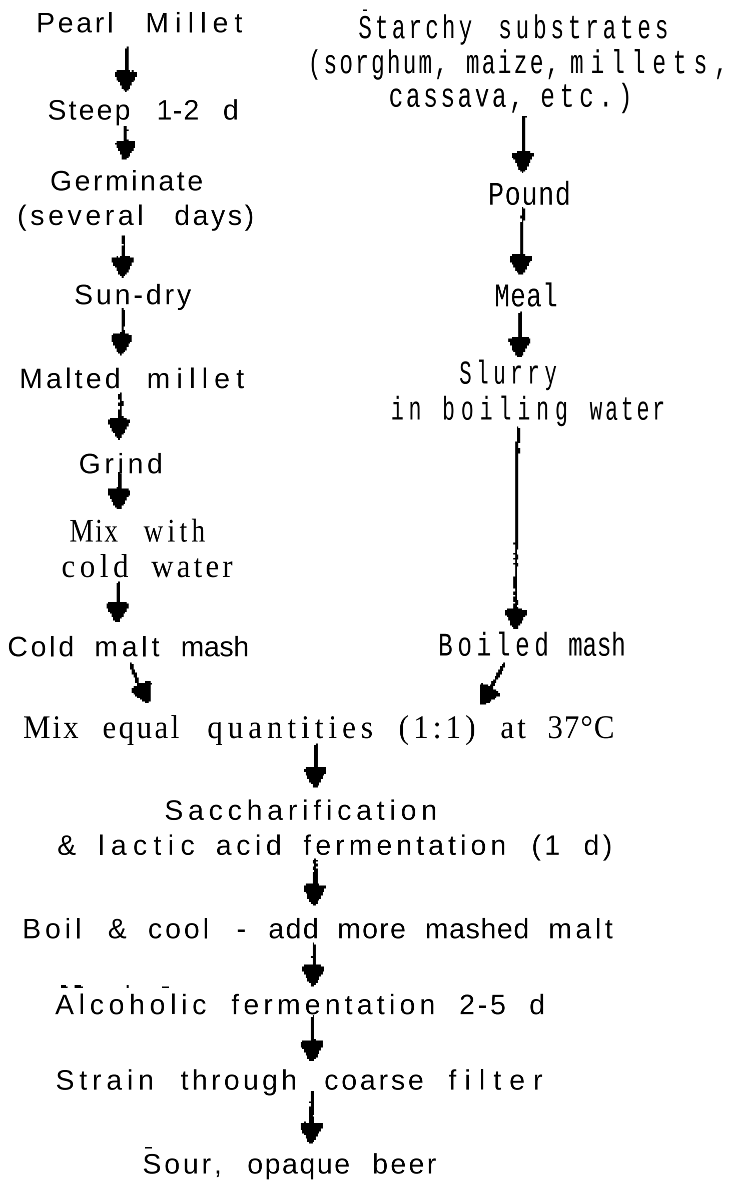



**Figure 7. Traditional method of production of African sour opaque beer.**

## Snacks and Special Uses

Pearl millet is used in a wide variety of snack foods made in every conceivable manner (Subramanian and Janbunathan 1980). In India, pearl millet is popped or parched and eaten directly or used to produce various snacks, beverages, and "predigested" weaning foods. Pearl millet is also harvested in the milk or dough stage, roasted and consumed like sweet corn.

## Quality Standards

Little information is available on the specific kernel characteristics that affect pearl millet quality for the various traditional foods. The information in Table 2 is compiled to provide a summary of acceptable

Table 2. Properties of pearl millet for traditional foods.

| | |
|---|---|
| Unfcrmcntcd breads—*roti* | Oval, globular, large kernels, thin pericarp, slate grey or white, sweet taste, keeping quality. |
| Fermented breads—*kisra, galletes* | Light color, yellow. |
| Rice-like—*annam* | White or light color, good keeping properties, globular, bold kernels. |
| Porridges—to | Keeping quality, globular, large kernels, sweet taste, light color or yellow. |

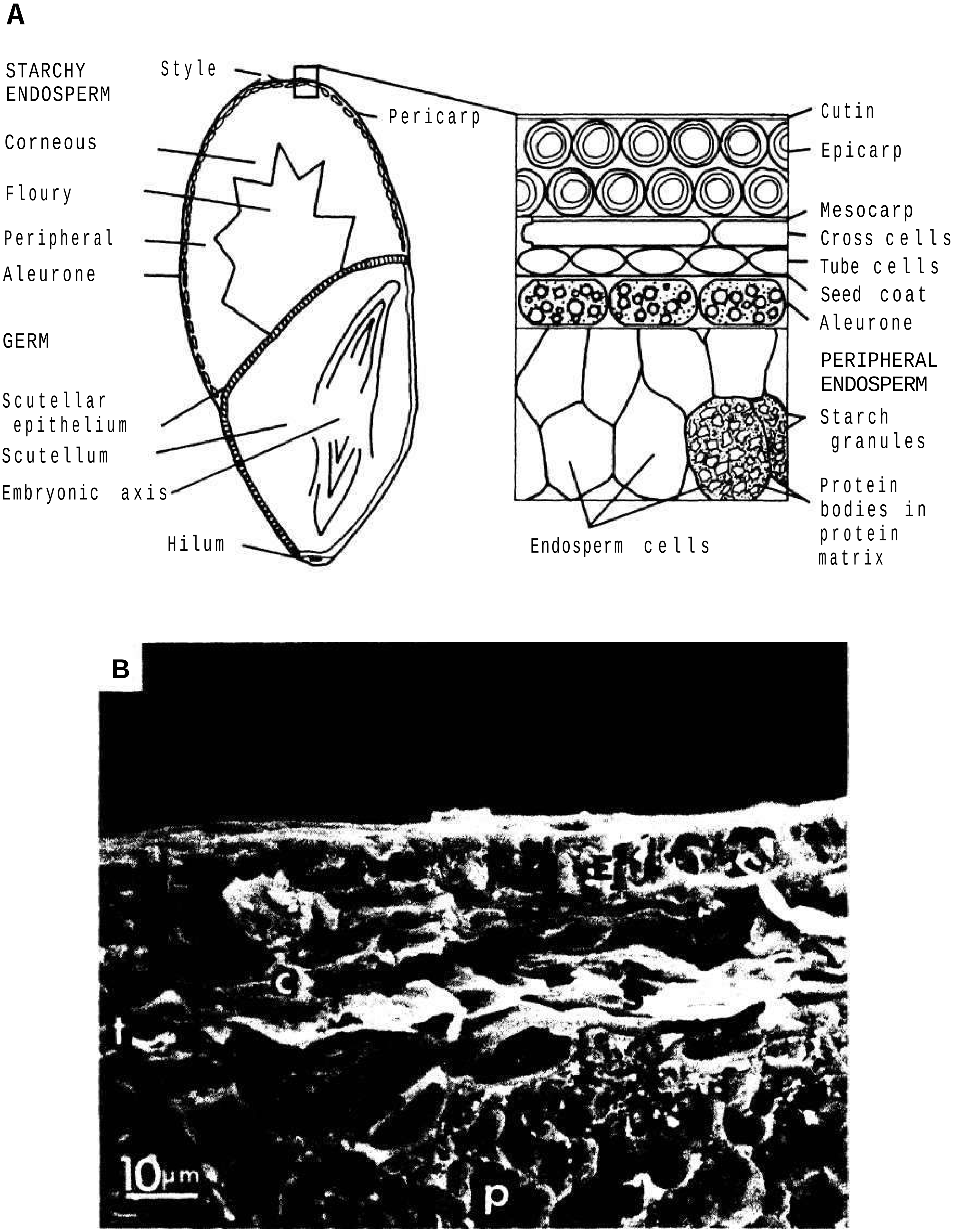



**Figure 8. A. Schematic cross section of a pearl millet caryopsis. B. SEM micrograph of the pearl millet pericarp and peripheral endosperm. (e = epicarp cells; c = cross cells; t = tube cells; s = seed coat; a = aleurone; and p = peripheral endosperm).**

properties for pearl millets. It is based on general information and must be refined as progress occurs in evaluating quality of pearl millet for specific products. The production of fermented or low-pH products apparently produces lighter-colored products because the pearl millet pigments of some cultivars are converted to colorless forms by acid.

## Factors Affecting Food Quality

### Kernel Structure

The kernel of pearl millet is a caryopsis similar in structural components to sorghum (Badi et al. 1976, Sullins and Rooney 1977, Zelaznek and Varriano-Marston 1982). Kernel shape, size, and appearance (color) vary significantly among pearl millet varieties, and within a sample, kernels vary significantly in size and shape. A drawing of the pearl millet caryopsis is presented in Figure 8a to enable readers to interpret the photomicrographs that follow. Scanning electron photomicrographs (Figs. 8b, 9a and 9b) show the structure of the pericarp, seed coat or testa, the aleurone cells, and the starchy endosperm. The endosperm contains starch granules surrounded by a protein matrix containing protein bodies. The center of the kernel has a soft floury endosperm surrounded by a flinty or translucent endosperm. The proportion of floury to hard endosperm varies among varieties, and among kernels within a variety. The protein content of the endosperm within a kernel decreases gradually from the aleurone layer to the starchy endosperm.

The pericarp is composed of three layers of tissue: the epicarp, mesocarp, and endocarp (Figs. 8a, 8b, 9a, 9b, and 10). The term bran refers to the pericarp, seed coat, and aleurone layers of the kernel. The outer layer (epicarp) has 1-2 cell layers of thick-walled, blocky cells that contain concentric layers of cell tissue surrounding pigments in the center (Figs. 10a, 10b, and 10c). There is a thin, waxy cutin layer on the outer surface of the kernel that could, in combination with the epicarp layer, help decrease the effects of weathering on the kernel by acting as a barrier between the environment and the internal portions of the kernel (Sullins and Rooney 1977).

The mesocarp layer varies in thickness and is composed of several tiers of collapsed cell walls (Figs. 9a and 9b). This layer has no apparent function in the mature seed, but the variability of its thickness determines whether the cultivar is classified as a thin or thick pericarp variety (Sullins and Rooney 1977). The thick pericarp is preferred by those who use the traditional mortar and pestle method of milling because the pericarp flakes off the kernel more easily (Kante et al. 1984, Scheuring et al. 1983).

The endocarp, located beneath the mesocarp, is composed of two types of cells: cross cells and tube cells (Fig. 10d). The cross cells are arranged longitudinally across the kernel and the tube cells lie perpendicular to the cross cells. The endocarp layer probably functions in the transport of water and nutrients around the kernel. During decortication, the pericarp splits away from the kernel beneath the aleurone layer (DeFrancisco et al. 1982) or the endocarp (Sullins and Rooney 1977, McDonough 1986).

A partial or total seed coat is present in all varieties, the partial seed coat predominates in the slate-colored varieties (McDonough 1986) (Figs. lOd and 10e). The seed coat is pigmented, but it is also very thin (0.4 $\mu$). It can contribute to the overall color perceived in kernels with a thin colorless pericarp (Rachie and Majmudar 1980).

The aleurone is one layer thick, with uniform cell sizes and variable cell walls (Figs. lOd and lOe). The cells range from 16-30 $\mu$m long and 14-33 $\mu$m wide. Fluorescence microscopy reveals that aleurone cells contain a large amount of protein and lipid bodies (McDonough 1986). Many cereals contain phytin (phosphorus) and nicotinic acid in the aleurone, but pearl millet appears to contain these materials only in the germ. The aleurone cells of some cultivars contain pigments that can produce unacceptable color in food products (McDonough and Rooney 1984, Rachie and Majmudar 1980).

The starchy endosperm is the part of the kernel that comprises the bulk of the flour (Fig. 11). The endosperm contains simple starch granules and protein in the form of matrix and bodies. Three distinct endosperm areas are visible from the outside to the inside of the kernel:

- the peripheral region that contains a large amount of protein bodies and matrix, surrounding small starch granules (Figs. 10f and 11a),
- the corneous area with large, uniform-sized, polygonal starch granules embedded in protein matrix with a small amount of protein bodies (Fig. Mb), and
- the floury endosperm area with large, round, starch granules, loosely packed in a small amount of thin protein matrix and a small number of protein bodies (Fig. 11c) (McDonough 1986). The flour fraction is composed of the free starch granules and protein released from the floury

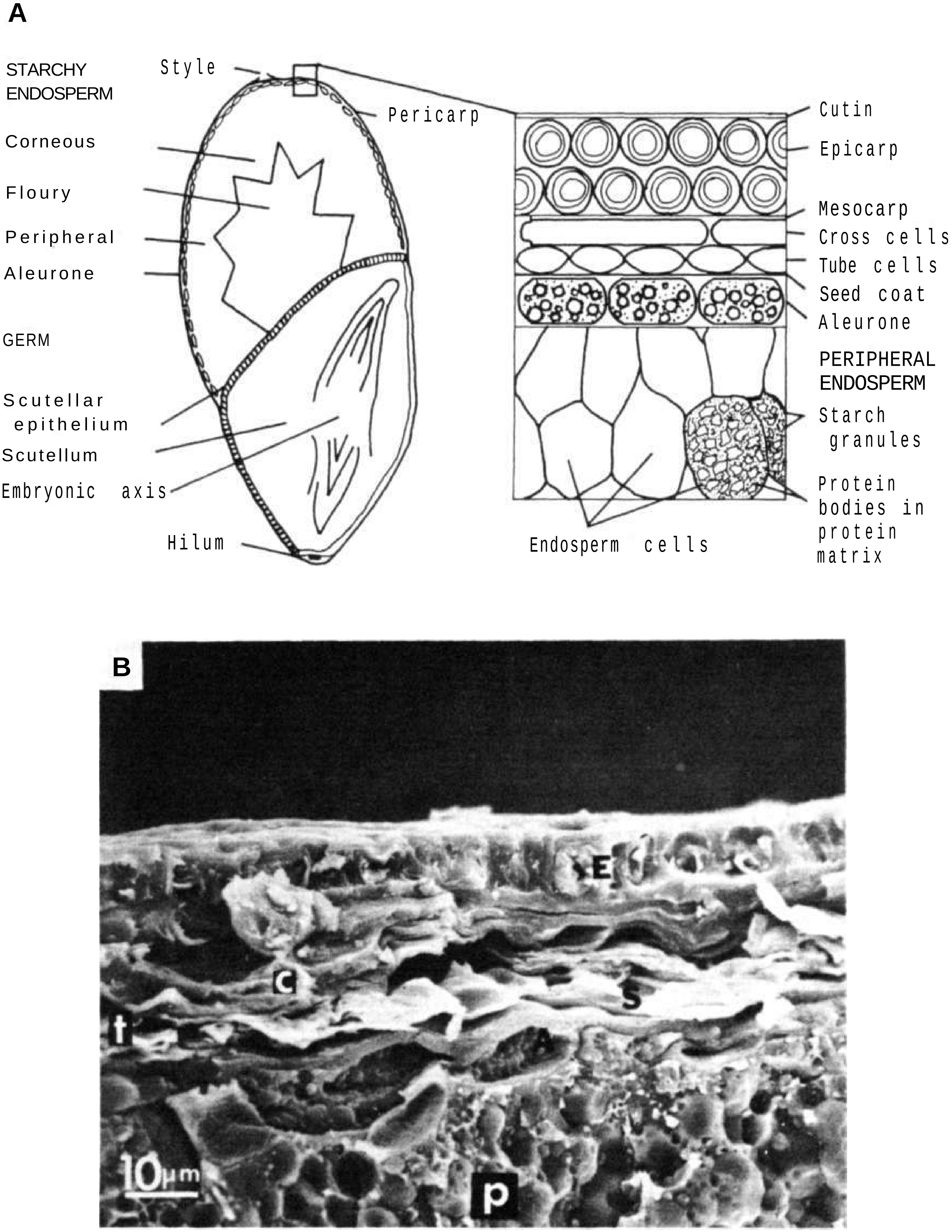



**Figure 8. A. Schematic cross section of a pearl millet caryopsis. B. SEM micrograph of the pearl millet pericarp and peripheral endosperm. (e = epicarp cells; c = cross cells; t = tube cells; s = seed coat; a = aleurone; and p - peripheral endosperm).**

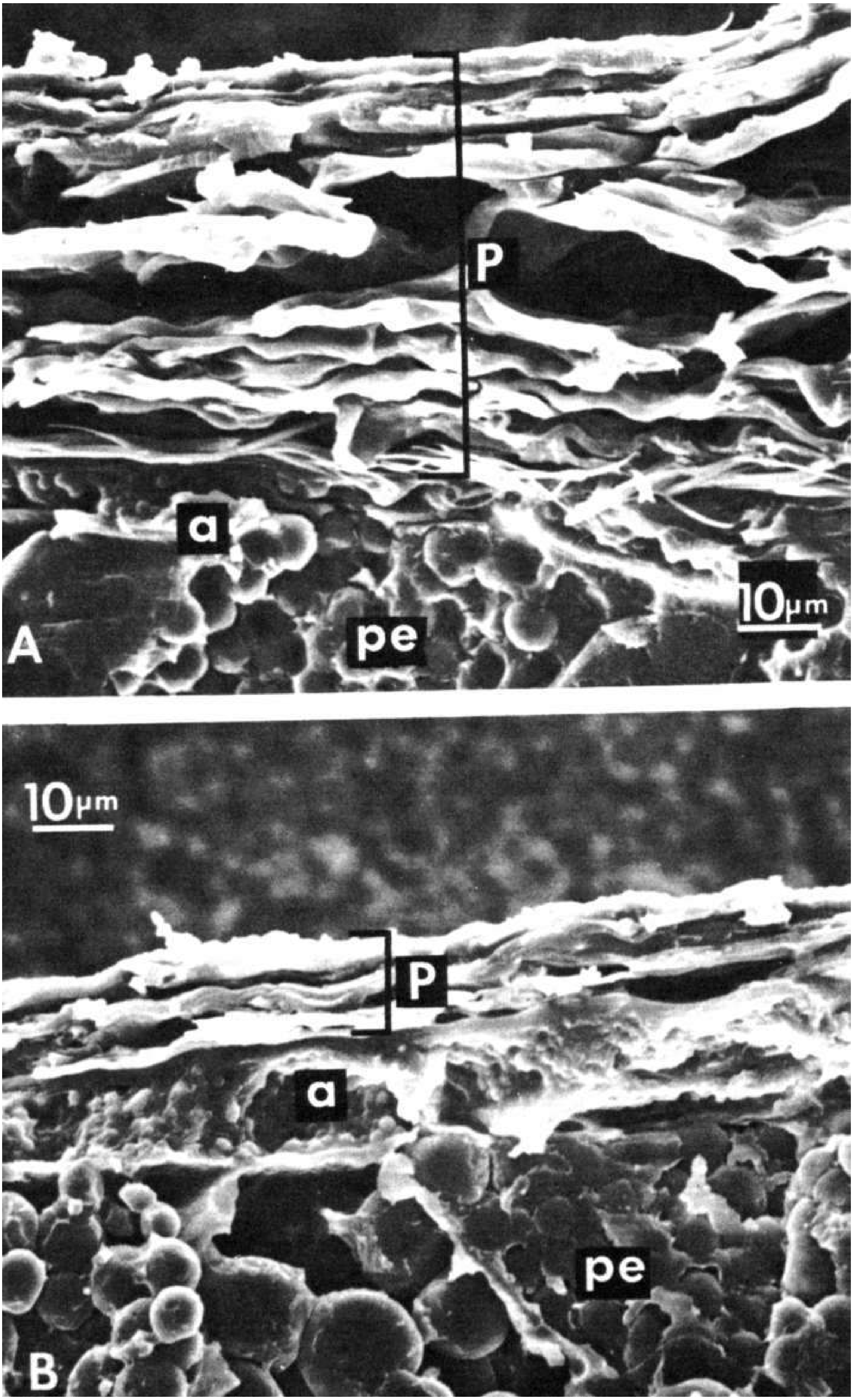



**Figure 9. A. Pearl millet with a thick pericarp. B. Thin pericarp.**

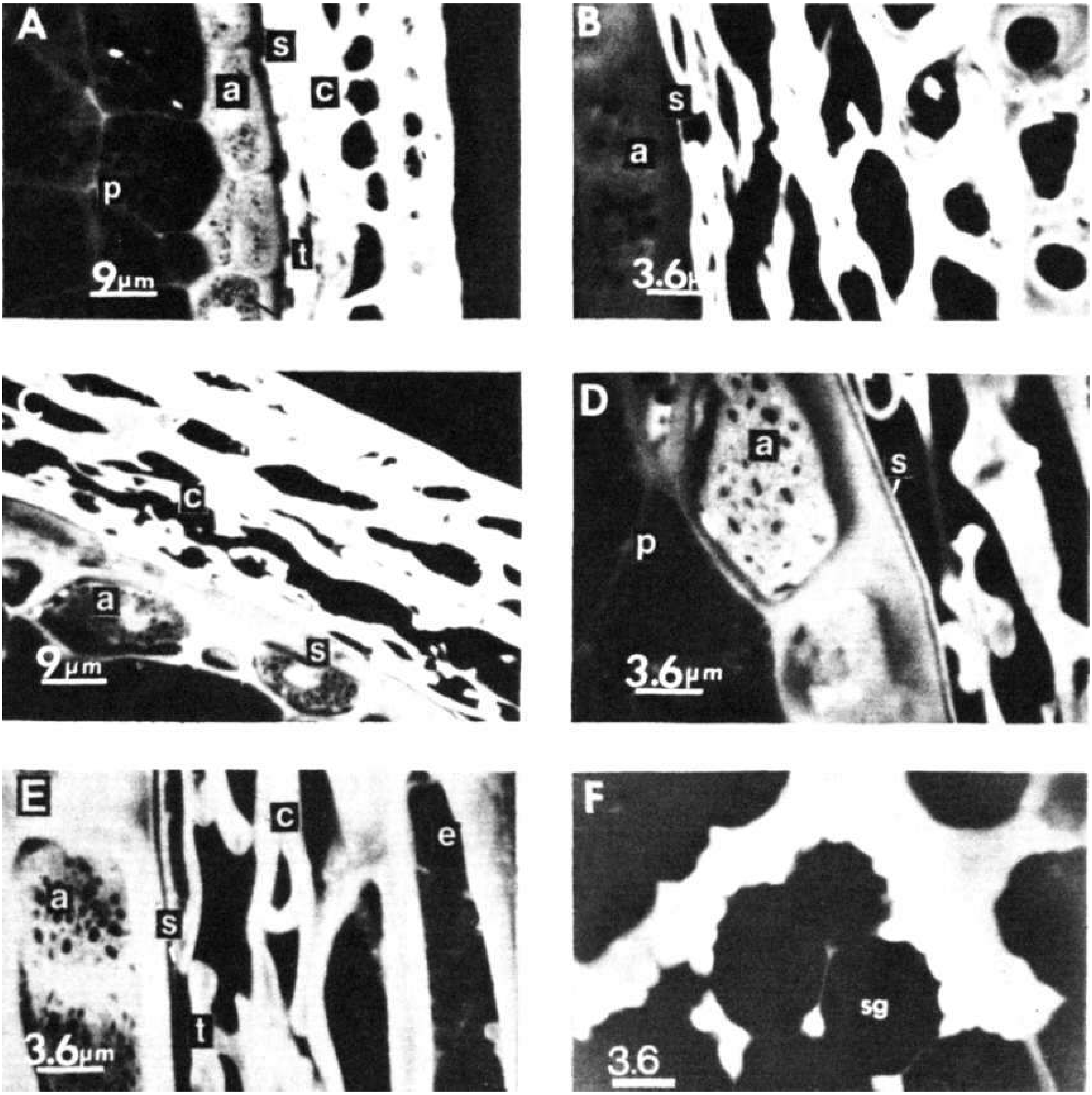



**Figure 10. Autoflourescence microscopy of pearl millet sections embedded in glycol methacrylate. A-D. Autoflourescence. A. 40X, bronze millet. B. 100X, bronze millet. C. 40X, blue-grey millet. D. 100X, blue-grey millet. E. Congo Red, 100X, bronze millet. F. Autoflourescence with Acid Fuschin dye, 100X, tan millet. (p = peripheral endosperm; a = aleurone; s - seed coat; t - tube cells; c = cross cells; e - epicarp cells; pb = protein bodies; sg = starch granules).**

endosperm and partial chunks of endosperm cells from the corneous and peripheral endosperm. There may also be pieces of bran left in the fraction as well as chunks of germ tissue.

The germ of pearl millet is about 17% of the total kernel mass (Table 3) (Abdelrahman et al. 1984), and contains about 25% lipid, 20% protein, and most of the phytin, vitamins, and enzymes. The protein content of the germ is of high quality with high levels of lysine, tryptophan, and theonine. The germ is firmly embedded inside the pericarp and endosperm so it is difficult to remove completely by milling processes. Many cereals contain phytin and nicotinic acid in the aleurone and germ, but pearl millet appears to contain these materials mainly in the germ (McDonough 1986). The high oil content and enzyme activities of the germ have a major effect on keeping properties and nutritional value of milled products. Thorough removal of the germ improves the flour storage stability, and decreases the nutritional value. The phosphorus content of the germ is high (Hoseney and Varriano-Marston 1981) which was confirmed by McDonough (1986).

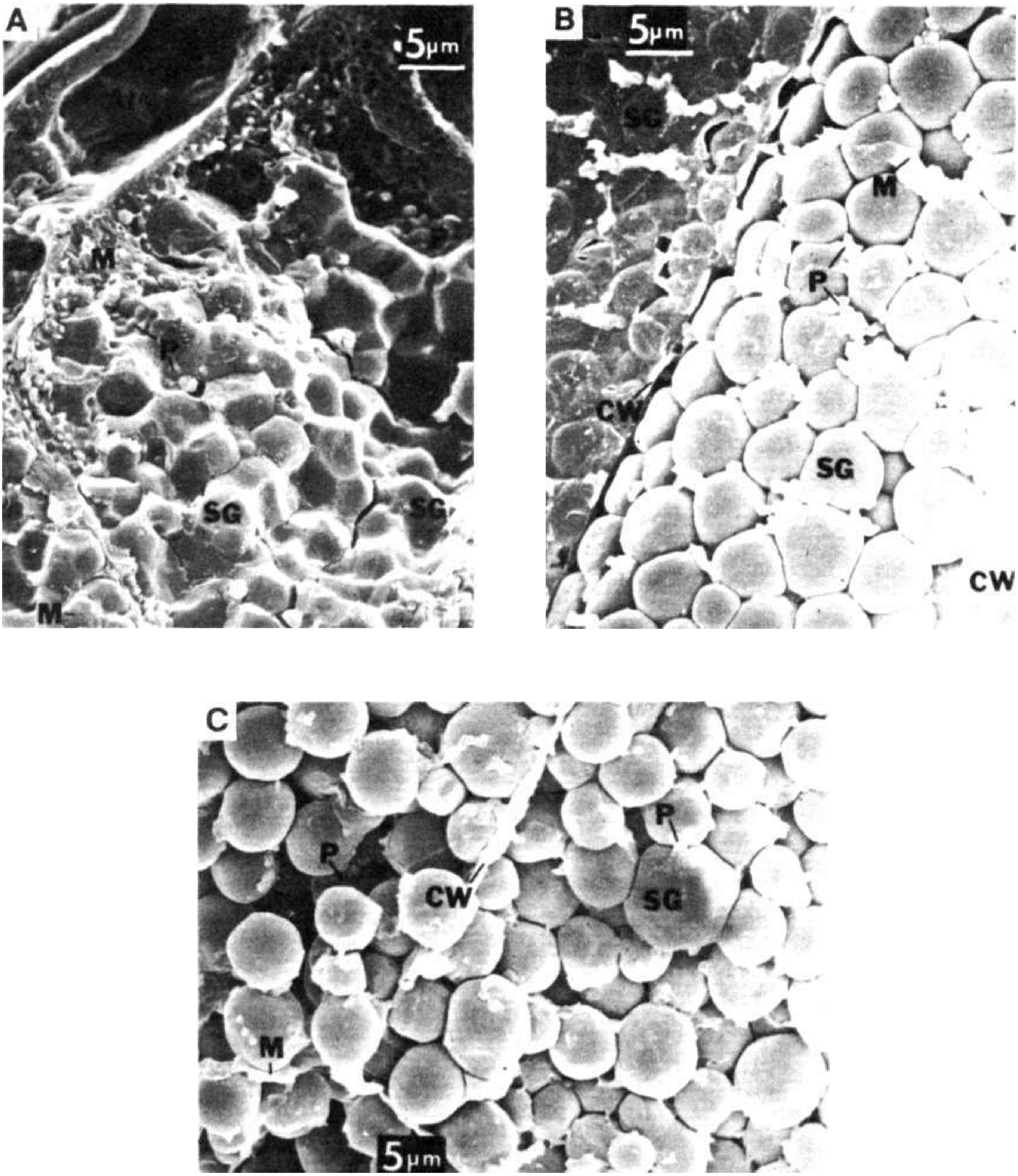



**Figure 11. Peripheral (A), corneous (B), and floury (C) endosperm sections of a pearl millet kernel, (al= aleurone; m = protein matrix; pb = protein bodies; sg = starch granules; and cw = cell wall.)**

| Table 3. Proportion of anatomical parts of pearl millet kernel[1]. | | | | |
|---|---|---|---|---|
| Kernel | | Endosperm | Germ | Bran |
| Size | Mass (mg) | | (%) | (%) |
| Large | 18.9 | 76.2 | 16.6 | 7.2 |
| Medium | 13.7 | 75.1 | 17.4 | 7.5 |
| Small | 10.4 | 73.9 | 15.5 | 10.6 |

1. Adapted from Abdelrahman et al. (1984).

Table 4. Proximate analysis of pearl millet grain[1,2].

| | n[3] | Mean (%) | Range {%) |
|---|---|---|---|
| Protein | 2 | 12.1 | 8.6-17.4 |
| Carbohydrate | 11 | 69.4 | 61.5-89.1 |
| Lipid | 18 | 5.0 | 1.5- 5.8 |
| Fiber | 11 | 2.4 | 1.4- 7.3 |
| Ash | 16 | 2.3 | 1.6- 3.6 |

1. Data adapted from Hulse et al.(l980).
2. Values are means representing multiple studies.
3. n = number of individual studies.

## Composition of Pearl Millet

The composition of pearl millet grain is summarized (Table 4). In general, pearl millet has more fat and higher protein content than sorghum grown under similar conditions (Rooney 1979). The starch, crude fiber, ash, and sugars are similar. Average figures mean very little because of the many environmental as well as genetic factors that affect protein content (Kumar et al. 1983). The energy level (784 calories $kg^{-1}$) is among the highest for whole grain cereals.

### Proteins

The proteins of pearl millet vary considerably in amino acid content often by a factor of two or more (Hoseney et al. 1981). Generally, pearl millet is low in lysine, threonine, and the sulfur-containing amino acids (Table 5). The leucine to isoleucine ratio of pearl millet varies significantly. The lysine content as a percentage of the protein decreases with increasing protein content. Protein content generally decreases as grain yields increase (Kumar et al. 1983). The amino acid content differs in the germ, starchy endosperm, bran, and aleurone layer. The germ proteins are high in essential amino acids, while those in the starchy endosperm are relatively low.

The proteins of pearl millet and sorghum contain large proportions of alcohol-soluble proteins. Jambunathan et al. (1984) showed that pearl millet proteins contained a lower proportion of cross-linked prolamins than sorghum (Table 6). The protein bodies contain relatively low levels of basic amino acids. In general, the prolamins of pearl millet have higher levels of lysine and tryptophan than sorghum. The reduced level of cross-linked prolamin may

Table 5. Protein content and essential amino acid composition of sorghum and pearl millet grains[1,2].

| Amino acids | Sorghum No. of samples | Sorghum Range | Sorghum Mean | Amino acid score | Pearl Millet No. of samples | Pearl Millet Range | Pearl Millet Mean | Amino acid score[3] | Pattern[4] |
|---|---|---|---|---|---|---|---|---|---|
| | | (g 16 $g^{-1}$ N) | | | | (g 16 $g^{-1}$ N) | | | (g 16 $g^{-1}$ N) |
| Lysine | 412 | 1.06- 3.64 | 2.09 | 38 | 280 | 1.59- 3.80 | 2.84 | 52 | 5.5 |
| Threonine | 29 | 2.12- 3.94 | 3.21 | 80 | 29 | 3.17- 5.66 | 4.07 | 102 | 4.0 |
| Valine | 29 | 3.84- 6.93 | 5.40 | 108 | 29 | 4.38- 7.67 | 6.01 | 120 | 5.0 |
| Methionine + cystine | 24 | 1.80- 2.69 | 2.36 | 67 | 29 | 1.43- 3.96 | 2.71 | 77 | 3.5 |
| Isoleucine | 29 | 2.85- 5.05 | 4.17 | 104 | 29 | 3.70- 6.34 | 4.56 | 114 | 4.0 |
| Leucine | 29 | 10.12-17.60 | 14.67 | 210 | 29 | 8.62-14.80 | 12.42 | 177 | 7.0 |
| Phenylalanine + tyrosine | 29 | 6.11-10.72 | 8.87 | 148 | 29 | 6.54-10.81 | 8.49 | 142 | 6.0 |
| Protein (%) | 412 | 4.60-20.25 | 11.98 | | 280 | 6.40-24.25 | 12.30 | | |

1. Determined by ion exchange chromotography.
2. Adapted from Jambunathan et al. (1981).
3. Percentage of recommended pattern.
4. From FAO/WHO (1973), p.67.

Table 6. Nitrogen distribution in sorghum and pearl millet grain[1].

| Fraction | % total nitrogen Sorghum[2] Mean | Pearl millet[3] Mean |
|---|---|---|
| I Albumin and globulin | 17.4 | 25.0 |
| II Prolamin | 6.4 | 28.4 |
| III Cross-linked prolamin | 18.8 | 2.7 |
| IV Glutelin-like | 4.0 | 5.5 |
| V Glutclin | 35.7 | 18.4 |
| VI Residue | 10.6 | 3.9 |
| Total | 92.9 | 83.9 |

1. Adapted from Jambunathan et al. (1981).
2. Based on 3 genotypes, M 35-1, CSH-8 and CSV-3.
3. Based on 4 genotypes, PHB-14, BK-560, WC-C75 and Ex-Bornu.

explain why pearl millet proteins generally have a higher digestibility than sorghum proteins (Hoseney et al. 1981).

## Carbohydrates

The starch content of pearl millet is similar to that of sorghum and corn. The cooking properties of the isolated starches are similar. The starch granules are simple, undergo loss of birefringence at temperatures similar to maize and sorghum starches, and have similar cooking and gelling properties. The apparent amylose content of pearl millet starches ranges from 17-29%. The wet milling recovery of starch from pearl millet is lower than that of sorghum and maize.

## Lipids

The level of free lipids extracted from pearl millet cultivars varies from 3.0-7.4% with free fatty acid levels of 2-12 mg 100 $g^{-1}$. The fatty acids of pearl millet oil are similar to those of maize and sorghum (Table 7).

Oleic, linoleic, and palmitic acids are the major fatty acids of pearl millet oils. The bound lipids of pearl millet are similar to bound lipids of sorghum (Hoseney et al. 1981).

## Polyphenols and Pigmentation

Reichert and Youngs (1979) determined that the color of slate-grey pearl millet flour products is pH-dependent, and can be controlled by soaking the grain or flour in tamarind extract or sour milk. In acid pH, a methanol extract of slate-grey pearl millet flour is colorless, while at alkaline pH, the solution is yellow-green. This is important in cooking pearl millet porridge dishes, because a colorless porridge is more acceptable than a yellow-green one. Reichert (1979) determined that the grey color was due to the presence of C-glycosylflavonoids.

The majority of the flavonoid pigments are located in the peripheral endosperm of the kernel and in the pericarp (McDonough 1986). In brown sorghum, tannins cause digestibility and palatability problems in the food products, however no condensed tannins have been reported in pearl millet (Hulse et al. 1980, McDonough and Rooney 1985). Differences were noted among varieties with different kernel colors that were tested with the Folin-Ciocalteu (FC) assay, which measures total phenol content. The bronze millet contained more extractable FC phenols than either yellow or blue-grey millets. The phenol levels in these millets were similar to those levels found in

Table 7. Fatty acid composition of sorghum and pearl millet cultivars[1].

| | No. of cultivars | Palmitic (%) | Stearic | Oleic | Linoleic (%) | Linolenic (%) |
|---|---|---|---|---|---|---|
| Sorghum | 22 | | | | | |
| Mean | | 12 | 1 | 34 | 50 | 3 |
| Range | | 10-14 | 2-1 | 28-42 | 42-56 | 1-5 |
| Pearl millet | 65 | | | | | |
| Mean | | 20 | 4 | 26 | 45 | 4 |
| Range | | 18-25 | 2-8 | 20-31 | 40-52 | 2-5 |

1. From Rooney (1978).

red and white sorghums without pigmented testas. The polyphenol content of the blue-grey millets was similar to that of the yellow millets. Thus, the pericarp color cannot be used as a clear indication of polyphenol content in the slate and yellow millets. It could, however, be used when comparing bronze millets to the other colored millets. McDonough and Rooney (1985), analyzed millets using HPLC, and found that pearl millet contained high levels of ferulic, coumaric, cinnamic, and gentisic acids, and that the kernel color affected phenolic acid levels. Total phenolic acid content was highest in the yellow millets.

## Industrial Utilization of Pearl Millet

Mechanical milling of pearl millet is most efficient when an abrasive process is used for decortication, followed by grinding on attrition mills or with a hammer mill (Perten 1983, Reichert 1982). Wheat flour mills produce pearl millet flour with high ash and oil content. Perten (1983) concluded that in Senegal and Sudan, the new milling processes produced flours with better storage quality than was possible with traditional sorghum and millet flours. The refined flours, mixed with wheat flour, have been used to produce breads with acceptable organoleptic properties. A wide variety of foods can be prepared from pearl millet, but frequently, they have been unable to compete with imported wheat and maize flours. When pearl millets are processed into commercial food products, there will be a need for larger supplies of more uniform grain with desirable milling properties and acceptable flavor, color, and keeping properties. Thus, new varieties should have large, spherical, uniform kernels with light color and acceptable taste. The development of pearl millet cultivars with improved dehulling properties is of critical importance if millet is going to be used on a wider scale in urban areas.

### Kernel Characteristics

The kernel characteristics of pearl millet vary considerably (Appa Rao et al. 1985, Brunken et al. 1977, Rachie and Majmudar 1980). The IBPGR (1981) has described pearl millet kernel shape as obovate, lanceolate, elliptical, hexagonal, and globular. Kernel colors are ivory, cream, yellow, grey, deep grey, grey-brown, brown, purple, and purplish-black. The endosperm texture was mostly corneous, partly corneous, and mostly starchy. The endosperm type was yellow or non-yellow. The descriptors for kernel characteristics should be defined more precisely with pictures and other simple standard measurements. This would facilitate documentation of pearl millet characteristics in relation to processing properties and food quality. The inheritance of pericarp thickness, color, texture, and other characters should be determined.

## Future Research Needs

Continuing research into the food quality of pearl millet in Africa and India is highly desirable. Research concentrated in the following areas should provide information and techniques to improve pearl millet quality.

- Breed pearl millet cultivars with improved dehulling properties.
- Identify a set of standard pearl millet varieties with good and poor quality for important classes of traditional foods.
- Define and illustrate the kernel characteristics of pearl millet in precise terms.
- Define laboratory methods to evaluate and improve food quality.
- Relate kernel characteristics to food quality.
- Determine the effect of traditional and mechanical processing methods on nutritional value and food quality.
- Develop practical village-scale processing equipment.

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# Discussion

The discussion of the paper by Harinarayana centered on the future of hybrid pearl millet cultivation in India. If the area under hybrids is to expand, will there be sufficient infrastructure to support the adoption of hybrids? There was doubt about the availability of irrigation needed for maximum production from hybrids, especially in Rajasthan, although the speaker said that hybrids did have a place in certain agroclimatic zones, with certain agronomic improvements.

There was some doubt about the relative productivity of hybrids in research station trials and on farmers' fields, but a number of hybrids, as well as varieties such as WC-C75, HC 4, and synthetics such as ICMS 7703, produce good yields on farmers' fields.

The disease reaction of hybrids, particularly to smut and ergot, the time and amount of pollen produced, and the relative advantages of different types of hybrids were discussed. The heterogeneity of multicross hybrids could be an advantage in reducing smut and ergot, but the literature is contradictory on this point. The speaker said the contradictions were due to changes in the composition of the mixtures, the locations they were grown in, and other factors. Pollen germinates faster and prior to the conidia of the pathogen, so early pollination by the use of mixtures of early and late flowering genotypes deserves investigation. Heterogeneous populations have shown less incidence of ergot or smut.

One scientist pointed out that the use of open-pollinated varieties is causing problems for seed certifying agencies. There was discussion on the amount of heterosis expressed in single-cross versus multiple-cross hybrids. At present the three-way cross hybrid, MBH 118, has produced grain yields better than those of the best single-cross hybrids.

In the paper by Spencer, hybrids were again discussed, relative to conditions in Africa. Most of what was said about West Africa also applies to East Africa. There was a query whether the lack of improved varieties is a major constraint, and whether there is a potential for hybrids in Africa. The speaker said that lack of improved varieties is not a serious constraint to increased production, because improved management with existing varieties could lead to a substantially increased production. However, improved varieties had an important role to play in the future, and must be planned for now. If hybrids are introduced, he said, they must have sufficient economic advantage to pay for the necessary investment in seed and infrastructure.

In response to a question whether low pearl millet production was due to poor pricing policy or poor systems of grain procurement, the speaker said that poor pricing policy was often used as a pretext for the poor performance of agriculture, but there was no indication that the pricing and other policies for millet have been any worse than for other food crops in West Africa, and the explanation probably lies in other technological and environmental factors.

The role of intercropping featured prominently in the discussion. Millet is usually intercropped with legumes, particularly cowpea, in West Africa. The speaker was asked if intercropping was to be encouraged in the Sahel, or whether a sole crop with higher population density would also contribute to increased productivity. Spencer said that many experiments in the Sahel had shown that increased density of millet, both sole and intercropped, yielded higher, but intercropping still maintains its economic advantages, and must be encouraged. Most of the soils on which millet is grown are sandy and low in nutrients, which may explain why intercropping gave the best yields, but it was questioned whether there will also be a good response to fertilizer. It was confirmed that the response to phosphorous was very good, but the response to nitrogen was poor. The phosphorous trials were conducted in Niger using traditional varieties, but improved varieties could use the fertilizer more efficiently.

In the discussion on the paper by Hanna, the comment was made that although triploids are usually sterile, triploid interspecific hybrids in Arachis had produced seed at ICRISAT Center, but did not under the short-season conditions in the USA. If a similar phenomenon occurred in pearl millet, the progeny from triploids could be valuable in gene transfer.

The yield increase in derivatives of wild species was discussed. This yield increase was probably due to a combination of genes from *monodii* which promote vigor and yield, with the morphological characteristics of the cultivated species, such as seed and inflorescence size, and floret density. When asked what part disease resistance played in this increased yield, Hanna said that most of the increase was due to the already mentioned yield components, but if plants became infected early in the season, the susceptible plants could be completely killed, but the resistant plants survive and produce a grain yield. There is no infection by rust, and the mechanism of smut resistance has not been studied.

In a discussion of male sterility, it was stated that the criterion for pollen viability after storage is its ability to pollinate cytoplasmic male-sterile plants and produce hybrids. Reversion of male sterility can occur due to mutation of cytoplasmic genes. Also, there is variation in a particular cytoplasm, and cytoplasmic male sterility may be more complex than is usually understood.

# Improvement through Plant Breeding

## Moderator's Overview

# Improvement Through Plant Breeding

**D.J. Andrews**[1]

It is a pleasure for me to chair this important session in which we have some outstanding speakers to bring us up to date on progress in breeding pearl millet.

However, I would first like to mention some principles which are important for the continued genetic improvement of pearl millet, and then review some important events.

When planning breeding activities, it is necessary to apply basic principles:

1. Analyze production constraints from which clear and realistic breeding objectives can be formulated.
2. Acquire and update regularly relevant genetic diversity.
3. Obtain as much direct evidence (if not available, the best indirect evidence) on the genetic nature of important traits.
4. Use breeding strategies consistent with the preceding three points that are within your budget.
5. Carefully choose test environments which consistently permit the best identification of the desired genotypes.

It should also be clear that in pearl millet, the main endeavors should be directed primarily to those environments where other cereals cannot compete. These are generally characterized by short growing seasons; sandy, nutrient-deficient soils; and low, erratic rainfall coupled with high temperatures leading to high evapotranspiration rates. There are exceptions of course, but we should not let them divert us from our principal task—breeding improved cultivars for the difficult environments I have described.

Lest you misunderstand me, I think that high yield potential is important in such environments.

Crop production increases of genetic origin are usually obtained steadily, inch by inch, by diligent research over the years. A 1% average yield increase in the major world crops is regarded as good. I think we have done better than this in pearl millet on the Indian subcontinent, and should make it known how this was done. There are more complex limitations to production in Africa, particularly in West Africa, but the route is clearer because of the demonstrated yield increases in Asia.

While there has been a basic gradual improvement, two important events have influenced yield gains in Asia, and already these are in gestation in Africa.

The first event was the breeding and adoption by farmers of hybrids in India. This gave us a hint of the yield potential of the crop, but drew our attention to the instability of individual hybrids as a result of nondurable disease resistance.

The second event was the use of recurrent selection in populations as a breeding strategy to produce increasingly higher-yielding, disease-resistant varieties and pollen parents. Recent AICMIP test results show that new varieties from the later cycles of populations are about 15% better than WC-C75, which in turn was 16% better than local varieties in 140 all-India tests. New hybrids are apparently even higher yielding: two 1986 releases are yielding about 25% more than WC-C75 in AICMIP tests.

The application of conventional breeding techniques will no doubt continue to increase yields of hybrids and varieties, but eventually returns will diminish and something else must be done. Before this time, we must be ready with new techniques.

The key will be increased growth rates—and this brings biotechnology to mind. But I think there is a more immediate way: the use of germplasm from wild and related species in breeding programs. Research at ICRISAT showed derivatives of controlled crosses between shibras and cultivated lines produced up to 40% higher growth rates. Dr. Hanna has indicated gains of a similar magnitude can be expected using wild pearl millet *(monodii)* sources. Additionally, there is the attractive possibility of fixing heterosis through apomixis. I believe that we have only just begun to tap the potential of pearl millet. But we need now to turn to the reviews of recent breeding research accomplishments, and use them to develop our future strategies.

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# Diversity and Utilization of Pearl Millet Germplasm

K. Anand Kumar[1] and S. Appa Rao[2]


## Abstract

*The extent of variability in genetic resource collections of staple food crops, and the effectiveness of its exploitation determines the potential and adaptation of future varieties. The availability of genetic resources has changed dramatically in the last 15 years with the establishment of the International Board for Plant Genetic Resources (IBPGR). Genetic resources conservation is now an internationally coordinated effort. ICRISAT has the responsibility for the collection, maintenance, conservation, documentation, and distribution of pearl millet genetic resources.*

*The greatest number of cultivated, wild, and weedy forms of pearl millet occur in tropical Africa where the crop was domesticated. The ICRISAT collection is over 17 000 accessions, of which over 10 000 are authentic landrace accessions from 42 countries.*

*With better screening methods available to identify desirable traits from such a large germplasm collection, use of genetic resources should expand and contribute to broadening the genetic base of the crop. Pearl millet geographic variability occurs for all characters of interest to breeders. Preliminary studies have helped to identify regions of maximum diversity, and to provide guidelines to group accessions for their effective utilization.*

*Intercrossing, selfing, and pooling are techniques to maintain accessions and increase seed. The merits of each are discussed and formation of trait-specific gene pools is advocated as a convenient system. Conditions for seed storage are described. General guidelines for the choice and use of accessions for breeding are outlined, and key examples are included.*

## Résumé

**Diversité du matériel génétique du mil et son exploitation :** *Le potentiel et l'adaptation des nouvelles variétés sont déterminés par la variabilité des ressources génétiques collectées ainsi que l'efficacité de l'exploitation de cette variabilité. L'établissement du Conseil international de ressources phytogénétiques (IBPGR) a augmenté sensiblement, au cours de ces 15 dernières années, le matériel génétique mis à la disposition de la recherche. Sa conservation fait l'objet d'un travail coordonné au niveau international. L'ICRISAT tient la responsabilité de prospecter, conserver, documenter et distribuer les ressources génétiques du mil.*

*L'Afrique tropicale, lieu de domestication du mil, présente le plus grand nombre de formes cultivées, sauvages et adventices de mil. La collection de l'ICRISAT comporte 17 000 accessions dont 10 000 sont des races non améliorées locales provenant de 42 pays.*

*L'amélioration des méthodes de criblage visant à identifier les caractères intéressants à l'intérieur d'une aussi grande collection permettra de mieux exploiter les ressources génétiques et d'élargir la base génétique de cette culture.*

*Il existe une variabilité géographique pour tous les caractères utiles aux sélectionneurs. Les études préliminaires ont permis de déterminer les régions présentant la plus grande diversité tout en faisant ressortir un système pour classer les accessions en vue de leur exploitation.*



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Submitted as CP 379 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

*Les avantages de l'entrecroisement, de l'autofécondation et de la mise au point des pools géniques, en tant que techniques de conservation des accessions et de multiplication des semences, sont examinés. Il convient de constituer des pools géniques en fonction des différents caractères. Les conditions d'emmagasinage des semences sont décrites. Le choix et l'utilisation des accessions sont expliqués avec des exemples utiles.*

## Introduction

Most of the staple crops grown today were domesticated and brought under cultivation thousands of years ago. With natural and human selection processes, they have diversified into innumerable varieties, each showing adaptation to the local environment. This invaluable genetic resource, or pool of genetic variation, forms the base for the plant breeder's ability to genetically change the crop in response to changing needs and situations (Lawrence 1975). These traditional landraces and their wild and weedy relatives possess characters such as resistance to physical and biotic stresses, which need to be incorporated into breeding material to increase both production and stability. The importance of a broad genetic base was recently demonstrated by the vulnerability of hybrids to downy mildew (Safeeulla 1977).

The necessity of searching available varieties for a particular character was recognized by early plant breeders. For example, Welsh and Johnson (1951) stated that to breed for rust resistance in oats "genes governing rust resistance cannot be created at will but must be searched for on the assumption that they exist somewhere in nature." In earlier years, no systematic efforts were made to collect and preserve genetic resources so there was little desired variation available to breeders. In recent times, the need for a diverse genetic base has been recognized.

Fortunately, the availability of genetic resources has improved very rapidly in the last 15 years with the establishment of the International Board for Plant Genetic Resources (IBPGR). Genetic resource conservation has been transformed from individual efforts into an internationally coordinated network. One of the first and significant tasks undertaken by the IBPGR, in collaboration with the French organization for scientific research overseas, Institut Francais de Recherche Developpment en Cooperation (ORSTOM), was the collection and conservation of pearl millet and sorghum in West Africa when the Sahelian drought of 1969-1974 threatened these two crops. The responsibility to collect, maintain, conserve, document, and distribute pearl millet genetic resources was entrusted to ICRISAT, and is being done in accordance with the recommendations made by the Advisory Committee on Sorghum and Millets Germplasm, jointly sponsored by the IBPGR and ICRISAT (IBPGR 1976).

## Domestication of the Crop

Pearl millet *(Pennisetum americanum)* almost certainly originated and was domesticated in tropical Africa. The greatest number of cultivated and related wild and weedy forms are found there (Pernes et al. 1984). Archaeological evidence suggests that this crop was domesticated before 1000 BC (Davies 1968). Harlan (1973) suggested that there is no apparent center of domestication, and that a diffused and important belt occurs from the Sudan in the east to Senegal in the west. Porteres (1976) attributed racial variation patterns in pearl millet to independent domestications and migrational events. He recognized four distinct, diverse areas: extreme West Africa, central West Africa, eastern Nile-Sudan, and eastern Africa and Angola. Once domestication occurred, it was introduced throughout the drought-prone areas of the Sahel and other semi-arid regions of Africa. In southern Africa, although several *Pennisetum* species are found, none of them cross easily with the cultivated form, leading to the conclusion that pearl millet is an introduced crop there (Appa Rao et al. 1985a). The shattering types found in a few isolated areas were attributed to the contamination by shibras of the original introductions and their perpetuation through survival of the seed shed in the soil. The crop was also introduced through early human migration into India, which is a secondary center of diversity (Purseglove 1976).

## Progenitors of Pearl Millet

Bilquez and Le Conte (1969) proposed that *Pennisetum violaceum* (= *P. americanum* ssp. *monodii)* should be considered a very primitive form of pearl millet, both of which have evolved from a common ancestor. Harlan (1975) observed that the evolution of pearl millet heads from the numerous small heads of *P. violaceum* is nothing short of spectacular. Cultivated forms have broad tipped, persistent spikeiets with protruding grains, but in the wild species the spikelets are narrower, pointed, readily shatter, and have small grains. Human selection has been for large grain, and spikelets that do not shatter.

## *Pennisetum* Gene Pool

Brunken (1977, 1979) and Brunken et al. (1977) grouped all the annual diploid species of penicillaria section, including cultivated pearl millet and its relatives, into the single species *P. americanum* because there are no genetic barriers to hybridization. This species was further subdivided into three subspecies: *americanum*, the cultivated form; *monodii*, the wild form; and *stenostachyum*, the intermediate and weedy types. The last of these subspecies mimics various pearl millet races morphologically, is generally characterized by nonpersistent involucres, and represents the hybrid swarms in all areas of contact between pearl millet and *monodii*. These three subspecies of *americanum* form the primary gene pool. The subspecies *americanum* was further subdivided into four races: *typhoides, nigritarum, globosum,* and *leonis,* based on the shape of the caryopses.

## Existing Collections

The first attempt to assemble a world collection of pearl millet was launched by the Rockefeller Foundation and the Indian Agricultural Research Institute during 1959-62. This led to the assembly by field collections in India and by correspondence from Africa and the USA, of 2716 accessions. However, these IP (Indian *Pennisetum)* accessions were so badly contaminated and modified that a new start had to be made (Rachie and Majumdar 1980, Harlan 1973).

ICRISAT, in collaboration with the IBPGR and national programs, has launched several expeditions to important millet-growing areas of Africa (15 countries, 22 expeditions, 1654 accessions) and India (14 expeditions, 2690 accessions) (Table 1). In addition, several researchers have made contributions to the collection held at ICRISAT. At present ICRISAT is the major repository for the world pearl millet germplasm with over 17000 accessions, of which 10803 are authentic landrace accessions, 6278 are inbreds from breeding programs, and 633 are weedy types. These authentic landraces were assigned IP numbers (International *Pennisetum)* and originate from 42 countries (Table 2). Burkina Faso, Cameroon, Ghana, India, Malawi, Mali, Niger, Nigeria, Senegal, and Sudan are relatively well represented in this collection, and have contributed more than half of the present collection. ICRISAT and the IBPGR have identified Chad, Egypt, Ghana, Mauritania, Ethiopia, Pakistan, and parts of India as priority areas for collection. It is hoped that in the future this world collection will include more accessions from these countries.

Besides the germplasm held at ICRISAT, which represents the largest collection of *Pennisetum* species, a collection of over 2700 accessions representing cultivated, weedy, and wild relatives is maintained by Services Scientifiques Centraux of ORSTOM at Bondy, France. These accessions are from 10 West African countries and represent collections made between 1975-82 by ORSTOM in collaboration with the IBPGR (Hamon, personal communication; Clement 1985a).

Most breeding programs in countries where pearl millet is an important crop generally hold small collections of local and immediate interest. These collections often include advanced or segregating breeding lines. An example is the accessions held at the Institut Senegalaise de Recherches Agricoles (ISRA) at Bambey, Senegal. This collection has over 2400 accessions and includes 1120 landraces and improved varieties from West Africa, and over 1300 introduced, or program-generated, advanced breeding lines (NDoye, personal communication).

The need to maintain national germplasm collections associated with germplasm conservation will soon be reduced because of the plans for holding a germplasm collection at the ICRISAT Sahelian Center (ISC), Niamey, Niger, in addition to the world collection at ICRISAT Center in India. At the ISC, major emphasis will be on collection, medium-term conservation, and evaluation of accessions in collaboration with national programs.

## Geographic Variability

The immense geographic variability of pearl millet (Bono 1973) in the three bioclimatic zones of West Africa is a result of human selection for maturity period, head size and shape, large grains, and non-shattering habit.

This variability cannot be grouped in a very systematic way, and so far, classification attempts have been on the basis of photoperiod response or maturity cycle. Both in the Sahelian (300-600 mm annual rainfall) and Sudanian Zones (600-900 mm), rainfall

Table 1. Pearl millet germplasm collected from 1980-85.

| Country | Year | No. of samples | Participating national program |
|---|---|---|---|
| Africa | | | |
| Botswana | 1980 | 47 | Dept. of Agric. Res., Gaborone |
| Burundi | 1982 | 2 | Min. of Agric, Bujumbura |
| Cameroon | 1983 | 20 | Inst. of Agron. Res., Maroua |
| | 1985 | 330[1] | Inst. of Agron. Res., Maroua |
| Gambia | 1980 | 17 | Dept. of Agric, Banjul |
| Ghana | 1981 | 135 | CRI, Kumasi & GTZ, Tamale |
| Malawi | 1979 | 277 | Min. of Agric & Nat. Res., Ngabu |
| Mozambique | 1981 | 15 | INIA, Maputo |
| Nigeria | 1981 | 15 | Inst. of Agric. Res., Samaru |
| | 1983 | 390 | Inst. of Agric Res., Samaru |
| Sierra Leone | 1983 | 59 | Min. Agric, Free Town |
| Somalia | 1979 | 3 | Min. of Agric Mogadishu |
| South Africa | 1982 | 30 | Res. Inst. for Grain Crops, Potchefstroom & Bot. Res. Inst., Pretoria |
| Sudan | 1979 | 19 | Gezira Agric Res. Stn., Wad Medani |
| | 1983 | 7 | Gezira Agric Res. Stn., Wad Medani |
| Tanzania | 1978 | 63 | Univ. of Dar es Salaam, ARI (Ilonga) |
| | 1979 | 102 | Min. of Agric, Dar es Salaam |
| | 1981 | 13 | Min. of Agric, Dar es Salaam |
| | 1985 | 12 | TARO, Dar es Salaam |
| Yemen Arab Rep. | 1984 | *10* | Min. of Agric. & Agric. Res. Auth., Taiz |
| Zambia | 1980 | 25 | Min. of Agric & Water Devpt., Lusaka |
| | 1982 | 63 | Res. & Spe. Ser., Harare |
| | 1985 | 340 | Res. & Spe. Ser., Harare |

1. Material yet to be released

is erratic, and selection by farmers has been towards two broad groups, early and late, as an attempt to provide stable production. Earliness and lateness are relative depending on the region. There is a north-south gradient for earliness, but early millets are not only confined to northern parts of the Sahel, but are also intercropped in wetter regions of the Sudanian Zone. In West Africa, approximately 80% of millet production is from early varieties. Information on geographic diversity of pearl millet has recently been summarized for nine West African countries (Clement 1985a), Botswana (Rao and Mengesha 1980), Ghana (Appa Rao et al. 1985b), Malawi (Appa Rao 1979b), Mauritania (Clement 1985b), Nigeria (Appa Rao et al. In press), Tanzania (Appa Rao and Mengesha 1980), Zambia (Appa Rao 1980a), Zimbabwe (Appa Rao and Mengesha 1982), and, following collection missions, for millets from Gujarat, Maharashtra, Rajasthan, and Uttar Pradesh in India (Appa Rao 1978, 1979a; Appa Rao and Reddy 1980).

In West Africa, farmers traditionally cultivate a particular landrace in any given region, but the variability within individual landraces is low. Landraces are called by different names depending on the ethnic group and region. For example, Haini Kirei, the predominant landrace of western Niger, is also called Foulania, Aderankobi, Henele, and Tiouma (Clement 1985a). Excluding the millets of the oasis, the early group matures in 70-90 d, the intermediate group in 90-120 d, and the late group in 120-180 d (Table 3).

The oasis millets of West Africa and North Africa and the desert types from Rajasthan and Gujarat (India) have a short cycle of 60 d and represent day-neutral millets. The landraces Djanet of Hoggar province of Algeria, and Faya and Ligui of Chad are oasis millets (Gast and Adrian 1965). The Chadi type from Rajasthan and Bhilodi of Gujarat represent desert types, and the Pittaganti type, grown by the hill tribes of the Eastern Ghats, represents an early type in India.

Table 2. Pearl millet accessions assembled at ICRISAT Center (as of December 19S5).

| Country | No. of accessions assembled by: Rockefeller Foundation | ICRISAT/ IBPGR/ ORSTOM | Plant Introduction (USA) | National Programs | Total |
|---|---|---|---|---|---|
| Africa | | | | | |
| Benin | 0 | 40 | 0 | 0 | 40 |
| Botswana | 0 | 45 | 0 | 0 | 45 |
| Burkina Faso | 22 | 365 | 0 | 0 | 387 |
| Cameroon | 0 | 191 | 0 | 0 | 191 |
| Cape Verde | 0 | 1 | 0 | 0 | 1 |
| Cent. Afr. Rep. | 0 | 58 | 0 | 0 | 58 |
| Chad | 62 | 0 | 0 | 0 | 62 |
| Congo | 3 | 0 | 0 | 0 | 3 |
| Ethiopia | 1 | 0 | 0 | 0 | 1 |
| Gambia | 0 | 13 | 0 | 0 | 13 |
| Ghana | 1 | 245 | 0 | 0 | 246 |
| Kenya | 2 | 67 | 0 | 0 | 69 |
| Malawi | 2 | 243 | 0 | 0 | 245 |
| Mali | 39 | 1003 | 0 | 0 | 1042 |
| Mauritania | 1 | 0 | 0 | 0 | 1 |
| Mozambique | 0 | 28 | 0 | 0 | 28 |
| Morocco | 0 | 3 | 0 | 0 | 3 |
| Niger | 36 | 997 | 0 | 0 | 1033 |
| Nigeria | 282 | 777 | 86 | 0 | 1145 |
| Senegal | 27 | 334 | 0 | 0 | 361 |
| Sierra Leone | 0 | 55 | 0 | 0 | 55 |
| Somalia | 0 | 3 | 0 | 0 | 3 |
| South Africa | 10 | 87 | 12 | 6 | 115 |
| | 2 | 557 | 0 | 0 | 559 |
| Tanzania | 0 | 138 | 0 | 0 | 138 |
| Togo | 0 | 75 | 0 | 0 | 75 |
| Uganda | 48 | 0 | 0 | 0 | 48 |
| Zambia | 0 | 81 | 0 | 0 | *81* |
| Zimbabwe | 2 | 97 | 26 | 50 | 175 |
| Source unknown | 11 | 0 | 0 | 0 | 11 |
| Subtotal | 551 | 5503 | 124 | 56 | 6234 |
| Asia | | | | | |
| India | 793 | 2720 | 24 | 7600 | 11 137 |
| Korea | 1 | 0 | 0 | 0 | 1 |
| Lebanon | 71 | 0 | 0 | 0 | 71 |
| Pakistan | 5 | 0 | 3 | 0 | 8 |
| Turkey | 0 | 0 | 1 | 0 | I |
| USSR | 0 | 14 | 0 | 0 | 14 |
| Yemen Arab Rep. | 0 | 17 | 0 | 0 | 17 |
| Subtotal | 870 | 2751 | 28 | 7600 | 11 249 |
| Europe | | | | | |
| UK | 0 | 27 | 0 | 0 | 27 |
| West Germany | 0 | 1 | 0 | 0 | I |
| Subtotal | 0 | 28 | 0 | 0 | 28 |
| The Americas | | | | | |
| Brazil | 0 | 0 | 1 | 0 | 1 |
| Mexico | 0 | 7 | 0 | 0 | 7 |
| USA | 48 | 0 | 42 | 8 | 98 |
| Subtotal | 48 | 7 | 43 | 8 | 106 |
| Australia | 0 | 0 | 0 | 0 | 4 |
| Total | 1469 | 8293 | 195 | 7664 | 17 621 |

471 accessions from 5 countries are awaiting release from plant quarantine authorities. In addition 330 accessions from Cameroon were collected recently.

Table 3. Maturity period variation of West African millets in different geographic regions.[1]

| | Maturity group (d) | | |
|---|---|---|---|
| Country | Early (70-90) | Inter-mediate (90-120) | Late (120-180) |
| Benin | Ignati<br>Nara | - | Amala |
| Burkina Faso | Iniadi | Haini<br>Gouri | Kazouya<br>Ouine |
| Cameroon | - | Mouri | - |
| Ghana | Nara | - | - |
| Guinea | - | - | Moutiri |
| Mali | Souna | Tiotioni | Sanio |
| Niger | Boudouma<br>Ba Angoure | Haini<br>Kirei | Soumno |
| Nigeria | Gero | - | Maiwa |
| Senegal | Souna | - | Sanio |
| Togo | Ignati | - | Amala |

1. Based on Clement 1985a.

Variability exists for all other agronomic characters of interest to breeders:

- tillering ability (Moro of Cameroun, Boudouma of Niger, and all Indian millets),
- head length (from 4 cm in oasis millets to 2 m in Zongo of Niger),
- head shapes differ greatly, and form a basis for classification after maturity. They range from lanceolate, cylindrical, conical, club, fusiform, to globular types,
- head girth (Ankoutess of Niger),
- peduncle length (Iniari millets as a class),
- grain size (up to 19 g $1000^{-1}$ in accessions from Ghana and Togo), and
- grain shape (hexagonal, obovate, elliptical, globular).

Bristle length and number also vary. The range observed for all of the qualitative characters scored in the world collection is as large as the range described in the IBPGR-ICRISAT descriptor list (1981).

## Genetic Diversity

Studies on genetic diversity using statistical techniques such as principal component analysis help to identify regions of maximum diversity, and to group accessions for effective utilization and maintenance (Pernes et al. 1984).

One of the first attempts to analyze genetic diversity in pearl millet was by Murty et al. (1967) using the first IP collection. They studied eight characters and found that major variability occurs in Africa, and that accessions from India showed low but distinct diversity.

Bilquez and Sequier (cited by Marchais 1975) analyzed genetic diversity in a West African collection and found that millets from Niger and Senegal are not distinct and were characterized by early maturity and long to medium-long heads (30-150 cm). Accessions from Burkina Faso formed a single group characterized by a long maturity cycle and short heads (20-40 cm). Iniadi, the early millet from the southern region and the long-cycle Ouine from Nouna region formed distinct groups. The Malian collection was split into two groups: the Niafunke-Timbouctou region and the Dogoun plateau. Oasis millets such as Massue of Mauritania, and Faya and Ligui of Chad, were grouped together.

Bono (cited by Marchais 1975) analyzed 11 characters of pearl millet from six West African countries. Millets from Senegal and Niger were grouped together, and the second group contained those from Mali, the Ivory Coast, Mauritania, and Burkina Faso. There seemed to be a transition from long to short heads on the east-west axis and thin to thick heads with large girth on the south-north axis. Accessions from Senegal and Ivory Coast were characterized by compact heads and small grains, and those from Niger and Burkina Faso by semicompact heads and large grains. Within Niger, Ankoutess formed a distinct cluster, and types Zongo, Haini Kirei, and Matam Hatchi were grouped together. As expected, both the long cycled Maiwa and Soumno types formed one group. Maximum diversity was found in Niger characterized by semicompact heads and large grains. Those from Senegal were characterized by intermediate head length (30-60 cm) and compact heads with small grains, while those from Mali had short heads with intermediate head girth. Accessions from Burkina Faso possessed thin, semicompact heads with large grains, and those from the Ivory Coast had compact heads with small grains.

Marchais (1982) found that Malian and Senegalese millets constitute two distinct groups. In Mali, there is a strong regionalization on a north-south axis, and accessions are relatively more diverse. Surprisingly, this study found that the millets of western Mali do not constitute an intermediate group, but are distinct and unrelated to the Senegalese millets.

There is a need for more systematic research on diversity, particularly to include new collections that have recently been added.

## Maintenance of Accessions

The principal objective of genetic resources maintenance is to obtain from the first grow-out, a cross-pollinated and representative sample of the original accession, and seed in sufficient quantities for subsequent evaluation, distribution, and storage. The subsequent maintenance determines the extent of original variability that will be conserved within an accession.

Recently Burton (1979, 1985) suggested three ways to increase and maintain accessions of cross-pollinated crops: intercrossing, selfing, and pooling.

**Intercrossing.** Increase by intercrossing 100 or more plants in isolation, would maintain an accession close to the original form in which it was collected. Unfortunately, because the number of isolations is limited, hand intercrossing has to be used. This should involve maximizing the intercross between 100 or more plants, and minimizing outcrossing with other accessions. Pollinating one receptive head on each plant with a mixture of pollen from the rest of the plants is an effective method of intermating. At ICRISAT, to avoid hand pollination, a cluster-bagging method was used to allow cross pollination. In this method, 10 equally spaced plants were planted in a cluster, and 20 clusters were grown for each accession. At flowering, one head from each plant within a cluster was enclosed in a paper bag, and at harvest an equal quantity of seed of each of the heads under the bag was bulked to constitute an accession (Appa Rao 1980b). In later years, this method was discontinued and was replaced by sowing the plants in rows and bagging heads from adjacent plants. Enclosing heads of several plants under one bag will intermate only those that flower at the same time. They will be isolated from others, with which they would have intermated in an isolated field, with a resultant undetermined amount of selfing (Burton 1983).

**Selfing.** Burton (1983) suggests that selfing, particularly of those plants that are used to describe an accession, is the best way to obtain large amounts of seed of a new accession. Selfing to produce $S_1$ seed offers a number of advantages: it requires less labor and time, is less likely to produce outcrosses, retains genes responsible for classification, uncovers recessive genes better than other seed increase methods, and can be used to screen for both dominant and recessive genes. Compared with intercrossing, plants grown from seed produced by selfing may have altered seed set and size, and plant vigor.

**Pooling.** The third method to increase and maintain accessions, is to form gene pools which are constituted by mixing together seed from a number of similar accessions (in pearl millet, as in many crops, accessions collected from any one region tend to be alike). The mixture is planted in an isolated field to intermate and seed is harvested from a part or all of the plants. Burton (1979) states that germplasm pools that are increased each year and contain many accessions offers an easy way to handle germplasm. It breaks linkages, increases gene interchange, and may improve adaptation. However, Burton (1976) found that advancing five germplasm pools for three generations has narrowed the phenotypic variability of the original pool, lost genes, and obscured "hard to recover characteristics".

To overcome loss of phenotypic variability in gene pools, Witcombe (1984b) suggested dividing accessions into pools on the basis of morphological characters and region of origin. The first step is to evaluate the accession and use the results to create trait-specific gene pools (TSGs) based on characteristics such as head length, seed size, and height. The TSGs are formed from accessions of a country or region, since they tend to be similar, thus insuring that only accessions of similar daylength sensitivity are pooled. As mentioned previously, multivariate analysis would provide the best basis of forming TSGs. Each TSG consists of a number of selected accessions which are mixed in equal proportions and maintained as a bulk by growing them as a single isolated population with natural crossing. For genetic resources purposes TSGs are best maintained by subjecting them to minimum selection pressures. By allowing natural selection to operate, adaptation to local conditions is improved. Using this approach, a TSG for large grain size has been formed at ICRISAT.

**Choosing a method.** The choice of the method to maintain accessions depends on the objective, number of accessions to be increased, and resources available. Setting appears to be better for individual accessions, but forming gene pools is recommended for accessions that are similar and originate within a narrow geographic region. Regardless of the method of increase employed, enough seed should be produced to facilitate evaluation, utilization, exchange, and storage.

## Storage Conditions

Seed storage in a favorable environment is the most efficient method to preserve accessions. Often lack of appropriate storage conditions has led to the loss of collections in some West African countries (ISC 1985). In a gene bank, it is necessary that seed be stored under optimum conditions to maximize longevity. Two factors influence viability of seed in storage: seed moisture content and storage temperature. Burton (1979) has been able to dry seed for long-term storage to 5-7% moisture content in a forced air oven at 40°C without any germination loss.

Two kinds of collections are generally maintained by gene banks: a base collection and an active collection. The base collection is for long-term storage and preservation, and the active collection is for medium-term storage for distribution, evaluation, and multiplication. The IBPGR has established two standards for seed storage. The preferred standards for long-term seed storage are -18°C or less with the seed at 5±1% moisture content in airtight containers. The second acceptable standard is 5°C with the seed at 5-7% moisture content in airtight containers, or at 5° C in unsealed containers with a controlled relative humidity (RH) of 20%. According to Witcombe (1984a) this level of humidity is not expensive to maintain in a well-designed store where unintended ventilation is well controlled. The rule of thumb is that each 1% reduction in seed moisture content and each 5°C temperature reduction doubles the longevity of the seed. It may be desirable to treat seed of active collections with an appropriate seed dressing to prevent fungal and insect damage, but it should be avoided if at all possible. In the ICRISAT gene bank, 500 g seed of each accession after treatment with insecticide and fungicide, is maintained at 4°C and 35% RH in aluminium cans with screw thread lids. Before the seed quantity of an accession falls to a critical level, the seed is rejuvenated in the post-rainy season, to permit the harvest of relatively dry, clean seed.

Other storage aspects such as sample size, periodic germination tests, RH control methods, and choice of containers are discussed by Witcombe and Erskine (1984), Chang (1985a), and Ellis et al. (1985).

## Utilization

The use of genetic resources to breed crop plants has received much attention and was reviewed by Krull and Borlaug (1970), Zeven and van Harten (1979), Hawkes (1981), and Chang (1985b).

If the use of a genetic resources collection is to improve yields, desirable genetic variability from the collection must be used by breeding programs to broaden the genetic base. A narrow genetic base in a breeding program is recognized when progress is poor despite vigorous breeding efforts (Simmonds 1983), or in the event of wide-scale disease or insect epidemics (NAS 1972). The success of a breeding program lies in the initial genetic base, which determines the potential and adaptability of future varieties.

Regional and national programs often feel that accessions held by an international gene bank represent true genetic resources. On the contrary, some plant breeders regard accessions in a gene bank as primitive landraces or wild and weedy species of little immediate value. The terms germplasm or genetic resources for plant breeders do not always refer to accessions drawn from a gene bank, but include genotypes chosen to incorporate or improve a given trait in a population. Thus, until very recently, the search for important genetic traits was limited to the material with which a breeder was familiar.

Generally five sources of new genetic material are available to a breeder (Simmonds 1983):

- locally adapted varieties produced by other breeders in similar environments, but which often have the drawback of being closely related;
- exotic and unadapted varieties, which are of value for specific attributes produced by backcrossing, but are usually unpromising for use as parents;
- landraces which may not contribute much potential apart from general adaptation;
- related species to provide specific attributes such as transfer of pearl millet genome into the cytoplasm of *P. violaccum* (Marchais and Pernes 1985); attempts towards interspecific gene transfer involving pearl millet, *P. orientale, P. squamula-*

*turn, P. purpureum*, (Dujardin and Hanna 1983a and b, Hanna 1983); and
- specific sources, which are needed for special traits such as cytoplasmic male-sterility and dwarfing.

General guidelines for choosing and using accessions include:

- Visualizing the potential of a given trait when incorporated into adapted backgrounds.
- Determining the region where this trait occurs in the local crop.
- What qualities the source possesses in its own area of adaptation.
- How closely the source and user regions compare climatically.
- Choosing appropriate breeding and screening methods to rigorously select from good agronomic types among the progeny for the desired trait.

This last step will determine the time required to make tangible gains. A practical solution to broaden the genetic base using unadapted material is to establish backup or source populations, and build a reasonable level of adaptation by manipulating day length (e.g., off-season nurseries to permit gene exchange between late and early accessions). After several generations with low selection pressure and deliberate recombination, source populations may approach the adaptation level of the local.

Systematic utilization of germplasm has been very low until very recently. In many instances, needs were not well defined, and there were problems obtaining desirable material. The growth habit of the accession and climate of the source region may have been unknown, and the necessity of an enhancement step, if the source was unadapted, consumed both time and resources.

This situation is rapidly changing. Following the establishment of the ICRISAT gene bank, the situation will change and improve as plans to evaluate accessions in regional and national programs in West Africa are implemented. The range of available germplasm is vastly increased, and has been evaluated and documented. Although the traits that need improvement in a breeding program usually include high yielding ability, stress tolerance or resistances, and grain quality characteristics, the development and availability of screening techniques for traits such as *Striga* resistance (Roger and Ramaiah 1983), growth rate (Bramel-Cox et al. 1984), seedling establishment under high soil temperature and drought (ICRISAT 1985), and drought resistance (Bidinger et al. 1982), will increase the future use of genetic resources in breeding programs.

## Examples of Utilization

Thanks to the efforts of participating national programs, ICRISAT, and the IBPGR, the fundamental collection step is nearly accomplished, and a reservoir of large genetic variability is now available.

Examples of the utilization of germplasm in breeding programs are given below, and their number should multiply with more reports from germplasm users.

Burton (1982) compared deriving inbreds from exotic germplasm by selfing either the introduction or by selfing the $F_1$ hybrid of the introduction with an elite inbred. He found that crossing exotic germplasm with elite lines before inbreeding may be expected to increase inbred seed yield up to 50%, and reduce losses due to poor seed set.

Experience at the ICRISAT Sahelian Center (ISC) has shown that sampling variability within generally heterogeneous and heterozygous accessions, by using individual plants in crosses and retaining better performing $F_1$s, is a very valuable approach in prebreeding. The attrition rate of crosses is very high, particularly when the weather conditions (low rainfall, sand storms, and high temperatures at the time of seedling emergence in the Sahel) are harsh. In the newly established program at the ISC, crosses between selected plants from landraces and improved varieties were made to generate variability. Over 500 $F_1$s were made and evaluated from crosses between single plants among 27 parents. At the $F_3$ generation over 840 progenies from 173 crosses were retained, while at the $F_5$ generation only 170 progenies from 87 of the original cross combinations involving only 12 of the parents were retained. This is a retention of only 17% of the original cross combinations. Analysis of pedigrees indicated that for retention of a cross, one of the parents had to be of local (Niger) origin.

Most of the improved varieties, particularly in West Africa, represent selections from locally adapted landraces (Lambert 1982). However, the variety CIVT (Composite Intervarietal de Tarna) of Niger represents the use of germplasm available within a country to breed an early-maturing, high-yielding variety. This variety involved four parental populations: $P_3$Kolo (an improved variety bred from crossing two landraces, Haini Kirei and Zongo), Haini Kirei, Guerguera, and Tamangagi (INRAN 1985).

Variety ITMV 8304, released in Niger, is an example of using germplasm from within its region. This variety was selected from a gene pool constituted from Ankoutess (of Niger), Souna (Mali), and Iniadi (Burkina Faso/Togo) landraces (INRAN 1985).

The first world collection assembled in India was successfully used in Nigeria to form populations, and in Uganda it was separated into restorers and nonrestorers to form appropriate recurrent selection bulks (Peters 1967).

Two composite populations formed at the Institute for Agricultural Research (IAR) of the Ahmadu Bello University, Nigeria, represent an efficient use of germplasm (F.H. Kadr, personal communication). The Nigerian Composite, now a released variety in Nigeria, was formed from 200 $S_4$ progenies derived from 275 accessions from Nigeria, and 54 from other West African countries. The World Composite was constituted from 144 $S_4$ progenies derived from over 1000 accessions of the first world collection, and East African and Nigerian Gero collections. At ICRISAT, the World Composite was used to breed a high-yielding and downy mildew-resistant variety, WC-C75 (ICMV 1), which was released for general cultivation in India in 1982 (Andrews et al. 1985a).

Pioneering work on the transfer of the $d_2$ dwarfing gene into populations was carried out by Chantereau and Etasse (1976). The variety Souna II was crossed with 11 dwarf lines from India, 3 from Tifton, Georgia, USA, and a partially dwarf line, 1472. The subsequent population served as a donor of the $d_2$ gene for the conversion of three tall populations Souna, Haini Kirei, and Ex Bornu, into dwarf versions. These are known as 3/4 populations, (e.g., 3/4 Souna), because only 1/4 of the genes are from the donor. Recently, the $d_2$ dwarfing gene has been introduced into seven tall composites which have been used in the recurrent selection program at ICRISAT. Preliminary yield trials have indicated that the $d_2$ dwarf versions of some of these composites have the potential to yield as much as, and even outyield, their respective tall counterparts (Andrews et al. 1985b). These now make available a broad genetic base in a dwarf background for further exploitation to breed dwarf open-pollinated varieties, and dwarf hybrid parents.

The most useful germplasm to supply desirable variability to breeding programs has come from Iniadi, a prominent, productive, bold-seeded, and early-maturing landrace that is found in Benin, Burkina Faso, Ghana, and Togo. This material was used in the formation of composites of the Serere series, and the male-sterile line Serere 10LA (EAAFRO 1974). Male-sterile Serere 10LA was used in the production of the current commercial Indian hybrid MBH 110. This material also forms the basis for dwarf, large-seeded, male-sterile lines bred at Kansas State University, USA. These were supplied to ICRISAT, where further selections for downy mildew resistance were made. Two of these male-steriles, 843 A (ICMA 2) and 842 A (ICMA 3) were recommended by the All India Coordinated Millet Improvement Program (AICMIP) for general use as seed parents (ICRISAT 1985).

A further male-sterile line, 834 A (ICMA 4), was bred at ICRISAT from SIOLA. Two varieties derived from a Togo population, ICTP 8202 and ICTP 8203, were among the highest-yielding varieties across 11 locations in India in the ninth ICRISAT-coordinated International Pearl Millet Adaptation Trial (IPMAT 9). In Sudan, variety ICTP 8202 yielded 30% more than the local control Bayuuda, and has been promoted for on-farm trials (ICRISAT 1985). Serere material also formed the basis for a variety, Ugandi, released for general cultivation in Sudan. Ugandi was selected from Serere Composite-2 (Jain 1981). In India, a variety called improved Ghana (later renamed as Pusa Moti), which is now lost, was bred from Ghana/Togo material (Joshi et al. 1961). In West Africa, descendents from Togo x Souna (Mali) crosses have been used extensively as parental material for composites from which varieties have been derived. In Burkina Faso, progenies derived from the photoperiod-sensitive local Kapelga * Iniadi cross are proving to be of immense value (Lohani 1985).

At ICRISAT, in a program to utilize new sources of genetic variability by hybridization, the largest variation in the segregating generations has generally been found in crosses between Indian and African material. Indian landraces, or lines from Indian millet breeding programs, have mainly served as sources of earliness, higher tiller numbers, superior harvest index, and local adaptation, whereas African material has been a good source of high head volume, large seed size, and disease resistances. Among African material, early groups have proved more promising in crosses at ICRISAT than late, photoperiod-sensitive groups. An investigation into the pedigrees of about 1700 promising lines pedigree-selected up to the $F_8$ generation showed that the breeding populations and lines contributed much more to useful genetic diversification than landraces. A general picture emerges of the great value of African material to the Indian breeding program. Moreover, African materials have been of most use when in the form of breeders' lines or populations, even though such materials have often only been selections from local landraces (Andrews et al. 1985b).

The development of effective disease resistance screening techniques for downy mildew (Williams et al. 1981), smut (Thakur et al. 1983), and ergot (Thakur et al. 1982) has permitted the identification of several resistant sources (ICRISAT 1985). Accession IP 2696 (Ligui) from Chad is used extensively to establish infector rows in downy mildew nurseries. The lack of disease screening facilities in most programs (with dependence on natural, erratic incidence) has prevented the effective utilization of resistant sources. Use was made of the smut-resistant screening nursery and smut-resistant lines to form the Smut Resistant Composite. ICMV 82132, derived from this composite, is currently in AICMIP trials. For rust, two sources of resistance are available (Andrews et al. 1985c, Hanna et al. 1985).

## Conclusion

Geographic and genetic diversity in pearl millet is enormous and the most important task of collection is nearly accomplished. Genetic erosion in the classic sense, replacement of landraces by improved varieties, does not pose an immediate danger to landraces in West Africa. On the contrary, decreasing rainfall and consequent droughts over the last 15 years, and infestations by pests and birds are indeed leading to significantly reduced variability among traditional varieties. Examples are provided by the near extinction of the landrace Thiotande in Mauritania and Senegal, and replacement of Souna in Mali because of attacks by cantharides and birds. Collection and preservation of variability should be undertaken as soon as possible in areas where genetic resources are under threat.

Accessions in the pearl millet gene bank at ICRISAT are maintained by bagging several heads and forming gemplasm pools, evaluated using the descriptors list (IBPGR-ICRISAT 1981), and are documented. Seed from this gene bank is freely available to scientists throughout the world.

A broad genetic base is important to breeding programs: it determines the potential and adaptation of future varieties. The use of genetic resources to improve pearl millet has been limited until recently. The examples cited indicate the opportunities available to broaden the genetic base and the potential to identify superior parents in collections. With the availability of appropriate screening methods, and identification of resistances to biotic and physical stresses, use of genetic resources will significantly expand and contribute to millet improvement programs. Breeders must now assign resources and time to systematically introduce new germplasm and broaden the base of their programs. What is done now will determine the potential of pearl millet as a crop in the future.

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# Amélioration variétale du mil en Afrique de l'Ouest

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**Résumé**

*L'Afrique de l'Ouest est le centre d'origine et de diversité du mil. Cette espèce y est cultivée sur environ 13 millions d'hectares avec une forte concentration dans la zone sahélienne. Les faibles rendements (en moyenne 460 kg $ha^{-1}$ sont attribuables aux conditions de culture : sols pauvres, faible technicité du paysan et déficit pluviométrique.*

*Les cultivars traditionnels sont très bien adaptés aux conditions écologiques locales et présentent une grande variabilité pour de nombreux caractères (cycle, taille des plantes, longueur des chandelles, etc.) ce qui s'avère intéressant du point de vue de l'amélioration de la production.*

*L'amélioration des cultivars locaux, commencée en 1931, visait à l'augmentation de leur productivité. La diffusion des variétés-populations améliorées était limitée à cause de leur faible supériorité par rapport aux variétés locales non améliorées, et du suivi inadéquat par la vulgarisation. Les moyens mis à la disposition de ces programmes étaient négligeables par rapport à ceux assignés aux cultures de rente.*

*Une meilleure intégration de tous les programmes de recherche sur le mil est nécessaire afin d'accroître sa production. La création variétale doit, parallèlement à l'amélioration du potentiel productif, chercher à stabiliser la production, car le paysan produit le mil d'abord pour se nourrir.*

## Introduction

En Afrique, le mil (*Pennisetum americanum*) constitue, avec le sorgho, la base d'alimentation de plusieurs millions d'habitants; d'où l'intérêt particulier que certains pays portent à l'amélioration de cette espèce. Sa culture est dispersée sur l'ensemble du continent avec une forte concentration sur plus de 13 millions d'hectares en Afrique de l'Ouest (FAO 1983).

De nombreux auteurs s'accordent à attribuer au mil une origine ouest-africaine. Cependant, s'il existe une unanimité concernant la localisation du foyer de domestication, des controverses (Murdock 1969, Munson 1972) subsistent quant à la période. A l'état actuel des connaissances archéologiques et ethnobotaniques, il est difficile de vérifier les différentes hypothèses. Brunken et al. (1977) pensent que l'espèce aurait été domestiquée dans le Sahara 2000-3000 ans av. J.C.

La faible productivité du mil est due essentiellement aux facteurs suivants : les conditions climatiques, surtout l'insuffisance et la mauvaise répartition des pluies; les conditions édaphiques liées aux sols pauvres en matières organiques et éléments nutritifs; enfin, le matériel végétal qui, tout en étant bien adapté aux conditions du milieu, présente un faible potentiel de production.

Une culture vivrière représente une ressource renouvelable dont le potentiel s'accroît avec chaque développement des sciences et des techniques agricoles. Pour atteindre une production suffisante, il faudrait maintenir un équilibre entre trois composantes de base : matériel végétatif (variété, hybride), techniques agronomiques, et protection des cultures (maladies et insectes ravageurs).

Tous ces aspects de l'amélioration de la culture du mil ont été abordés dans les travaux de recherche en Afrique de l'Ouest depuis 1931 (Etasse 1966).

Malgré les progrès appréciables enregistrés en sta-

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tion, le niveau des rendements en milieu réel reste bas (environ 460 kg $ha^{-1}$).

En Afrique de l'Ouest, les principaux pays producteurs sont le Niger, le Nigéria, le Mali, le Tchad, le Burkina Faso et le Sénégal. Les rendements varient de 200 kg $ha^{-1}$ en Mauritanie, pays désertique, à 842 kg $ha^{-1}$ en Gambie, pays situé en partie en zone soudanienne. Un rendement exceptionnel de 4000 kg $ha^{-1}$ a été obtenu sous irrigation en Egypte.

## Principaux facteurs limitant la production en Afrique de l'Ouest

Il est très difficile de répertorier toutes les contraintes tant elles sont complexes. Ainsi, selon Scheuring (1980), dans certaines régions du Mali, les pertes liées au mildiou peuvent atteindre 40% de la production. McIntire (1982) a observé des pertes de 27 à 37% au Niger à cause de plusieurs facteurs, y compris *Raghuva* et shibra. Les rendements des mils, même améliorés, restent médiocres à cause des conditions climatiques, notamment en zone sahélienne.

## Contraintes abiotiques

### Edaphiques

Les sols destinés à la culture du mil sont en général pauvres en matières organiques et en éléments fertilisants (Stoop et al. 1982). Ces sols sont le plus souvent sableux et pauvres en phosphore, et parfois latéritiques; la teneur en argile est toujours faible et de mauvaise qualité (kaolinite). Ils sont peu profonds avec une faible capacité d'échange et ont tendance à s'encroûter, entraînant ainsi une mauvaise levée.

En début de saison des pluies, les températures du sol sont souvent élevées, et des vents de sable fréquents entraînent un ensevelissement des jeunes pousses avec, comme conséquence, une mauvaise installation de la culture.

### Techniques culturales

Les paysans sahéliens sont peu équipés et l'utilisation de la daba ou de la hilaire est quasi générale. Le pourcentage des exploitations équipées en matériel de culture attelées est très faible (environ 30% au Mali et moins de 10% au Niger); de sorte que le travail du sol n'est effectué que sur quelques exploitations.

Le démariage ne se fait presque jamais faute de temps, entraînant une compétition importante au niveau des poquets. Un simple retard de 7 jours dans le premier sarclage peut provoquer une perte de 10% sur le rendement (Matlon 1983). La seule amélioration des techniques culturales permet d'augmenter la production des mils traditionnels de 40% (Siband 1983).

### Climatiques

Le climat en zone sahélienne est caractérisé par une opposition très nette entre la saison sèche sans pluviosité et la saison des pluies dont la durée varie de 3 à 5 mois. Dans tous les pays on note un gradient de pluviométrie décroissante allant du Nord au Sud.

La saison des pluies est en général plus longue dans la zone soudanienne avec très peu de variabilité; tandis que la saison en zone sahélienne est caractérisée par une très grande variabilité quant à la répartition et la hauteur des pluies, notamment en début et en fin de saison. C'est dans cette zone que la culture du mil est particulièrement importante, et où il n'est pas rare d'effectuer trois semis à cause d'une mauvaise installation de la campagne agricole.

## Contraintes biotiques

### Entomologiques

Voir la communication présentée par Ndoye et Gahukar à ce sujet dans ces comptes rendus.

### Phytopathologiques

**Mildiou (*Sclerospora graminicola*).** Peu d'informations sont disponibles actuellement sur les pertes de rendement causées par ce parasite (Scheuring 1980, Diaby 1982). Cependant, le mildiou est considéré comme la plus importante maladie du mil en Afrique de l'Ouest (Delassus 1964, Girard 1975). Les cultivars locaux présentent une grande diversité de tolérance. D'importantes sources de résistance se trouvent surtout en Afrique de l'Ouest, en particulier dans le Nigéria du nord, le Niger du sud, au Burkina Faso et au Mali (Williams et Andrews 1982).

**Ergot** (*Claviceps fusiformis*). Ce parasite est rare dans le Sahel, et se manifeste surtout dans les zones plus humides (Gambie, Ghana). La plupart des cultivars locaux sont assez tolérants à la maladie (Selvaraj 1980).

**Charbon** (*Tolyposporium penicillaria*). Il s'agit de la deuxième maladie par ordre d'importance en Afrique, mais ses dégâts sont moindres sur les cultures locales.

### Malherbologiques

La lutte contre les mauvaises herbes constitue un volet important, les pertes de récoltes étant estimées à 25%. Il faut signaler que les mils traditionnels, grâce à leur haute taille, sont assez compétitifs face aux adventices.

En dehors des adventices classiques fréquentes chez les cultures pluviales, les espèces suivantes posent des problèmes :

**Striga** (*S. hermonthica*). Le striga constitue un des plus importants facteurs responsables des baisses de rendement, allant jusqu'à 60-70% (NDoye 1984), chez le mil dans la zone sahélienne.

**Shibra** (*P. stenostachyum*). Cette forme adventice du mil provient d'un croisement entre le mil cultivé et le mil sauvage. Leur fréquence atteint parfois 20%, avec une incidence défavorable sur la productivité des cultivars infestés. L'élimination des shibras d'un cultivar permettrait donc une augmentation significative de sa production (Tompa 1983, Williams et Andrews 1983).

### Autres prédateurs

Les oiseaux granivores, dont l'attaque varie d'une année à l'autre, représentent un véritable fléau dans certaines zones. Ils sont responsables des bas rendements observés chez les mils précoces. L'espèce *Quelea Quelea* ou travailleur à bec rouge est la plus importante (Rachie et Majmudar 1980, Pradat 1962). Certains cultivars aristés, Sarakoua au Niger et Konotiné au Mali, sont considérés comme tolérants aux attaques d'oiseaux. Cette tolérance n'est que relative puisqu'en l'absence de formes mutiques, les épis aristés sont également ravagés.

## Caractéristiques des mils en Afrique de l'Ouest

### Généralités

La plus grande diversité morphologique se trouve en Afrique de l'Ouest, centre d'origine du mil. Les deux autres formes de mil non céréalières de la section des pénicillaires y sont également présentes à l'état spontané. Il s'agit de *Pennisetum purpureum*, ou herbe à éléphant, espèce tétraploïde pérenne probablement un amphidiploïde résultant du croisement d'un mil diploïde inconnu avec une forme ancestrale de *P. americanum* (Bilquez et Lecomte 1969); et de *P. monodii*, espèce diploïde annuelle qui se croise fréquemment dans la nature avec le mil cultivé produisant des hybrides vigoureux et fertiles appelés n'douls au Sénégal et shibras au Niger.

### Variabilité des mils ouest africains

Seule la forme cultivée présente une grande variabilité phénotypique (Bono 1973, Grouzis 1980), due vraisemblablement à l'action humaine qui a façonné des types cultivés très divers, adaptés à des zones écologiques différentes. Les grandes migrations ethniques ont probablement contribué aussi à l'accroissement de cette variabilité et à son manque de clarté géographique (Marchais 1982). Il est très difficile de regrouper les types rencontrés tant la variabilité est grande et différente d'un pays à l'autre. Le plus souvent, le regroupement est fait selon le cycle des variétés. Dès la domestication de cette céréale, les cultivateurs ont sélectionné deux groupes de variétés qu'ils appellent couramment les précoces et les tardives; la notion de cycle précoce ou tardif étant relative à la localité. L'importance de chaque groupe dépend de la situation géographique du pays; en général, les variétés sont plus tardives en allant du nord au sud. Les formes précoces sont considérées comme cultures de soudure quand elles sont exploitées en association avec les formes tardives.

La sécheresse a amené une extension des aires de culture des formes précoces. Au Niger, on rencontre actuellement la variété Ankoutess beaucoup plus au sud de son aire originelle de culture (ORSTOM 1976). Au Sénégal, les formes tardives ne sont quasiment plus cultivées dans la zone centrale (Dancette 1980) où elles sont remplacées par les Sounas plus précoces. En bonnes conditions pluviométriques, les mils précoces donnent généralement des rendements inférieurs à ceux des mils tardifs.

Les variétés tardives, malgré un haut potentiel de rendement, sont mal adaptées à une pluviosité déficitaire. Leur production étant donc très aléatoire, le paysan par mesure de sécurité leur associe généralement à une culture de soudure (mil précoce, niébé, maïs etc.).

Au Sénégal, un essai entrepris pendant quatre ans afin de comparer les Sounas (précoces) aux Sanios (tardifs) a confirmé la supériorité des premiers sur les seconds (Tab. 1) (Etasse 1970). Désormais les travaux de sélection au Sénégal, ont été axés sur l'amélioration des Sounas.

**Tableau 1. Comparaison des rendements des cultivars Souna et Sanio au cours d'un essai mené au Sénégal.**

| Année | Date de semis | Pluviométrie (mm) | Rendement ($kg\ ha^{-1}$) Souna | Sanio |
|---|---|---|---|---|
| 1965 | 9 Juil. | 603 | 2300-2400 | 1700-1800 |
| 1966 | 8 Août. | 567 | 1700-2000 | 2500 |
| 1967 | 5 Juil. | 843 | 2100 | 1700 |
| 1968 | 15 Juil. | 357 | 1700-2000 | - |

Source : Etasse 1969.

### Variabilité des autres caractéristiques

Les cultivars locaux présentent un très grand polymorphisme pour beaucoup de caractères. Bono (1973) a évalué un certain nombre dont nous ne mentionnons ici que quelques-uns.

**Longueur des épis.** La plus grande variabilité se trouve au Niger où la longueur des épis varie de 8 à 210 cm (Bono 1973). Ces épis ne sont pas très compactes. La forme conique serait la plus répandue en Afrique de l'Ouest, suivie de la structure fusiforme. Le nombre de grains par involucre (1 à 6) serait également beaucoup plus élevé au Niger.

**Vitrosité.** Elle conditionne les qualités organoleptiques et de conservation. Les mils précoces donnent des grains plus vitreux que les mils tardifs. Il existe une relation étroite entre la forme et la vitrosité du grain, les grains étroits (Souna) ayant tendance à être plus vitreux que les grains globuleux. Les grains les plus vitreux se rencontrent au Sénégal. Les variétés nigériennes sont intermédiaires entre les variétés maliennes et les variétés burkinabè.

**Couleur du grain.** Les couleurs dominantes sont le jaune et le gris. La couleur jaune se rencontre surtout au Niger. A l'exception des variétés ghanéennes et togolaises, les variétés précoces sont jaunes, tandis que les variétés tardives sont plutôt grises (Sénégal, Mali).

**Goût.** Ce caractère est très difficile à apprécier puisqu'il est lié aux habitudes alimentaires. Les paysans caractérisent certaines variétés par des qualificatifs tels que "ce mil donne la force", "celui-là gonfle le ventre". Ces caractéristiques sont liées à la vitrosité (Bono 1973). Au Mali, les consommateurs préfèrent les grains de grande taille, de couleur gris clair, et faciles à décortiquer.

**Aristation.** Au Sénégal, ce caractère sert surtout à distinguer les mils précoces des mils tardifs. Ailleurs, l'aristation est indépendante du cycle.

Les variétés locales sont généralement caractérisées par un système racinaire puissant qui assure une absorption efficace des éléments minéraux dans des sols peu fertiles (Jacquinot 1972, Ramond 1962). Le tallage relativement abondant permet à la plante de s'adapter aux conditions pluviométriques et au parasitisme.

En 1974, la prospection des formes cultivées et sauvages fut entamée sous l'égide du Conseil international de ressources phytogénétiques (IBPGR) pour la conservation du patrimoine génétique (Acheampong et al. 1984) (Tab. 2).

### Evaluation de l'hétérosis des croisements entre cultivars locaux

Des croisements ont été réalisés entre des mils en provenance du Mali, du Sénégal, du Burkina Faso et du Niger afin d'évaluer l'hétérosis (Bono 1973). Les résultats montrent de l'hétérosis (rendement) chez les croisements Sénégal × Mali et Sénégal × Burkina Faso.

Purata Velarde (1976) a obtenu les même résultats dans ses analyses d'hybridation inter-pays et intra-pays, d'après lesquelles les hybridations inter-pays Sénégal × Mali manifestent un pourcentage d'hétérosis plus important (Tab. 3).

## Bilan succint des travaux d'amélioration variétale

### Historique

Les recherches variétales sur le mil en Afrique de l'Ouest francophone ont débuté en 1931 au Centre

**Tableau 2. Mils prospectés en Afrique de l'Ouest sous l'égide de l'IBPGR.**

| Pays | Echantillon total | Formes cultivées | Formes sauvages | Formes adventices | Autres formes | Introductions de l'ICRISAT |
|---|---|---|---|---|---|---|
| Bénin | 221 | 183 | 1 | 37 | - | 17 |
| Burkina Faso | 590 | 462 | 10 | 97 | 21 | 34 |
| Gambie | 17 | - | - | - | 17 | 17 |
| Ghana | 135 | - | - | - | 135 | 265 |
| Guinée (Conakry) | 72 | 72 | - | - | - | - |
| Mali | 1022 | 931 | 54 | 37 | - | 873 |
| Mauritanie | - | - | - | - | - | 1 |
| Niger | 742 | 565 | 20 | 145 | 12 | 1032 |
| Nigéria | 278 | 177 | 23 | 8 | - | 610 |
| Sénégal | 264 | 228 | 18 | 18 | - | 360 |
| Tchad | - | - | - | - | - | 62 |
| Togo | 165 | 165 | 150 | - | 13 | 58 |

Source : Acheampong et al. 1984.

**Tableau 3. Evaluation de l'hétérosis chez différents croisements intra- et inter-pays.**

| Croisement | Pourcentage de croisements présentant l'hétérosis |
|---|---|
| Intra-pays | |
| Niger : Maïwa × Nigérien | 30 |
| Mali : Mopti × Maliens | 50 |
| Inter-pays | |
| Sénégal × Mali | 80 |
| Sénégal × Niger | 40 |
| Mali × Niger | 40 |
| Iniadi × Mali | 30 |
| Iniadi × Niger | 37 |
| Iniadi × Sénégal | 50 |

Source : Purata Velarde 1976.

de recherche agronomique (CRA) de Bambey, sous l'égide de l'Institut de recherches agronomiques tropicales et des cultures vivrières (IRAT). A cette époque le CRA de Bambey devait jouer le rôle de station centrale pour l'Afrique de l'Ouest francophone. On peut distinguer trois grandes périodes dans le domaine de l'amélioration variétale du mil (Etasse 1966).

**De 1931 à 1951.** Période pendant laquelle les céréales occupaient très peu de place dans le programme général. Les travaux ont surtout porté sur l'amélioration des populations locales par sélection généalogique.

**De 1951 à 1959.** Une section spécialisée pour les céréales fut créée ayant pour objectif la mise au point d'une méthode de sélection massale complexe utilisable dans les petites stations éloignées de la zone.

**De 1959 à 1961.** L'indépendance politique de nombreux pays en Afrique de l'Ouest francophone a abouti à la création des organismes de recherche agronomique nationaux. Le CRA de Bambey cède alors la place aux Services centraux de l'IRAT qui prennent en charge l'élaboration des programmes.

Les programmes nationaux, tout en étant coordonnés par les Services centraux de l'IRAT, ont évolué indépendemment avec une certaine similitude des thèmes et objectifs de recherche. Très peu d'attention avait été accordée aux problèmes de maladies et d'insectes puisqu'ils étaient jugés comme ayant une influence peu importante sur les rendements (Etasse 1965).

Depuis lors, les programmes nationaux se concentrent sur trois thèmes principaux : a) amélioration des mils traditionnels; b) amélioration du rapport grain/paille; et c) exploitation de la vigueur hybride.

## Amélioration des mils traditionnels

Ce programme vise à homogénéiser un caractère donné (cycle, couleur du grain, caractères de l'épi chez une ou plusieurs variétés locales (Bono et Leclerc 1963, Lambert 1983). La productivité et la stabilité du rendement sont également évaluées au cours des études.

### Sélection massale

Au Niger, en 1967, cette méthode fut appliquée à la variété Haini Kirei menant à la création de deux populations améliorées Haini-Kirei normale (HKN) et Haini-Kirei précoce (HKP). La sélection de la population HKP a abouti à l'obtention du synthétique HKP. Au Mali, la sélection a mis au point trois populations très précoces : $M_2D_2$, $M_9D_2$, et $M_{12}D_1$ sont les seules à être proposées à la vulgarisation jusqu'à présent.

### Sélection récurrente avec test topcross

Démarré en 1961 au Sénégal, ce programme a porté sur l'amélioration de cinq populations : trois précoce (PS 32, PC 33, PC 28) et deux tardives (PS 34 et 35).

Les meilleures descendances de ces trois populations précoces ont été recombinées pour donner une population synthétique, Souna 2. Un nouveau programme de sélection a été initié à partir de ces descendances. Les meilleurs topcross ont permis de constituer un nouveau synthétique, Souna 3, la seule variété actuellement vulgarisée au Sénégal.

Au Niger, cette méthode de sélection récurrente a été utilisée pour l'amélioration de la population locale Zongo. Trois écotypes de cette population ont été observés. Les meilleures lignées de Zongo issues des tests topcross ont été recombinées pour constituer la variété synthétique Zongo améliorée; mais celle-ci ne s'est pas montrée supérieure au matériel d'origine dans les tests de rendement.

Au Mali, la population synthétique PS 71 sélectionnée de quatre populations ne s'est pas révélée supérieure au témoin.

Au Burkina Faso, la méthode a permis d'obtenir la variété synthétique 71 de Saria.

### La sélection recurrente avec test des $S_1$

Au Niger, le matériel obtenu par recombinaison des meilleures descendances de KHP n'a mis en évidence aucun gain de productivité. Le travail était alors dirigé vers la création d'un composite intervariétal à partir des cultivars Guerguera, $P_3$ Kolo et Tamangagi. En 1974, la recombinaison des $S_1$ dérivés de ces cultivars a permis d'obtenir le CIVT.

Au Mali, deux cultivars tardifs ($M_5$ et $M_9$) et deux mils précoces ($M_2D_2$, NKK) soumis à cette méthode de sélection récurrente ont donné des résultats décevants. Il a donc fallu arrêter ce programme.

Au Burkina Faso, les résultats obtenus avec les populations $M_9$, $M_{12}D_1$ du Mali et mil de Dori montrent un net gain de production. Le gain par rapport à la population d'origine est le plus élevé chez la variété $M_{12}D_1$.

### Conclusion

Le programme axé sur l'amélioration des cultivars locaux a fourni dans la plupart des pays des variétés locales améliorées.

Dans de nombreux cas, ces variétés améliorées n'ont pas pu confirmer leur potentialité au niveau paysan (Matlon 1985). Rares sont les pays où elles ont connu une large diffusion. Certaines obtentions ont pu s'imposer, sont vulgarisées ou sont en cours de vulgarisation (HKP et CIVT au Niger, $M_2D_2$ et $M_9D_3$ au Mali, Souna 3 au Sénégal).

Les causes de la lente diffusion des variétés améliorées sont multiples. Outre leur faible supériorité marginale par rapport aux témoins locaux en milieu paysan, ces variétés n'ont pas été bien suivies au niveau de la vulgarisation pour mieux exploiter leur potentialité. L'amélioration de cultivars locaux est très complexe, surtout dans un centre de diversité où chaque écotype "colle" à sa localité. La variabilité de l'environnement est telle qu'on est tenté de conclure qu'il faut sélectionner pour chaque niche écologique.

Les programmes d'amélioration du mil ont manqué de moyens physiques et humains, qui étaient souvent inférieurs par rapport à d'autres programmes (riz, cotonnier, arachide) (Bono 1962).

## Amélioration du rapport grain/paille

A la fin des années 1960, les programmes d'amélioration se sont penchés sur la diminution du rapport grain/paille par un raccourcissement de la tige souvent très grande chez les cultivars africains.

Les mils traditionnels sont caractérisés par un développement végétatif exubérant (Jacquinot 1972). Cette caractéristique très intéressante dans le cadre d'une agriculture traditionnelle (rusticité et adaptation aux techniques rudimentaires), devient un facteur limitant à l'intensification des cultures, puisque qu'elle inhibe la réponse de la plante aux intrants agricoles (Etasse 1972). Chez les variétés de grande taille, le nombre d'épis $m^{-2}$ dépasse rarement 8 à 10 $m^{-2}$ (Chantereau et Etasse 1976); au-delà ce nombre, les risques de verse deviennent importants. En régions humides, la production de matière sèche, en conditions favorables (techniques culturales), peut s'élever à 15-20 t pour 1,8 à 2,5 t de grain (Jacquinot 1972), entraînant une mobilisation importante d'éléments minéraux hors de proportions avec la production de grain. Une étude comparative des besoins en azote de différentes espèces a démontré que l'utilisation la plus efficace de l'azote absorbé se trouve chez les variétés produisant le moins de paille (Blondel 1971). Les résultats obtenus dans cette étude et ceux sur d'autres céréales ont amené à conclure que les facteurs limitant l'amélioration de la productivité étaient liés à l'architecture des mils traditionnels. Par conséquent, pour l'intensification de cette culture il est nécessaire de sélectionner des variétés à faible production de paille.

A cet effet l'IRAT a entrepris le transfert du gène de nanisme $D_2$ à partir de la lignée I 25 aux variétés locales. I 25 est une lignée introduite de l'Inde qui présente un feuillage réduit, un bon tallage et des épis à bonne exertion. Les cultivars auxquels le gène était transféré sont : Souna du Sénégal, Haini-Kirei Normal du Niger, Ex Bornu du Nigèria et NKK du Séno au Mali.

Ce programme sur le mise au point des populations naines a commencé en 1968 au Sénégal, puis s'est poursuivi au Niger, au Burkina Faso et au Mali. Les mils issus du programme devraient présenter en plus de leur taille réduite, une potentialité moyenne pour le tallage, un port érigé pour éviter l'encombrement permettant donc d'augmenter la densité du semis, et une tolérance aux insectes et maladies rencontrés dans la zone.

## Etapes de l'amélioration du rapport grain/paille

Au Sénégal, la lignée naine I 25 a été croisée avec la population locale améliorée Souna 2. Jusqu'en 1973, la nouvelle population 1/2 Souna a été soumise à une nouvelle sélection visant à la résistance au mildiou. Certaines lignées ont été prises de ce programme pour servir de géniteurs dans les programmes nigérien et malien.

Une nouvelle population naine a été créée à cause des nombreux défauts (sensibilité au mildiou et au charbon, exertion inadéquate) présentés par le 1/2 Souna locale; il s'agit de la population naine 3/4 Souna. A partir de 1973, le programme de sélection fut confié à la Station de Tarna au Niger où on a procédé à la création de populations naines 3/4 Haine-Kirei et 3/4 Ex Bornu. Un essai comparant les populations 1/2 locales aux populations 3/4 locales, a permis une augmentation de 50% dans le poids de grain chez le 3/4 Souna par rapport au 1/2 Souna.

Après 1974, les trois populations naines ont subi une nouvelle sélection afin d'homogénéiser les caractères agronomiques.

En 1976, au Mali, la population naine 3/4 Séno a été obtenue à partir de la variété NKK.

La sélection récurrente cumulative appliqué aux populations 3/4 locales visait à éliminer les principaux défauts (cycles inadaptés, floraison échelonnée, sensibilité au charbon et au mildiou).

Parallèlement à ce programme conduit sous l'égide de l'IRAT, un autre programme a été entrepris par le Groupe d'amélioration du mil ou GAM. Il était également axé sur la création des variétés naines beaucoup plus élaborées, avec possibilité d'exploitation de l'hétérosis.

En 1975, l'IRAT a mené des essais régionaux (inter-états) sur les populations naines 3/4 locales (Tab. 4). Seuls les résultats de Bambey semblent très encourageants. Aux autres points d'essai un fort parasitisme lié à la précocité des populations naines par rapport aux témoins locaux, est responsable des bas rendements obtenus. A Sotuba (Mali), les attaques d'insectes ont également baissé le rendement du témoin. Cependant, un certain progrès a été réalisé par rapport aux objectifs, compte tenu de la nette amélioration de la production par unité de surface malgré une production grain/paille inférieur au témoin local (Tab. 5).

Un essai comparant trois variétés naines, trois variétés améliorées de grande taille à un cultivar local de grande taille, a été conduit à Tarna entre 1980 et 1982. L'essai a été mis en place sur deux parcelles : l'une avec apport de 10 t $ha^{-1}$ de fumure organique et l'autre sans apport de matière organique. La densité de semis était de 0,80 m × 0,40 m (31 250 poquets $ha^{-1}$) pour les mils nains et de 1 m × 1 m (10 000 poquets $ha^{-1}$) pour les mils de grande taille. L'apport de fumure minérale était de 100 kg $ha^{-1}$ de phosphate supersimple à la préparation du sol et 100 kg $ha^{-1}$ d'urée au démariage (3 plants/poquet) (Tab. 6).

La variété CIVT, déjà vulgarisée dans les zones à bonne pluviométrie, s'est nettement imposée en donnant 135% du témoin (Zongo). Les mils nains 3/4 HK et le composite nain de Tarna, bien que très exigeants, ont donné des rendements satisfaisants sur ces sols ne contenant pratiquement pas de matière organique. Mais ils ne se distinguent pas très nettement du témoin. La variété HKP de grande taille et à

**Tableau 4. Rendement en grain (en kg $ha^{-1}$) des populations naines 3/4 locales, obtenu à six points d'essai en Afrique de l'Ouest.**

| | Points d'essai | | | | | | |
|---|---|---|---|---|---|---|---|
| Entrées | Tarna (Niger) | Kolo (Niger) | Bambey (Sénégal) | Sotuba (Mali) | Seno (Mali) | Gorom (Burkina Faso) | Moyenne |
| 3/4 Souna | 1901 | 1794 | 2611 | 944 | 1065 | 715 | 1506 |
| 3/4 Haïni Kirei | 2025 | 1732 | 2865 | 1214 | 1204 | 884 | 1654 |
| 3/4 Ex Bornu | 2050 | 1815 | 2962 | 1492 | 1492 | 675 | 1693 |
| Témoin local | 1647 | 1877 | 2279 | 405 | 1456 | 856 | 1420 |

Source : Chantereau et al. 1977.

**Tableau 5. Comparaison de la production par unité de surface et la production grain/paille chez les populations naines par rapport à une population locale.**

| | Poids grain $m^{-2}$ | | Poids grain/épi | |
|---|---|---|---|---|
| Entrées | (g) | (%/T) | (g) | (%/T) |
| 3/4 Souna | 181 | 117 | 23.8 | 55 |
| 3/4 Haïni Kirei | 196 | 126 | 24.3 | 55 |
| 3/4 Ex Bornu | 208 | 134 | 24.0 | 55 |
| Témoin local | 155 | 100 | 43.8 | 100 |

**Tableau 6. Rendements obtenus sur une parcelle sans traitement de matière organique au cours d'un essai comparatif à Tarna.**

| | Rendement (kg $ha^{-1}$) | | |
|---|---|---|---|
| Entrées | 1980 | 1981 | 1982 |
| Composite Nain | 1620 | 1350 | 1520 |
| 3/4 Haïni Kirei | 1600 | 1350 | 1560 |
| 3/4 Séno | 1640 | 1260 | 1380 |
| CIVT | 1820 | 1520 | 1800 |
| HKP | 1610 | 1360 | 1840 |
| Composite Zongo | 1490 | 1390 | 1490 |
| Témoin (Zongo local) | 1600 | 1250 | 1260 |
| Pluviométrie (mm) | 511 | 412 | 286 |

cycle très précoce a dépassé toutes les variétés testées avec 139% du témoin.

Compte tenu des résultats obtenus, on peut se demander s'il était nécessaire d'aller jusqu'aux structures naines. Ces structures se justifient dans le cadre d'une agriculture intensive (forte fertilisation, densité élevée, mécanisation), et dont les conditions sont loin d'être réunies dans la zone. Il existe assez de variabilité au sein des cultivars locaux pour la taille afin d'atteindre l'objectif d'amélioration du rapport grain/paille. La sélection à l'intérieur de ce matériel local aurait été plus fructueuse puisqu'elle ne pose pas les problèmes d'adaptation liés aux 1/2 locales et 3/4 locales.

En outre, les réserves accumulées dans les tiges seraient utiles dans l'alimentation des épis en cas de stress hydrique comme cela a été démontré chez le maïs (Duncan 1975) et le riz (Reyniers et al. 1983). La production de paille d'un mil nain de 75 jours ne serait pas différente de celle d'un mil Souna de taille moyenne de 90 jours (Dancette 1983).

En ce qui concerne le programme GAM, le matériel mis au point s'est montré très sensible au mildiou avec une mauvaise grenaison.

## Exploitation de la vigueur hybride

Depuis longtemps, l'exploitation de la vigueur hybride a été étudiée au Sénégal et au Niger. Différentes formules variétales ont été expérimentées (hybrides $F_1$, synthétiques, etc.). Au Sénégal, des gains de 40 à 60% ont été obtenus avec des $F_1$ et des synthétiques issus des populations locales.

Les meilleures combinaisons faisaient intervenir deux lignées : l'une à un bon degré de tallage et l'autre à bon poids de grain par épi (Etasse 1970). Au Niger, lors des essais de topcross entre les lignées naines ($S_2$) et les variétés locales en 1975, la combinaison 3/4 Souna 74-28-1 × CIVT a donné le meilleur rendement avec environ 143% du témoin (Chantereau et Etasse 1976). Mais ce programme n'a pas été poursuivi faute de lignées mâle-stériles adaptées à la zone.

Le programme du GAM qui a poursuivi les travaux de création variétale de mil au Sénégal après l'IRAT, prévoyait, en seconde phase du projet, l'exploitation d'hybrides $F_1$ à partir des cytoplasmes $A_1$ et $A_2$ (Bilquez 1975).

De nouvelles lignées mieux adaptées aux conditions locales ont été sélectionnées à partir des croisements avec 23-D2-A1 et 239-D2-A2. Mais les premiers hybrides créés ont été totalement détruits par le mildiou. La création d'hybrides $F_1$ a cédé la place à l'exploitation des populations synthétiques. Le matériel issu de ce programme a été repris par le programme sénégalais de l'ICRISAT pour en corriger les principaux défauts (Gupta 1984).

Au Centre sahélien de l'ICRISAT à Sadoré, Niger, une recherche exploratoire a été entreprise sur les hybrides. Les hybrides évalués en 1984 étaient relativement précoces, avec une hauteur et une longueur d'épi réduites, et un bon tallage. Ces hybrides se sont révélés plus productifs que les variétés améliorées sous une faible pluviométrie (250 mm en 1984).

L'étude d'un croisement mil sauvage × mil cultivé a mis en évidence un nouveau système de stérilité mâle différent de $A_1$, $A_2$, et $A_3$ (Marchais et Pèrnes 1985).

## Orientations futures

Une intégration plus poussée des différents programmes tient une importance primordiale pour l'avenir. La sélection devrait tenir compte du fait que 80 à 90% des agriculteurs de la zone ne sont pas équipés, c'est-à-dire ils ne pratiquent ni labour, ni démariage; les sarclages sont également limités à cause d'un calendrier cultural chargé. Il ne s'agit donc pas de sélectionner des variétés adaptées aux mauvaises conditions culturales, mais qui sont comparables aux variétés locales sous conditions actuelles et ayant en même temps le potentiel de les dépasser en conditions améliorées.

La structure variétale utilisée (variétés-populations, composites, synthétiques ou hybrides) dépend surtout du niveau de développement de chaque pays. Etant donné la situation actuelle dans la zone (faible pouvoir d'achat et technicité), les variétés à retenir sont celles à pollinisation libre (variété-population, composite, synthétique), puisqu'elles s'adaptent plus facilement aux conditions traditionnelles que les hybrides. Il ne faut pas écarter pour autant la création de variétés hybrides qui portent un intérêt à long terme.

### Création variétale

Les travaux de création variétale doivent porter sur :

- la diversification de la base génétique du matériel dans chaque pays, des prospections, des introductions provenant des autres foyers de diversité (Inde, Afrique orientale, Maghreb). Une recherche prospective sur l'utilisation des formes sauvages doit être entamée afin de définir leur contribution à l'amélioration des cultivars locaux.

L'exploitation de ce matériel par la sélection des meilleurs cultivars locaux, le croisement entre variétés à caractères complémentaires et d'origine géographique différente. Une importance particulière doit être accordée aux composantes du rendement (longueur de l'épi, grosseur du grain, degré de tallage). La création de composites à partir des meilleurs $F_2$ permet, par sélection cumulative, d'obtenir à court terme un matériel plus performant que les cultivars locaux. La sélection des lignées de différents groupes de précocité dérivées de ces croisements et des variétés-populations, permettra la création de variétés synthétiques adaptées à différentes zones climatiques.

Dans le cadre du programme sur l'amélioration du rapport grain/paille, il faut poursuivre la sélection des populations 3/4 locales déjà obtenues afin d'augmenter le poids du grain par épi ainsi que la résistance au mildiou et au charbon. Des variétés de courte taille (1,80 à 2,50 m) sont adéquates et correspondent au niveau technique des paysans. Cependant, il ne faut pas sous-estimer l'importance de la production de paille qui joue un rôle non négligeable dans l'intégration de l'agriculture à l'élevage.

### Résistance à la sécheresse

La sélection pour la résistance variétale à la sécheresse occupera une place importante dans l'amélioration du mil. Les mécanismes de contrôle de la résistance sont très complexes et difficiles à combiner avec le rendement. Il est impossible de cumuler chez une même variété ou lignée tous les mécanismes de la résistance à la sécheresse, sans entraîner un effet défavorable sur le rendement.

En Afrique de l'Ouest, en particulier dans la zone sahélienne, où les périodes de sécheresse sont très aléatoires et surviennent à n'importe quel stade de développement, il faut sélectionner des variétés qui sont résistantes pendant les phases critiques.

Le service agrométéorologique de chaque pays pourrait, à partir des données disponibles, délimiter les différentes zones écologiques et définir pour chaque zone les périodes de risque de sécheresse. Ceci permettra de mieux déterminer les critères de sélection pour chaque zone (sécheresse pré- ou post-florale).

La pluviométrie est plus aléatoire en début et en fin de cycle, donc pendant la période d'implantation et de floraison-fructification (Dancette 1983).

Les travaux de recherche sur la résistance variétale à la sécheresse doivent être axés sur :

**Sélection de matériel ayant une bonne vigueur à la levée.** Le matériel sera sélectionné selon l'aptitude des plantules à supporer les hautes températures et les stress hydriques, ainsi que la résistance à l'encroûtement et à la compacité des sols.

**Sélection de variétés précoces.** Etant donné que les besoins en eau du mil sont fonction du cycle (Dancette 1983), les variétés à cycle court demandent beaucoup moins d'eau. Il s'agit d'ajuster leur cycle aux limites probables de la saison des pluies, en collaboration avec l'agrométéorologiste. Les variétés à cycle court ont plus de chances de bénéficier d'une saison des pluies suffisantes. Mais l'utilisation des variétés à cycle court pose certains problèmes parasitaires (maladies, insectes, oiseaux) et de conditionnement des récoltes (Dancette 1976).

Malgré l'importance donnée à la précocité il ne faut pas sous-estimer l'intérêt de la sensibilité à la photopériode. Il n'est pas rare de resemer deux à trois fois à cause de la mauvaise levée due à l'encroûtement, aux vents de sable, aux attaques des prédateurs, ou à un brusque arrêt des pluies. La sensibilité à la longueur du jour assure une certaine production, sans égard à la date de resemis. Les variétés sensibles à la longueur du jour seraient également plus tolérantes aux mauvaises conditions de culture, que les variétés nonsensibles dont le tallage est bloqué plus rapidement par la floraison (Siband 1983, Lambert 1983). L'étude de ce mécanisme en tant que facteur d'adaptation s'impose pour une meilleure exploitation de ce matériel. L'agrométéorologie aura un rôle important à jouer dans ce domaine.

**Sélection de variétés ayant un bon système racinaire.** Ce caractère assure une meilleure exploitation des horizons du sol vers la fin de la campagne. Les sols ouest africains ne sont pas profonds (Stoop et al. 1982). Les études sur le riz ont révélé une variabilité génétique très importante au niveau des différentes caractéristiques du système racinaire (Ahmadi 1983). L'évaluation de la diversité chez les cultivars locaux de mil sera entamée suite à la détermination des caractères associées à la tolérance à la sécheresse et la mise au point d'une méthode efficace de mesure.

## Conclusion générale

En Afrique de l'Ouest, et surtout en zone sahélienne, les conditions environnementales sont très dures. Les sols sont très fragiles, la pluviométrie capricieuse et les hommes démunis (Franquin 1984). Le paysan y produit le mil d'abord pour se nourrir; seule une très faible quantité est commercialisée.

Pour nourrir une population sans cesse croissante, il faut accroître la production agricole de la région. La stratégie à promouvoir devrait tenir compte des réalités du milieu tout en cherchant de les améliorer progressivement.

Parallèlement à l'amélioration du potentiel productif, la création variétale devrait assurer une production plus stable par la mise au point de variétés ayant de bonnes caractéristiques d'adaptation (résistance à l'encroûtement, tolérance à la sécheresse pré- et post-florale, bon système racinaire).

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# Varietal Improvement of Pearl Millet in West Africa

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***Abstract***

*West Africa is the center of pearl millet origin and diversity. The crop is grown throughout West Africa on about 13 million ha, concentrated mainly in the Sahelian zone. The generally low yields are frequently due to the cropping conditions: poor soils, deficit rainfall, and low technology.*

*Highly variable landraces are well adapted to the local ecological conditions, and several characters, including crop duration, plant height, and head length, could be used for crop improvement.*

*Varietal improvement work began in 1931 with the objective to increase productivity of local cultivars. Only a few of the resulting populations were released since they were only marginally superior to the landraces. Monitoring of the new varieties by the extension services was also not adequate. Funding for food-crop programs was insufficient compared to cash-crop programs.*

*If production is to increase in the future, a closer integration of the various millet research programs is required. Because millet is essentially grown as a food crop, the primary objective should be yield stability.*

## Introduction

Pearl millet *(Pennisetum americanum),* along with sorghum, is the staple food crop for millions of people in Africa, hence the priority assigned by certain countries to its improvement. Pearl millet is grown throughout Africa, but particularly in West Africa, where the cultivated area covers about 13 million ha (FAO 1983).

Pearl millet is reported to have originated in West Africa, but while there is general agreement regarding the location for the domestication of the species, the period remains controversial (Murdock 1959, Munson 1972). It is difficult to verify the different hypotheses with the current archeological and ethnobotanical data. Brunken et al. (1977) believe that millet was domesticated in the Sahara region between 2000 and 3000 B.C.

Low yields are primarily due to factors such as climatic conditions, particularly inadequate and poorly distributed rainfall; soils low in organic matter and nutrients; and plant material with a low production potential although adapted to the environment.

Agricultural production is a renewable resource—the potential increases with each development in agricultural science and technology. Adequate yields are obtained by using a proper balance of components: plant material (variety or hybrid), cultural techniques, and crop protection (diseases and pests). All these aspects of crop improvement have been studied in the research work carried out in West Africa since 1931 (Etasse 1966).

Substantial progress has been made at the research stations, but yields in farmers' fields have not risen above 460 kg $ha^{-1}$ in the Sahelian zone.

The major food-producing countries in West Africa are Niger, Nigeria, Mali, Chad, Burkina Faso, and Senegal. Millet yields range from 200 kg $ha^{-1}$ in Mauritania, a desert country, to 842 kg $ha^{-1}$ in Gambia, partially located in the Sudanian zone. Exceptionally high yields of 4000 kg $ha^{-1}$ have been recorded under irrigation in Egypt.

## Major Limiting Factors in West Africa

The complex nature of the constraints makes them difficult to classify. In Mali, yield losses due to mil-

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dew may reach 40% in certain regions (Scheuring 1980), while *Raghuva* infestations and shibras are responsible for losses up to 27-37% in Niger (Mclntire 1982). Low yields of local or improved cultivars can also be attributed to climatic conditions, especially in the Sahelian zone.

## Abiotic Constraints

### Soils

Pearl millet is grown on soils that are generally poor in organic matter and nutrients (Stoop et al. 1982). These shallow soils are mostly sandy with a low phosphorous content, sometimes lateritic; clay content is always low and of poor quality (kaolinite); and the cation exchange capacity is low. Crust formation is frequent and impedes emergence. At the start of the rainy season, soil temperatures are high with frequent sand storms, so that the seedlings are often buried under the sand, and crop establishment is poor.

### Cultural Techniques

Crop cultivation in the Sahel is usually manual and based on hand tools such as the "daba" and "hilaire." The use of animal traction is rare—about 30% in Mali and less than 10% in Niger—so that tillage operations are carried out only on a few farms. Plants are not thinned due to lack of time, leading to high within-hill populations and competition between plants. A 1-week delay in the first weeding operation can result in a 10% yield loss (Matlon 1983). Hence, improved cultural techniques alone can increase production by 40% (Siband 1983).

### Climate

The climate in the region is characterized by two distinct seasons: a dry season with no rainfall and a wet season extending 3-5 months. A north-south gradient of increasing rainfall can be observed in each country.

In the Sudanian zone, the rainy season is generally longer with less rainfall variation. But in the Sahelian zone, the wet season is characterized by highly variable rainfall amounts and distribution, especially at the beginning and end of the season. It is under these conditions that millet is usually grown and is frequently replanted—up to three times, due to poor crop establishment.

## Biotic Constraints

### Insect Pests

Refer to NDoye and Gahukar's paper, these proceedings.

### Diseases

**Mildew *(Sclerospora graminicola).*** Not much information is available on yield losses due to this disease (Scheuring 1980, Diaby 1982), but it is generally considered to be the most important pearl millet disease in West Africa (Delassus 1964, Girard 1975). Local cultivars exhibit highly diverse tolerance to mildew. West Africa has important sources of resistance, particularly in northern Nigeria, southern Niger, Burkina Faso, and Mali (Williams and Andrews 1983).

**Ergot (*Claviceps fusiformis).*** This disease rarely occurs in the Sahel but is frequent in wetter zones (Gambia, Ghana). Most local cultivars are usually not badly affected by ergot (Selvaraj 1980).

**Smut *(Tolyposporium penicillaria).*** Although smut is the second most important millet disease in Africa, local crops are less affected by it.

### Weeds

Weed control is important since yield losses from weeds are estimated at 25% but because of their height, landraces are able to successfully compete with weeds. Weeds other than those found in rainfed crops are:

***Striga (S. hermonthica).*** Yield losses from this parasitic weed can reach 60-70% in certain countries (NDoye 1984), and this is one of the most important factors that reduces pearl millet yields in the Sahelian zone.

**Shibras *(P. stenostachyum).*** Shibras are a weedy form resulting from a wild millet x cultivated millet cross. In certain fields their occurrence (20%) can reduce yields of the infested crop, but eradication of the weedy form can significantly increase production of the related cultivated variety (Tompa 1983, Williams and Andrews 1983).

### Other Parasites

Birds are a real danger in certain zones; their incidence varies each year. The most important species is *Quelea quelea* (Rachie and Majmudar 1980, Pradat 1962). Birds are responsible for low yields in early pearl millet crops but certain bristled cultivars, Sarakoua in Niger and Konotine in Mali, are supposed to be relatively tolerant to bird attack; however, they are equally susceptible in the absence of nonbristled cultivars.

## Pearl Millet Characteristics in West Africa

### General

West Africa is probably where pearl millet originated, and also the region where the greatest morphological diversity is found. The two other noncereal forms of the section Penicillaria are found in Africa. *Pennisetum purpureum* or elephant grass, is a perennial tetraploid, probably an amphidiploid derived from a cross between an unknown millet diploid with an ancestral form of *P. americanum* (Bilquez and Lecomte 1969). The second form, *P. monodii,* is an annual diploid species that crosses spontaneously with cultivated millets to produce vigorous and fertile hybrids called n'doul in Senegal and shibra in Niger.

### Pearl Millet Variability in West Africa

Only the cultivated form shows phenotypic variation (Bono 1973, Grouzis 1980), probably due to selection pressure exerted by man who has unconsciously selected a large range of cultivated types to suit different ecological zones. Large ethnic migrations may have contributed to increased variability, which became less location specific (Marchais 1982). This variability is too large and different in each country to group the material, but common practice is to group them according to crop duration. Since the domestication of pearl millet, farmers everywhere, especially in the Sahelian and Sudanian-Sahelian zones, have established two groups, commonly called early and late varieties. The notion of earliness and lateness is relative and varies with each location. The importance of each group depends on the geographical location of the country; a north-south gradient of decreasing earliness can be observed. When early cultivars are grown with late cultivars, they are considered as "hungry-season" crops.

After the recent drought, there appears to be a general extension in the cultivated areas of early varieties. In Niger, the variety Ankoutess can be found further south of its original limit (ORSTOM 1976) and in Senegal, cultivation of late varieties has almost been abandoned, and they are being replaced by the early Sounas. Under adequate rainfall conditions, early pearl millets yield less than late varieties.

Although the late varieties are potentially more productive, they are not suited to low-rainfall conditions. This unstable production pattern is related to rainfall. Farmers therefore usually intercrop the late varieties with a stop-gap crop (early millet, cowpea, maize, etc.) to reduce risk.

Four years of comparative trials of Sounas and Sanios in Senegal have shown the superiority of the Sounas (Table l)(Etasse 1970). Consequently, breeding programs in Senegal are focused on the improvement of Souna varieties.

### Variability of Different Characteristics

Local cultivars exhibit great morphological variability for a large number of characters. Bono (1973) has evaluated certain characters:

Head length. The greatest variability for this character is found in Niger where length varied from 8-210 cm (Bono 1973). These leads are not very compact, and conical shapes appear to be more

Table 1. Comparison of the yields of Souna and Sanio cultivars during a trial conducted in Senegal.

| Year | Planting date | Rainfall (mm) | Yields ($kg\ ha^{-1}$) Souna | Sanio |
|---|---|---|---|---|
| 1965 | 9 Jul | 603 | 2300-2400 | 1700-1800 |
| 1966 | 8 Aug | 567 | 1700-2000 | 2500 |
| 1967 | 5 Jul | 843 | 2100 | 1700 |
| 1968 | 15 Jul | 357 | 1700-2000 | |

Source: Etasee 1969.

common in West Africa than fusiform. The number of grains/involucre varies from 1-6; the highest number is found in Niger.

**Vitreousness.** This character is related to superior food and keeping qualities of the grain. It is reportedly higher in early than in late millets. Grain shape and vitreousness are probably correlated. Narrow grains (Souna) tend to be more vitreous than globular grains. The highest degree of vitreousness is found in Senegal. Varieties from Niger are intermediate between the Malian and Burkina Faso varieties for this character.

**Grain color.** The predominant colors are yellow and gray. Yellow grains are mainly found in Niger. Except for varieties from Ghana and Togo, early varieties are usually yellow, while late varieties are gray (Senegal, Mali).

**Food quality.** This characteristic is difficult to evaluate because it is linked to food habits. However, certain varieties are known by their food qualities, for example, "healthy millet," "flatulent millet." These qualities may be related to vitreousness (Bono 1973). In Mali, bold, light gray grain that is easy to hull is preferred.

**Bristled heads.** In Senegal, bristled heads serve to distinguish between early and late millets. In other countries, however, this character is not linked to crop duration.

**Other characters.** All local cultivars are characterized by a strong root system for efficient absorption of minerals from generally less fertile soils (Jacquinot 1972, Ramond 1962). Relatively abundant tillering enables the plant to adverse rainfall conditions and pest attack.

Collection of wild and cultivated forms of pearl millet was started in 1974, sponsored by the International Board of Plant Genetic Resources (IPBGR), to conserve pearl millet germplasm (Acheampong et al. 1984) (Table 2).

### Evaluation of Heterosis in Local Cultivar Crosses

Pearl millet germplasm from Mali, Senegal, Burkina Faso, and Niger was crossed to evaluate heterosis (Bono 1973). There was a heterosis effect on yield in the Senegal x Mali and Senegal x Burkina Faso crosses.

The same results were obtained in a study on inter- and intra-country crosses (Purata Velarde 1976) among which, the Senegal x Mali cross exhibited the highest percentage of heterosis (Table 3).

## Review of Varietal Improvement Work

### Background

Varietal research on pearl millet in French-speaking West Africa began in 1931 at the Centre de Recherches

Table 2. IBPGR-sponsored pearl millet collection in West Africa.

| Country | Sample total | Cultivated forms | Wild forms | Weedy forms | Other forms | ICRISAT introductions |
|---|---|---|---|---|---|---|
| Benin | 221 | 183 | 1 | 37 | . | 17 |
| Burkina Faso | 590 | 462 | 10 | 97 | 21 | 34 |
| Gambia | 17 | - | - | - | 17 | 17 |
| Ghana | 135 | - | - | - | 135 | 265 |
| Guinea | 72 | 72 | - | - | - | - |
| Mali | 1022 | 931 | 54 | 37 | - | 873 |
| Mauritania | - | - | - | - | - | 1 |
| Niger | 742 | 565 | 20 | 145 | 12 | 1032 |
| Nigeria | 278 | 177 | 23 | 8 | - | 610 |
| Senega] | 264 | 228 | 18 | 18 | - | 360 |
| Chad | - | - | - | - | - | 62 |
| Togo | 165 | 165 | 150 | - | 13 | 58 |

Source: Acheampong et al. 1984.

Table 3. Evaluation of heterosis in different intra- and inter-country crosses.

| Cross | Crosses showing heterosis *(%)* |
|---|---|
| Intra-country | |
| Niger: Maiwa x Nigerian | 30 |
| Mali: Mopi x Maliens | 50 |
| Inter-country | |
| Senegal x Mali | 80 |
| Senegal x Niger | 40 |
| Mali x Niger | 40 |
| Iniadi x Mali | 30 |
| Iniadi x Niger | 37 |
| Iniadi x Senegal | 50 |

Source: Purata Velarde 1976.

Agronomiques (CRA) in Bambey, Senegal, and was sponsored by the French Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres (IRAT). The CRA in Bambey served as a central station for the entire area. The development of pearl millet improvement work can be divided into three periods (Etasse 1966).

From 1931 to 1951. Cereals occupied a relatively small place in the general program. Local populations were improved through pedigree selection.

From 1951 to 1959. A section specialized on cereals was established. It focused on the development of a complex mass selection method that could be used at the small outreach stations in the zone.

From 1959 to 1961. This period coincides with the independence of some French-speaking West African countries, and the establishment of national agricultual research programs in several countries. The responsibilities of the CRA were taken over by IRAT headquarters in France.

Although the national programs were coordinated by IRAT, they evolved on their own following similar research themes and objectives. Diseases and pests received little attention at this time because they were considered to have little influence on yields (Etasse 1965). The national research programs have always focused on three main research areas:

- improvement of landraces;
- improvement of the grain/dry matter ratio;
- use of the heterosis effect.

## Improvement of Landraces

In most cases the goal was uniformity in one or more varieties for a certain character, such as duration, grain color, or head characteristics (Bono and Leclercq 1963, Lambert 1983). Yield and yield stability were also evaluated.

## Mass Selection

This method was used in Mali and in Niger to improve the variety Haini Kirei in 1967. Two populations were produced: Normal Haini Kirei (HKN) and early Haini Kieri (HKP). Further selection of the HKP population led to the HKP synthetic. In Mali, selection was continued until the three earliest populations were obtained—$M_2D_2$, $M_9D_2$, and $M_{12}D_1$. So far these are the only varieties to be recommended for release.

## Recurrent Selection with Topcross Testing

This program, initiated in 1961, focused on the improvement of five populations in Senegal: early populations PS 32, PC 33, and PC 28; and late populations PS 34 and 35.

The best progeny of the three early populations were recombined to produce the synthetic Souna 2. A new breeding program was started using its progeny and a new synthetic Souna 3 was developed from the best topcrosses. This is the only variety to be released in Senegal.

In Niger this method was used to improve the landrace Zongo. Three ecotypes of the landrace were identified. The best lines from them were identified by topcross testing and were recombined to produce a synthetic variety, improved Zongo but it did not perform better than the original material in yield tests. In Mali, the same selection method was used on four populations to develop the synthetic PS 71, but it was outyielded by the test control. In Burkina Faso, Saria synthetic 71 was produced using this method.

## Recurrent Selection with $S_1$ Testing

In Niger, when this method was applied to population KHP, the recombined material from the superior progenies did not offer any yield advantage. An intervarietal composite was formed by intermating

Guerguera, $P_3$ Kolo, and Tamangagi. In 1974, the S,s from these cultivars were recombined to produce the composite CIVT.

In Mali, the same selection method was applied to two late cultivars, $M_5$ and $M_9$, and two early cultivars, $M_2D_2$ and NKK. Poor results led to this breeding program being discontinued. In Burkina Faso, the populations used were $M_9$, $M_{12}D_9$, and Dori millet. $M_{12}D_9$ showed a definite yield advantage compared to the original population.

## Conclusion: Improving Local Varieties

The programs to improve local varieties have been successful in most countries. However, the new varieties have not reached their full potential in farmers' fields (Matlon 1985), and their acceptance has been limited in most countries. Those that have been more successful have been or are being released (HKP and CIVT in Niger, $M_2D_2$ and $M_9D_3$ in Mali, and Souna 3 in Senegal).

This slow spread can be attributed to several factors. The improved varieties showed marginal superiority when compared to the local controls in farmers' fields. Monitoring by extension services was inadequate; their potential was not fully exploited. Improvement of local cultivars is extremely complicated, especially in a center of diversity where each ecotype remains location specific. The broad range of environmental variation almost requires breeding material for each location. Moreover, the pearl millet breeding program, unlike those for rice, cotton, and groundnut, had severely limited material and human resources to carry out its work (Bono 1962).

## Improvement of Grain/Straw Ratio

By the late 1960s, breeding programs were working to reduce the grain/straw ratio by shortening the stem, which is particularly long in most African cultivars.

Landraces are characterized by abundant vegetative development (Jacquinot 1972). While this is an advantage (hardiness, adaptation to rudimentary techniques) in traditional farming, it becomes a limiting factor when cropping is intensified because it affects plant response to inputs (Etasse 1972). In tall varieties, the number of heads $m^{-2}$ rarely exceeds 8-10 (Chantereau and Etasse 1976), but when it does, there is risk of lodging. In wet areas, under adequate cropping conditions (cultural techniques), straw production can rise to 15-20 t for 1.8-2.5 t of grain (Jacquinot 1972). This implies a high rate of mineral mobilization that is disproportionate to the grain yield. In a study comparing the nitrogen requirements of different species, the species producing less straw used the absorbed nitrogen most effectively (Blondel 1971). It was evident from this study and others conducted with other cereals, that the limiting factors to increased production were related to the plant structure of the landraces. Therefore, selection of varieties with low straw production is essential to intensify pearl millet cultivation.

IRAT attempted to reduce straw production by transferring the dwarfness gene $d_2$ from the line 125 to local cultivars. 125 is an introduction from India, with less foliage, good tillering habit, and vigorous heading. The gene was transferred to cultivars Souna (Senegal), Haini Kirei Normal (Niger), Ex Bornu (Nigeria), and NKK from Seno (Mali).

The program to breed dwarf populations by backcrossing was started in 1968 in Senegal and continued in Niger, Burkina Faso, and Mali. Apart from reduced height, the new pearl millet varieties were expected to have a medium tillering potential, upright structure suited to denser plant stands, and tolerance to local pests and diseases.

## Stages in the Improvement of the Grain/Straw Ratio

In Senegal, the dwarf line I 25 was crossed with the improved local cultivar Souna 2. The resulting 1/2 Souna was selected for mildew resistance until 1973. Certain lines were taken from this program to serve as parents in the Niger and Mali programs.

Because of mildew and smut susceptibility and poor heading in 1/2 Souna, it was decided to develop another population, without these defects. This was 3/4 Souna. After 1973, the entire breeding program was moved to the Tarna Station in Niger, where dwarf populations 3/4 Haini Kirei and 3/4 Ex Bornu were developed. A trial comparing the local 1/2 and 3/4 populations confirmed a 50% increase in individual grain mass in 3/4 Souna compared to 1/2 Souna. After 1974, the three dwarf populations were further selected for uniform agronomic characters.

In Mali, dwarf population 3/4 seno was obtained from variety NKK in 1976. Cumulative recurrent selection was aimed at eliminating the major defects (unsuitable crop duration, staggered flowering, and smut and mildew susceptibility).

Table 4. Grain yield of local 3/4 populations at six test locations in West Africa.

| Entries | Tarna, Niger | Kolo, Niger | Bambey, Senegal | Sotuba, Mali | Seno, Mali | Gorom, Burkina Faso | Average |
|---|---|---|---|---|---|---|---|
| | Test locations | | | | | | |
| 3/4 Souna | 1901 | 1794 | 2611 | 944 | 1065 | 715 | 1506 |
| 3/4 Haini Kirei | 2025 | 1732 | 2865 | 1214 | 1204 | 884 | 1654 |
| 3/4 Ex Bornu | 2050 | 1815 | 2962 | 1492 | 1492 | 675 | 1693 |
| Local control | 1647 | 1877 | 2279 | 405 | 1456 | 856 | 1420 |

Source: Chantereau at al. 1977.

Apart from the IRAT-sponsored program, breeding work was carried out by the Groupement d'Amelioration du Mil (GAM), which also focused on the development of more advanced dwarf varieties using the heterosis effect.

International regional trials of the local 3/4 dwarf populations were conducted by IRAT in 1975 (Table 4). Results were promising only in Bambey. High pest incidence on the comparatively early dwarf material reduced yields at other locations. At Sotuba, Mali, pest attack was also responsible for low yields of the control variety. However, some progress was made because there is a definite increase in the unit area production although the grain/ straw ratio is lower than the control (Table 5).

From 1980-82 a trial comparing three dwarf millets, three tall improved varieties, and one tall local cultivar, was conducted at Tarna, Niger. One plot received 10 t $ha^{-1}$ manure, the other plot received no organic fertilizer. Plant spacing was 0.8 x 0.4 m (31 250 hills $ha^{-1}$) for dwarf millets and 1 x 1 m (10000 hills $ha^{-1}$) for tall millets. Mineral fertilizer was applied at the rate of 100 kg $ha^{-1}$ of supersingle phosphate during tillage operations, and 100 kg $ha^{-1}$ of urea at thinning (3 plants $hill^{-1}$) (Table 6).

CIVT was superior with yields 135% higher than the control Zongo. This cultivar had already been released in high-rainfall areas. Dwarf 3/4 HK and the dwarf Tarna composite, although input-intensive, yielded satisfactorily on soils with no manure treatment. They did not differ greatly from the control. Tall, very early HKP outyielded all entries at 139% of the control.

In retrospect, the program's stress on dwarf material is questionable. The need for such material would be justified with intensive cultivation (heavy fertilization, high density, and mechanization), but these conditions rarely exist in the target zone. If the objective was to improve the grain/ straw ratio, local cultivars offer sufficient variability for height. The breeding effort would then have been more productive, since the problem of adaptation with the 1/2 and 3/4 material would not arise.

Reserves accumulated in the stems can also be used by leads during drought stress, as demonstrated for maize (Duncan 1975) and rice (Reyniers et al. 1982). Straw production in a 75-day dwarf millet

Table 5. Comparison of the unit area production and grain/dry matter production of dwarf and local populations.

| Entries | Grain mass $m^{-2}$ (g) | Grain mass $m^{-2}$ (%/ control) | Grain mass per head (g) | Grain mass per head (%/ control) |
|---|---|---|---|---|
| 3/4 Souna | 181 | 117 | 23.8 | 54 |
| 3/4 Haini Kirei | 196 | 126 | 24.3 | 55 |
| 3/4 Ex Bornu | 208 | 134 | 24.0 | 55 |
| Local control | 155 | 100 | 43.8 | 100 |

Table 6. Yields from a nontreated plot with no organic matter application in a comparative trial at Tarna.

| Entries | Yield ($kg\ ha^{-1}$) 1980 | 1981 | 1982 |
|---|---|---|---|
| Dwarf composite | 1620 | 1350 | 1520 |
| 3/4 Haini Kirei | 1600 | 1350 | 1560 |
| 3/4 Seno | 1640 | 1260 | 1380 |
| CIVT | 1820 | 1520 | 1800 |
| HKP | 1610 | 1360 | 1840 |
| Composite Zongo | 1490 | 1390 | 1490 |
| Control (Local Zongo) | 1600 | 1250 | 1260 |
| Rainfall (mm) | 511 | 412 | 286 |

does not differ from that in a medium-height, 90-day Souna (Dancette 1983). The GAM material proved to be very susceptible to mildew with poor grain formation.

## Use of Hybrid Vigor

Since early in the program, several varietal selections ($F_1$ hybrids, synthetics) were made in Senegal and Niger to exploit hybrid vigor. In Senegal, yield advantages of 40-60% were obtained from $F_1$s and synthetics from local populations.

The best combinations were those including one line with good tillering habit and the other with high grain mass per head (Etasse 1970). In Niger, topcrosses between dwarf $S_2$ lines and local varieties were tested in 1975; 3/4 Souna 74-28-1 x CIVT gave the highest yield, 143% of the control (Chantereau and Etasse 1976), but the program could not be continued without locally adapted male-sterile lines.

The GAM program, which took over varietal breeding from IRAT in Senegal, planned to use F, hybrids derived from $A_1$ and $A_2$ cytoplasm in the second phase of the project (Bilquez 1975).

New lines with better adaptation to local conditions were selected from crosses with 23-D2-A1 and 239-D2-A2, but the initial hybrids were completely destroyed by mildew. The production and testing of F, hybrids was soon replaced by the use of synthetics. The material from this program was incorporated in the ICRISAT program in Senegal for further breeding work (Gupta 1984).

At the ICRISAT Sahelian Center in Sadore, Niger, exploratory research was conducted on hybrids. During the 1984 season, test hybrids were relatively early with reduced height and head length, and good tillering. They outyielded the improved varieties under low rainfall conditions (250 mm in 1984).

A study on crosses between wild and cultivated pearl millets revealed a system of male sterility different from the $A_1$, $A_2$, and $A_3$ systems (Marchais and Pernes 1985).

## Future Trends

**The different research programs should be more closely integrated in the future. Often 80-90% of the farmers do not have adequate equipment; soil cultivation and thinning are often not carried out, and weeding operations are limited by time. These problems should not be overlooked by breeding programs.** This does not mean that varieties should be selected to suit poor cultural practices, but rather should be capable of performing well compared to local cultivars under existing conditions, and to outyield them under improved conditions.

The varietal structure (population, composite, synthetic, or hybrid) that is adopted depends primarily on the level of development in each country. Given the low purchasing power and technological levels prevailing in the region, open-pollinated varieties (populations, composites, and synthetics) should be retained, since they adapt more easily to traditional cultural practices than hybrids. Hybrid breeding should not, however, be abandoned, since hybrids could be useful for certain locations in the future.

### Variety Breeding

Breeding work should focus on:

- diversification of the genetic base in each country through collections, and introductions from other centers of diversity (India, East Africa, northwestern Africa). Research on the use of wild relatives will determine their contribution to the improvement of local cultivars.
- use of the collected material to select better local cultivars, and crosses between varieties of different origin with complementary characteristics. Importance should be given to yield components (head length, grain size, and tillering). The creation of composites by recombining superior $F_2$ lines should provide, for the short term, better material than local cultivars. Lines selected from different groups of early material derived from these crosses and populations can be used to form synthetics adapted to different climatic zones.

In the breeding program for a better grain/straw ratio, selection of the local 3/4 population should be continued to improve the grain mass per head as well as smut and mildew resistance. Short-stemmed (1.8-2.5 m) varieties should be adequate given the local technological capacity. The importance of straw should not, however, be underestimated if crop and livestock production are integrated.

### Drought Resistance

An important aspect of the breeding program is based on selection of drought-resistant varieties. Resistance mechanisms are very complex, especially when combined with yield characters. It is impossible to assemble all the drought-resistance mechanisms in one variety or line, but even if it could be done, productivity would be considerably reduced.

In West Africa, especially in the Sahelian Zone, drought periods are very unpredictable and may occur at any stage of crop development. Selected varieties should therefore be able to resist drought stress at these critical periods. The agrometeorological service in each country can analyze available data to determine the different ecological zones and periods of high drought risk during the cropping season. Selection criteria can thus be better adapted to the needs for each ecological zone (pre- or postflowering drought) (Dancette 1983). Rainfall variability is highest at the beginning and end of the crop cycle, i.e., at planting and flowering-seedset stages. Research on drought resistance should focus on:

Breeding for good seedling vigor. Material should be selected according to the ability of the seedlings to tolerate high temperatures and drought stress, and to resist soil crusting and compactness.

Breeding for earliness. Water requirements of millet depend on crop duration (Dancette 1983); short-duration varieties therefore require less water. Duration of the crop has to be adjusted to that of the wet season, in collaboration with the agroclimatologists. Short-duration varieties stand a better chance of fitting in the period of adequate rainfall, but their use raises the problem of pests (diseases, insects, and birds) and postharvest treatment (Dancette 1976).

The advantages of earliness should not obscure the importance of photoperiod sensitivity. Poor emergence due to soil crusting, sandstorms, pest attacks, or a sudden break in rainfall often compels farmers to replant two or three times. Sensitivity to daylength always ensures a certain yield irrespective of the date when the crop is replanted. Photoperiod-sensitive varieties are also more tolerant to poor cropping conditions than photoperiod-insensitive varieties because tiller development is often blocked by flowering (Siband 1983, Lambert 1983). This mechanism should be studied in relation to adaptation factors to enable a better use of photoperiod-sensitive material. The agroclimatologist plays an important role in this research area (Dancette 1980).

Breeding for a good root system. This character enables a better use of the soil horizon at the end of the cropping season. Soils in West Africa are not deep (Stoop et al. 1982). Studies on rice (Ahmadi 1983) show that there is high genetic variability for different characteristics of the root system. Evaluation of the diversity in local millet cultivars will be undertaken once the drought-tolerance associated characters have been determined and an efficient evaluation method has been developed.

## Conclusion

In West Africa, especially in the Sahelian Zone, environmental conditions are extremely difficult with very fragile soils, erratic rainfall, and resource-poor farmers (Franquin 1984). Pearl millet is grown in this zone essentially as a food crop; only a small percentage is sold. In order to provide food for the constantly increasing population, the region must increase its crop production. Strategies should be relevant to the difficult conditions. Breeding programs should, parallel to the objective of improved yield potential, aim to stabilize production under the present cropping conditions through selection for good adaptability to resistance to soil crusting, resistance to pre- and postflowering drought, and good root system development.

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# Practical Recurrent Selection in Cross-pollinated Crops[1]

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***Abstract***

*Techniques used to carry out recurrent selection, especially in cross-pollinated crops, are discussed in some detail. Topics covered are (1) the influence of effective population size and selection pressure on fixation of favorable genes, (2) choice of the population in which to practice selection, (3) the target environment, (4) sampling environments, and (5) blocking techniques. Intrapopulation and interpopulation selection methods are discussed and compared, including advantages and disadvantages of each and the appropriate prediction equations. Data from a large study comparing line per se selection with reciprocal recurrent selection are reported. Results indicate a similar rate of gain in the variety cross using each of the two systems, but in each case the gain is due to very different genetic changes. Line per se selection has apparently increased the variety cross largely through additive effects while reciprocal recurrent selection appears to have improved the performance of the variety cross through nonadditive effects, as suggested by theory.*

**Résumé**

**Techniques pratiques de sélection récurrente chez les cultures allogames :** *Les techniques de sélection récurrente, en particulier chez les cultures allogames sont examinées de près. Les questions abordées concernent : (1) l'influence de l'importance de la population utile et de la pression de sélection sur la fixation des gènes favorables, (2) le choix de la population faisant l'objet de la sélection, (3) le milieu auquel sera destiné le matériel sélectionné, (4) l'échantillonnage des milieux et (5) les techniques de mise en blocs. L'étude et la comparaison des méthodes de sélection intra- et interpopulation démontrent les avantages et les inconvénients de ces méthodes avec équations de prévisions correspondantes. Les résultats d'une importante étude comparant la sélection phénotypique et la sélection récurrente réciproque sont présentés. Ces résultats révèlent un taux de gain semblable dans le croisement variétal avec ces deux systèmes, quoique dû à des modifications génétiques différentes. En théorie, l'augmentation phénotypique serait due aux effets additifs, tandis que dans le cas de la sélection récurrente réciproque il s'agirait des effets non additifs.*

## Introduction

Both pearl millet *(Pennisetum americanum)* and maize *[Zea mays* (L.)] are highly cross-pollinated crops, but far more quantitative genetic studies and recurrent selection experiments using maize as a test organism have been reported (Sprague 1977, Hallauer and Miranda 1981). Much more data, therefore, are available for maize which can be of value to those engaged in recurrent selection in pearl millet. While the genetic responses to selection in pearl millet and maize are expected to be similar (Rai and

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Andrews 1984), there are operational differences as a consequence of their morphological differences.

Pearl millet is generally earlier maturing than maize and tillers freely at low plant densities. Large amounts of seed (1000 or more) can be produced on each of several heads (which can be used separately for different breeding operations), and more tillering produces an increased range of flowering per plant. Selfed seed can be produced without manipulating pollen, merely by bagging heads before stigma emergence. A cross can be made by a single pollination of a previously bagged head where the stigmas have emerged but not the anthers.

In pearl millet, commercial hybrid production depends on the use of cytoplasmic-genetic male sterility and hence, is limited to combinations of fertility restorers and lines into which male sterility has been introduced by tedious backcrossing. In maize, hybrids can be made between any two lines by detasselling either line. This is possible because the male and female flowers are on separate inflorescences. These differences are acknowledged in the following discussion, which deals largely with maize experiences. In general, apart from the current restriction of available seed parents for pearl millet hybrids, pearl millet is an easier organism than maize in which to conduct recurrent selection.

## General Principles of Recurrent Selection

In a broad sense, recurrent selection has been practiced since people first began domesticating plants. A definition of recurrent selection should include the steps (not necessarily separate from each other) of

- observation of individuals or progenies followed by selection,
- recombination of the selected fraction, and
- a repetition of the procedure.

A better definition might well include the objective of maintaining genetic variation in the population in which recurrent selection is taking place. This then, requires a structured recurrent selection program. Decisions are required on selection intensity and effective population size. Once these choices have been made, the future of the selection prograrm is in part determined. The higher the selection intensity, the greater the rate of gain. The smaller the effective population size, the sooner the population will plateau with a lowered selection limit. Thus, selection intensity and effective population size are in conflict with each other.

These concepts can be expressed in terms of the probability that a favorable allele will be fixed in a population. This probability is determined by the initial frequency of the allele ($q_0$), the effective population size (n), and the selection pressure that can be brought to bear on the allele (s). Hill and Robertson (1966) showed that the probability of fixing an allele could be expressed as

$$\mu(q) = \frac{1-e^{-2nsq_o}}{1-e^{-2ns}}$$

where e = 2.178 and is the base for natural logarithms.

Table 1 contains approximate probabilities of fixing an allele with $q_0$ varying from 0.05-0.7, n varying

**Table 1. The probability of fixation of a favorable allele[1].**

| | | Initial frequency (qo) | | | | |
|---|---|---|---|---|---|---|
| n | s | 0.05 | 0.1 | 0.3 | 0.5 | 0.7 |
| 64 | 1/2 | 0.9 | 1.0 | 1.0 | 1.0 | 1.0 |
| 32 | 1/2 | 0.8 | 0.9 | 1.0 | 1.0 | 1.0 |
| 16 | 1/2 | 0.5 | 0.8 | 1.0 | 1.0 | 1.0 |
| 8 | 1/2 | 0.3 | 0.5 | 0.9 | 1.0 | 1.0 |
| 8 | 1/4 | 0.2 | 0.3 | 0.7 | 0.9 | 1.0 |
| 8 | 1/8 | 0.1 | 0.2 | 0.5 | 0.7 | 0.9 |

1. Where e = 2.718 and is the base for natural logarithms, qo is the initial gene frequency, n is the effective population size, and s is the selection coefficient.

Calculated from $\frac{1-e^{-2nsq_o}}{1-e^{-2ns}}$

from 8-64, and s either 1/8, *1/4*, or 1/2. It is apparent that with a low initial gene frequency many favorable alleles will not be fixed, even with strong selection pressure. With lower selection pressure and small effective population size as well, those alleles are not sure to get fixed even at intermediate initial frequencies. These examples are somewhat artificial since they assume that the loci are independent, that they only have additive effects, and that each locus has very small effects. However, the probabilities tell us that effective population size is very important if we are going to achieve much of the potential in a breeding population.

### How Many Traits Should Be Selected for?

This question has to be dealt with carefully because of the dilution effect. For example, in a sequential selection for first one trait, then another, followed by still another, the selection intensity for each is determined by the equation $\sqrt[N]{P}$ where N is the number of traits and P is the selected proportion. The proportion selected for each trait is shown in Table 2. In a test of 100 traits to select 10 (P = 0.1) with a goal to improve three, choose a 0.46 proportion for each trait, i.e., 0.46 x 100 = 46 for trait 1,0.46 x 46 = 21 for trait 2, and 0.46 x 21 = 10 for trait 3. The important point is that the selection pressure for each trait is much reduced by adding more traits. Even though selection may not be in sequence as in this illustration, the dilution of selection pressure will be true with any kind of selection with additional traits. The solution is to include only important traits. If it is unclear that a trait is important, eliminate it from the selection criterion.

### How Does a Breeder Choose the Population to be Improved?

This is an easy question to pose, but can be quite difficult to answer. A simple example can be used to illustrate what can be involved. Suppose there is a potential choice among three different populations:

- an adapted elite population that does not have as much genetic variation as the other two;
- a population with a lower initial yield potential but a somewhat greater amount of genetic variation; and
- a population with the lowest yield potential of the three but the largest amount of genetic variation.

If it is assumed that the trait to be improved is controlled by a very large number of genes, each with very small effects so that response will continue linearly over the long term, and that the rate of response is proportional to the amount of genetic variation, the response patterns in Figure 1 might be expected. The shorter the time available, the more weight should be placed on the initial mean of important traits. The more one is interested in ultimate selection limits, the more weight should be placed on genetic variation. It is desirable, of course, to have both a high initial mean and a high amount of initial genetic variance, but this may not often be possible. In practice, some populations might be chosen to satisfy short term needs and others for longer term programs. Ultimately, it probably depends upon the source of funding and program objectives.

### What Should be the Target Environment?

It seems logical to subdivide a large potential set of macroenvironments into subsets, each having some cohesive internal relationship. In quantitative genetics, the reasoning is that genetic variation for a population is defined relative to these environmental subsets. If this environment is too broad, more of the genetic variation would go into G * E interaction, but if the target environment is narrow, the useful

Table 2. Selected proportions of a population for each trait selected in sequence with the proportion for each trait equal[1].

| Over-all selected proportion (P) | Number of traits (N) to be improved 1 | 2 | 3 | 4 | 8 | 16 |
|---|---|---|---|---|---|---|
| 0.05 | 0.05 | 0.22 | 0.37 | 0.47 | 0.69 | 0.83 |
| 0.10 | 0.10 | 0.32 | 0.46 | 0.56 | 0.75 | 0.87 |
| 0.20 | 0.20 | 0.44 | 0.59 | 0.67 | 0.82 | 0.90 |

1. Calculated from the Nth root of P: $P^{\frac{1}{N}}$ or $\sqrt[N]{P}$

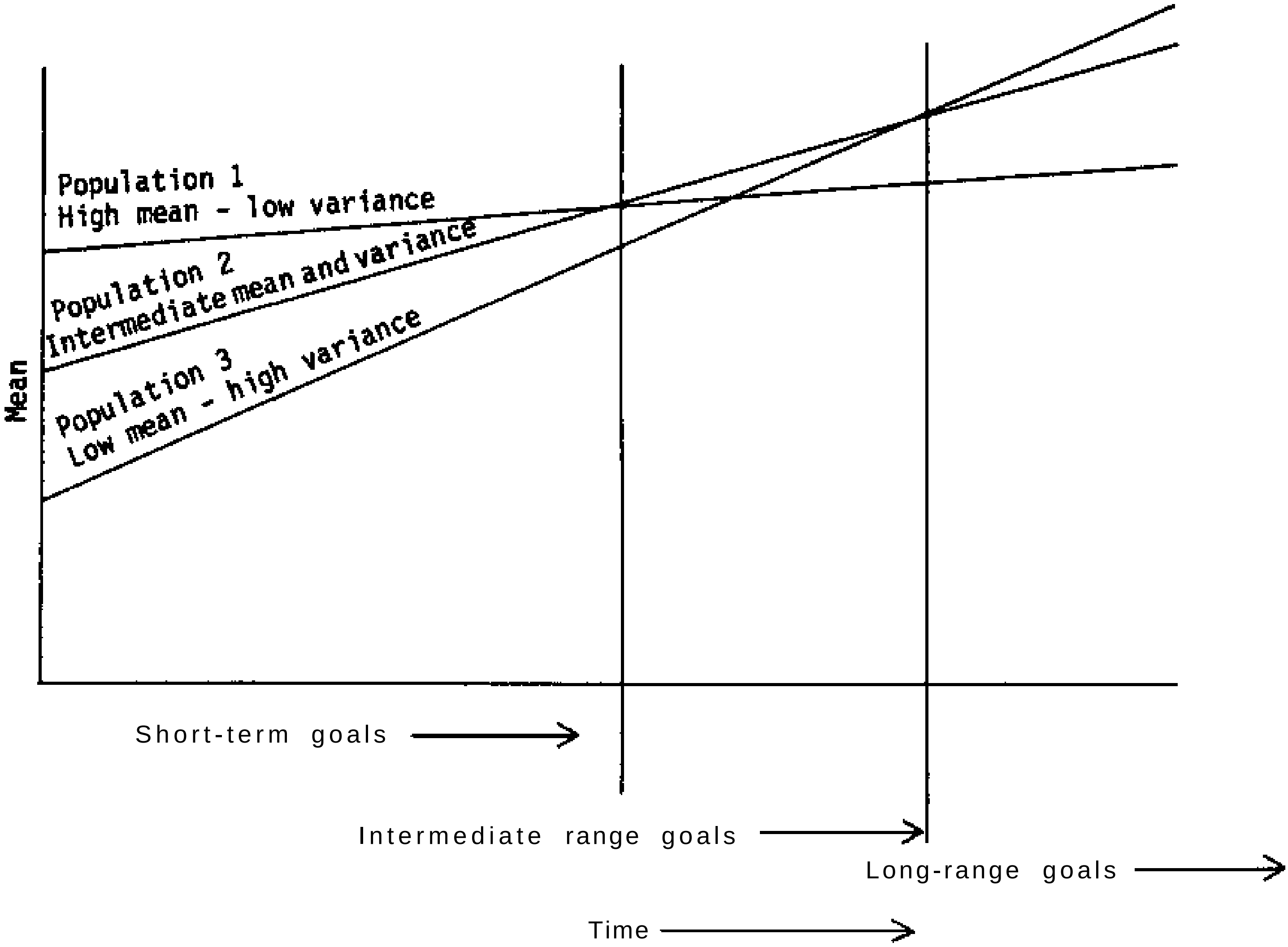


**Figure 1. Three populations and their expected response patterns.**

genetic variation is increased. In practice compromise is necessary. The Nebraska hybrids are very different in breadth of adaptation: some must be grown under very specific conditions or in only certain areas, while others may be very broadly adapted (for instance, the maize hybrid B73 x Mo17 has been grown all over the world). Admittedly not much is known about this problem because it is apparently complex. It seems prudent that a breeder restrict the target set of environments to a logical subset among which G * E interaction is not too large. For maize, Nebraska is divided into three zones that form a logical grouping (Figure 2). Western Nebraska (Zones I and II) requires earlier maize varieties than the eastern portion, so population improvement is done within these zones.

## Sampling Environments

To sample environments within a subset, families may be tested with only one replication in each location when seed quantities are restricted. This *is* not a major problem except for the difficulty of handling missing plots. The two analyses of variance with and without replication at each location are shown in Table 3. Note that the appropriate test of significance for entries is present even without replication at each location, assuming that locations are random. Thus a broader array of macroenviron-

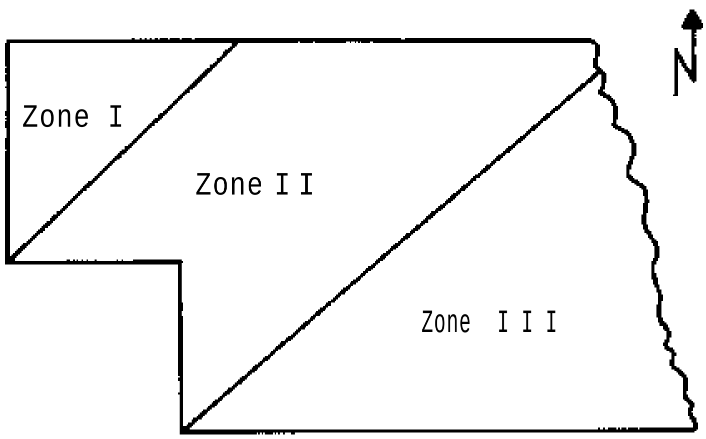


**Figure 2. Corn-growing zones in the state of Nebraska in the central part of USA.**

Table 3. Two analyses of variance showing that the location * entry interaction is the appropriate test either with or without replication at each location

| | Analysis of Variance I | |
|---|---|---|
| Source | df | E.M.S. |
| Locations | $l$-1 | |
| Entries | e-1 | $\sigma^2 + \sigma^2_{LE} + l\sigma^2_E$ |
| L x E | ($l$-1)(e-1) | $\sigma^2 + \sigma^2_{LE}$ |
| | **Analysis of Variance II** | |
| Source | df | E.M.S. |
| Locations | $l$-1 | |
| Replications in Locations | $l$(r-1) | |
| Entries | e-1 | $\sigma^2 + r\,\sigma^2_{LE} + rl\sigma^2_E$ |
| L x E | ($l$-l)(e-1) | $\sigma^2 + r\,\sigma^2_{LE}$ |
| Error | $l$(r-1)(e-1) | $\sigma^2$ |

ments may be sampled with a given number of replications rather than precisely evaluating each entry in a smaller number of environments.

## Blocking

In testing families, the breeder usually is faced with experiments containing many entries. Blocking is required in order to remove environmental variation arising from differences in the field from one part of a replication to another. Lattices work well but a simpler approach is to use incomplete blocks. For example, a test of 100 entries could be divided into 10 incomplete blocks of 10 entries each. Each incomplete block will contain the same entries in all replications. In a blocks-in-replication design, the blocks are randomized in each replication. In a replication-in-blocks design all the replications of a block containing the same entries are grown together in the block to minimize the error term. The blocks-in-replication design is somewhat better from a selection point of view, and is also adaptable to testing entries with one replication in each location since locations can be substituted for replications. However, the replication-in-blocks is slightly favored for estimating genetic variances. Analyses of variance and further discussion of these designs are found in Ross and Gardner (1985). Whatever the type of experimental design used, some sort of blocking is almost always required.

When making selections there are two ways to handle the blocks. One way is to calculate the mean of each block and the overall mean, and then adjust the entries in the block by the deviation of the block mean from the overall mean. The other way to make selections is to select equally from each block. Both systems work well, but care is necessary not to have the blocks too small. The fraction $\sigma^2_G/e$ (where e is the number of entries per block) of the genetic variance $\sigma^2_G$ will go into block-to-block variance and be lost. If e is large enough (say 10 or more) this fraction may not be sufficiently large to cause worry. Blocks that are too large (say 50 or more), however, may not remove enough of the environmental variance.

## Improving Populations or Varieties and their Crosses

### Intrapopulation (Variety) Improvement

Methods most usually seen are mass, half-sib, including ear-to-row, full-sib, and line per se selection, or some combination of these.

In the prediction equations for each method (Table 4a, b, c, d), some common terms are used so the schemes can be compared with each other.

$N_e$ = effective population size

$\Delta g$ = gain per cycle

k = selection coefficient based on proportion selected

$\sigma^2_H$ = total genetic variation

$\sigma^2_A$ = additive genetic variance

$\sigma^2_D$ = dominance genetic variance

Table 4a. Prediction equations, advantages, and disadvantages for intrapopulation improvement using mass selection.

| | | |
|---|---|---|
| Prediction equation: | | |
| Mass Selection 1 | $$\Delta g = \frac{k\,(1/2)\sigma^2_A}{\sqrt{\sigma^2 + \sigma^2_H}}$$ | for selection after pollination. |
| or | | |
| Mass Selection 2 | $$\Delta g = \frac{k\,\sigma^2_A}{\sqrt{\sigma^2 + \sigma^2_H}}$$ | for selection prior to pollination. |
| Time per cycle -1 year | | |
| Advantages | 1. Can maintain large Ne.<br>2. Selection intensity can be high so that the selection differential can be large.<br>3. No yield trial plots, inexpensive.<br>4. Simple to conduct. | |
| Disadvantages | 1. If heritability of selected trait is very low, progress may be difficult.<br>2. Requires isolated plots.<br>3. Cannot apply usual types of selection indices.<br>4. High population densities may not work well. | |

$\sigma^2_M$ = variance among half-sib families = 1/4 $\sigma^2_A$

$\sigma^2_F$ = variance among full-sib families = 1/2 $\sigma^2_A$ + 1/4 $\sigma^2_D$

$\sigma^2_e$ = plot-to-plot environmental variance or family x replication interaction

$\sigma^2$ = plant-to-plant environmental variance

r = number of replications

n = number of plants per plot

$\sigma^2_{S_1}$ or $\sigma^2_{S_2}$ = genetic variance among $S_1$ or $S_2$ lines

$\sigma^2_{H_1}$ or $\sigma^2_{H_2}$ = total genetic variance at S, or $S_2$ level of inbreeding

The advantages and disadvantages of each method are outlined in Table 4.

## Interpopulation Improvement

In interpopulation improvement the breeding objective is to improve the performance of the population cross. Any of the population improvement schemes may also improve intrapopulation (variety) crosses, but it is logical that if the interpopulation cross is to be improved, selection should be based on cross performance because it is then a direct rather than an indirect response to selection. Following that line of reasoning, Reciprocal Recurrent Selection was suggested by Comstock et al. (1949). Their idea was to use cross-bred, half-sib families (as described for half-sib 1 in Table 4b with the other population used as the tester and vice versa).

### Reciprocal Half-Sib Selection (RHS)

Individual plants from population A are self-pollinated and also crossed to several plants from population B. The crossed seed is bulked to form one entry for testing. Population B individuals are also selfed and crossed to several plants from population A. Thus, two sets of half-sib families are produced. If 100 entries are to be tested from each population a total of 200 are grown. If 20 is judged to be a reasonable effective population size ($N_e$), then a 20% selection intensity will result in the selection of 20 from 100 in each variety.

### Reciprocal Full-Sib Selection (RFS)

A more recent interpopulation scheme used for a number of years at Nebraska in maize is reciprocal full-sib selection. As populations of maize have been

Table 4b. Prediction equations, advantages, and disadvantages for intrapopulation improvement using half-sib selection.

Half-sib 1 Selection of selfed males based upon progeny tests

$$\Delta g = \frac{k\,(1/2)\sigma^2_A}{\sqrt{\dfrac{\sigma^2 + \sigma^2_H - \sigma^2_M}{rm} + \dfrac{\sigma^2_e}{r} + \sigma^2_M}}$$

Advantages
1. Progeny tests can be as extensive as desired.
2. Good flexibility of the system because of choice among several types of testers.
3. Each selfed male is a potential new inbred line.

Disadvantages
1. Takes three growing seasons.
2. Can be relatively costly, as in any system with yield trials.
3. Effective population size may be small.
4. Rate of gain may depend upon tester chosen.

Half-sib 2 Selection and recombinatiion of the half-sibs themselves.

$$\Delta g = \frac{k\,(1/4)\sigma^2_A}{\sqrt{\dfrac{\sigma^2 + \sigma^2_H - \sigma^2_M}{rm} + \dfrac{\sigma^2_e}{r} + \sigma^2_M}}$$

Advantages
1. Can test extensively because there is ample seed.
2. Less costly and easy to do.
3. Takes two growing seasons.
4. Can maintain large effective Ne.

Disadvantages
1. Costly yield trials.
2. Do not have a start toward inbred line development.

Half-sib 3 Modified ear-to-row, 1 generation/cycle.

$$\Delta g = \frac{k\,(1/8)\sigma^2_A}{\sqrt{\dfrac{\sigma^2 + \sigma^2_H - \sigma^2_M}{rm} + \dfrac{\sigma^2_e}{r} + \sigma^2_M}} + \frac{k^1\,(3/8)\sigma^2_A}{\sqrt{\sigma^2 + \sigma^2_H - \sigma^2_M}}$$

Advantages
1. 1 season cycle length.
2. Can maintain large Ne.

Disadvantages
1. Costly yield trials and detasselling labor.
2. Do not have a start toward inbred line development.
3. Large isolation needed.

Half-sib 4 Modified ear-to-row, 2 generations/cycle.

$$\Delta g = \frac{k\,(1/4)\sigma^2_A}{\sqrt{\dfrac{\sigma^2 + \sigma^2_H - \sigma^2_M}{rm} + \dfrac{\sigma^2_e}{r} + \sigma^2_M}} + \frac{k^1\,(3/8)\sigma^2_A}{\sqrt{\sigma^2 + \sigma^2_H - \sigma^2_M}}$$

Advantages
1. Smaller isolation than in 1 yr/cycle scheme.
2. Less costly in labor.
3. Can still maintain large Ne.
4. Yield trials only in alternative seasons so less costly.

Disadvantages
1. Do not have a start toward inbred line development.
2. Gain per year slightly reduced over 1 generation/cycle scheme if one only grows 1 generation per year.

Table 4c. Prediction equations, advantages, and disadvantages for intrapopulation improvement using full-sib selection.

$$\Delta g = \frac{k\,(1/2)\sigma^2_A}{\sqrt{\dfrac{\sigma^2 + \sigma^2_H - \sigma^2_F}{rm} + \dfrac{\sigma^2_e}{r} + \sigma^2_F}}$$

Advantages
1. Time per cycle can be two growing seasons.
2. Easily recombined because only one pollination for each new full sib required.
3. General advantages of family testing such as control of G x E interaction.
4. Good control of additive variance in numerator.
5. Can maintain good Ne because each selected FS has two parents so Ne is twice as large as when selecting an equal number of selfed males.

Disadvantages
1. Phenotypic variance is a little larger than with half-sib selection.
2. Have to be careful to pollinate each ear after good silk emergence to keep up seed number in maize. In pearl millet this would not be a problem.

improved for yield, prolificacy has increased. In the RFS scheme prolificacy is exploited to both self and cross single plants. One plant from population A is matched with one from population B. The second ear of each is self-pollinated and 2 d later the top ears are crossed. At harvest only reciprocal crosses between parents that have set selfed seed are chosen for testing. Since they are genetically the same, the crossed top-ears can be bulked together to form one entry. If 200 are tested, as for RHS, 10% can be selected and still have an $N_e$ of 20 for each population because each entry tests a plant from both populations at once. If cost is a major concern, 100 entries could be tested with 20 selected from each, so only half as many yield-trial plots are used as for RHS. There is an increase in the phenotypic variance of RFS over RHS so all is not in favor of RFS. Table 5 shows the prediction equations for RHS and RFS. Jones et al. (1971) compare the two schemes.

## Reciprocal Inbred Line Tester Selection

Another reciprocal scheme of some value is to use an inbred tester (RIS). In this scheme plants from populations A and B are selfed and also crossed to an elite

Table 4d. Prediction equations, advantages, and disadvantages for intrapopulation improvement using line selection.

$S_1$ line per se

$$\Delta g = \frac{k\,\sigma^2_A}{\sqrt{\dfrac{\sigma^2 + \sigma^2_{H_1} - \sigma^2_{S_1}}{rm} + \dfrac{\sigma^2_e}{r} + \sigma^2_{S_1}}}$$

$S_2$ line per se

$$\Delta g = \frac{k\,(1.5)\,\sigma^2_A}{\sqrt{\dfrac{\sigma^2 + \sigma^2_{H_2} - \sigma^2_{S_2}}{rm} + \dfrac{\sigma^2_e}{r} + \sigma^2_{S_2}}}$$

Advantages
1. Large numerator in the prediction equation.
2. Additive (A) x A epistasis coefficient is the square of the A coefficient, so A x A, if it exists, would be utilized with this scheme.
3. Inbred maize lines selected for line per se yield so that they are superior for seed production.

Disadvantages
1. If overdominance is present in large amounts, line per se selection may be poor procedure.
2. G x E interaction is amplified with inbreeding in maize so is more of a factor with line per se.
3. Requires nursery work both in making up families and recombining.
4. Requires three growing seasons.
5. Difficult to get good stands and also other yield trial problems.

Table 5. Prediction equations for interpopulation improvement methods—Reciprocal Half-sib Selection and Reciprocal Full-sib Selection.

Half-sib Selection (RHS)

$$\Delta g = \frac{k(1/4\,\sigma^2 A_A)}{\sqrt{\dfrac{\sigma^2 + \sigma^2 H_A - \sigma^2 M_A}{rm} + \dfrac{\sigma^2 e_A}{r} + \sigma^2 M_A}} + \frac{k'(1/4\,\sigma^2 A_B)}{\sqrt{\dfrac{\sigma^2 + \sigma^2 H_B - \sigma^2 M_B}{rm} + \dfrac{\sigma^2 e_B}{r} + \sigma^2 M_B}}$$

Reciprocal Full-sib Selection (RFS)

$$\Delta g = \frac{k(1/4\,\sigma^2 A_A) + 1/4\,\sigma^2 A_B}{\sqrt{\dfrac{\sigma^2 + \sigma^2 H - \sigma^2 F}{rm} + \dfrac{\sigma^2 e}{r} + \sigma^2 F}}$$

Note: $\sigma^2 F_{AB}$ = genetic variance among A x B full-sibs = $1/2\sigma^2_A + 1/4\,\sigma^2_D$ in AB population.
$\sigma^2_{M_A}$ genetic variance among half-sibs.

or $\sigma_{M_B} = 1/4\,\sigma^2 A_B$.

line from the other population. Thus, every entry has one elite line parent and therefore, is a potential commercial hybrid, assuming further inbreeding and selection in the selected S, lines. Comstock (1979) concludes that RHS using the counterpart populations as testers is superior to RIS using pure line testers for improving the population cross. The RIS scheme has an advantage from a line development point of view and has been used by some commercial breeders.

The major advantages and disadvantages of RRS procedures are outlined in Table 6.

## Response to Selection

This section concentrates primarily on a comparison of S, line per se with reciprocal full-sib selection (RFS) because considerable data on these methods is available and because of their expected contrasting responses. Line per se selection would be expected to perform best only if additive types of effects were involved while reciprocal selection schemes like RFS would be best able to capitalize on nonadditive (especially overdominance) effects.

A very large and comprehensive comparison of

Table 6. Advantages and Disadvantages of Reciprocal Recurrent Selection (RRS) Procedures.

Advantages
1. Dominance types of relationships are important in cross-fertilized crops, and basing selection on crossed families seems the most logical way to take advantage of this heterotic vigor.
2. Some forms of RRS can be integrated into applied line-development programs.
3. The ultimate selection limit may be highest for this type of selection because any type of genetic variation that can contribute is exploited, though it may take a long time to make use of epistatic combinations on a population basis.

Disadvantages
1. Requires considerable labor for hand pollinations, both in making up families for testing and for recombination.
2. Expensive, requires many yield-trial plots (especially for RHS and RIS).
3. As in most other family schemes (with exception of intra-population full-sib selection) requires 3 growing seasons per cycle.

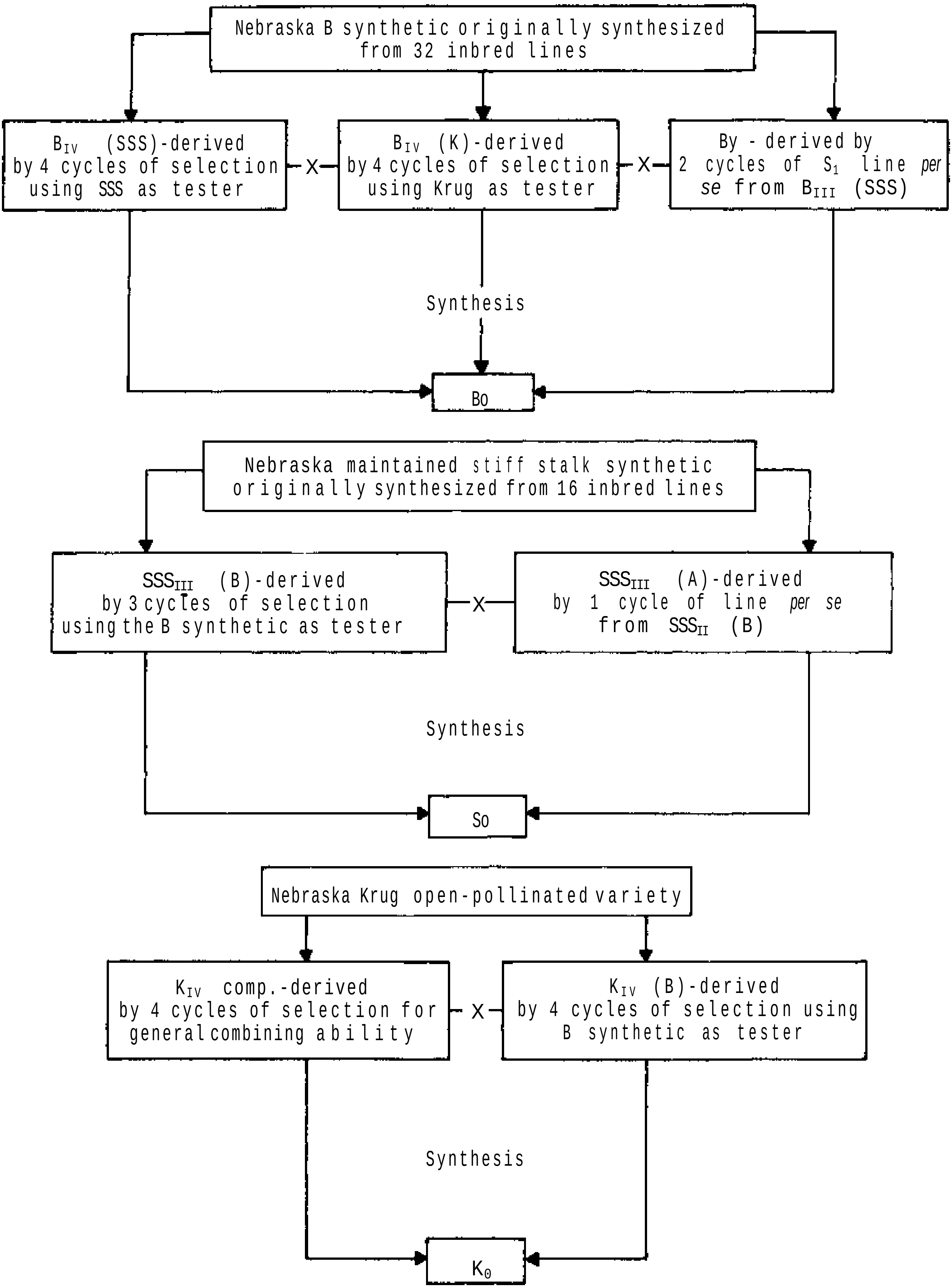


**Figure 3. Composition of base populations $B_0$, $S_0$, and $K_0$.**

these two methods has been undertaken at Nebraska. Three base populations, called $S_0$, $B_0$, and $K_0$ are shown in Figure 3. From these, replicate subpopulations were created using either RFS or $S_1$ line per se selection as shown in Figure 4. The replicates are continued independently of each other and provide an error term for comparing breeding methods. Some drift is likely among these replicates because only 10 S, lines are selected for recombination in each cycle. Five cycles of selection are now completed in this study, but evaluation is not yet complete. The responses reported here were originally reported by Thomas (1979) and cover the first two cycles with very extensive evaluation.

The cycles of $S_1$ per se and RFS selection were tested as bulked inbred populations, as random mated populations, and in variety crosses. By selfing 100 or so plants and bulking seed from them, an inbred population would be formed that could then be tested to measure the direct response to $S_1$ per se selection and an indirect response to RFS selection. Similarly, the variety crosses were used to measure the direct response to RFS and the indirect response to $S_1$ per se selection. The random-mated populations not only permitted the evaluation of each type of selection for intravarietal improvement but also allowed the calculation of changes in heterosis and inbreeding depression.

The selection criterion used is an index of yield (kg $ha^{-1}$) multiplied by the proportion of upright plants and the proportion of plants without dropped ears. This produces a value best called machine harvestable yield (MHY) calculated from hand harvested data:

$$\text{Index (MHY)} = \begin{array}{c}\text{Yield}\\ \text{adjusted to}\\ \text{15.5\%}\\ \text{moisture}\end{array} \times \begin{array}{c}\text{Proportion}\\ \text{upright}\\ \text{plants}\end{array} \times \begin{array}{c}\text{Proportion}\\ \text{plants}\\ \text{without}\\ \text{dropped ears}\end{array}$$

This index has been applied to all of the family selection studies at Nebraska for some years with apparent success [cf. Subandi et al. (1973), Compton and Lonnquist (1982)].

The experiment was conducted with five replications in two watering treatments at two locations in 2

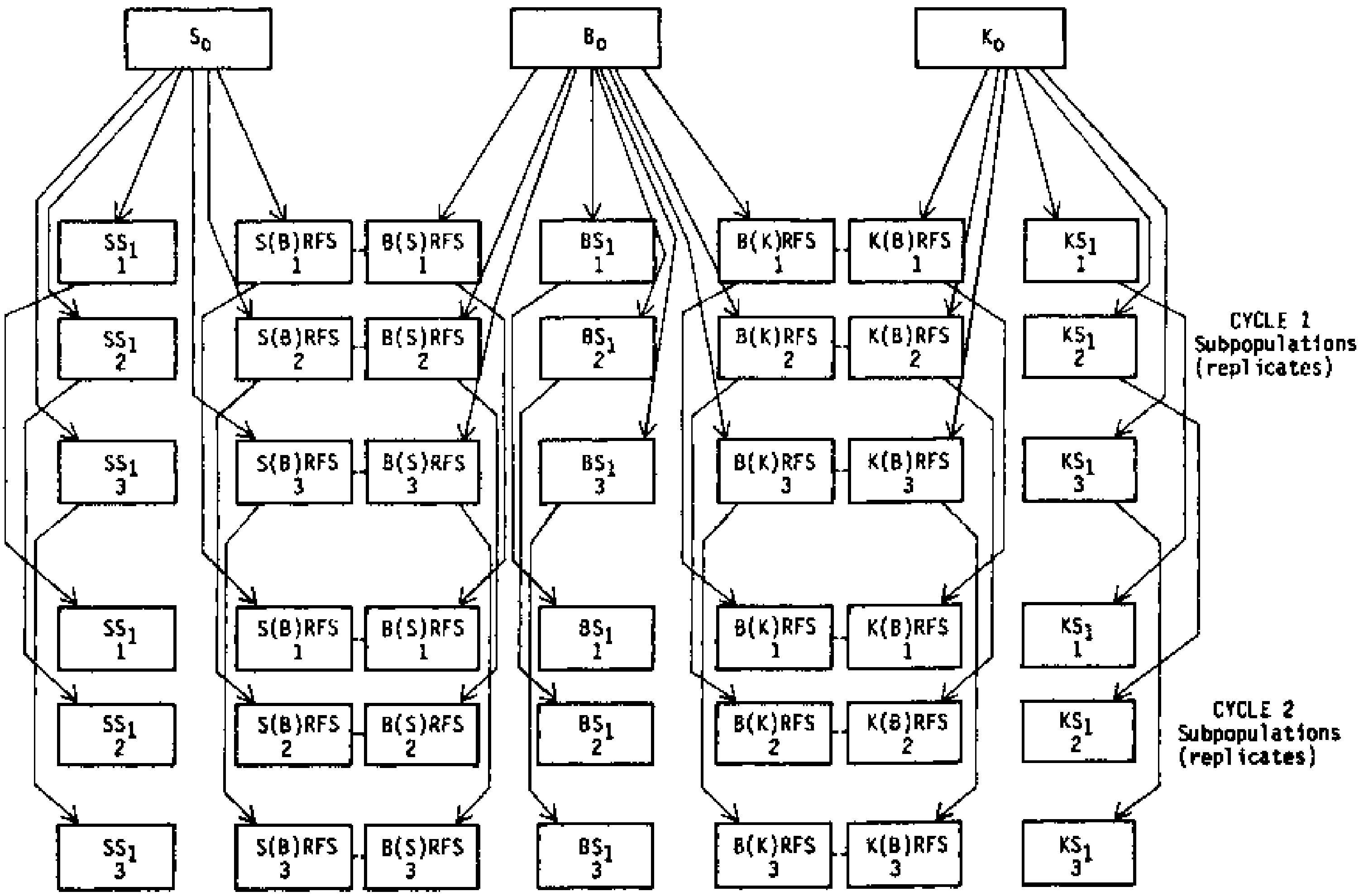


**Figure 4. Subpopulations (relicates) formed by two cycles of $S_1$ line per se selection and 2 cycles of RFS selection in the B, S, and K populations. — = generations advance, — = testcross.**

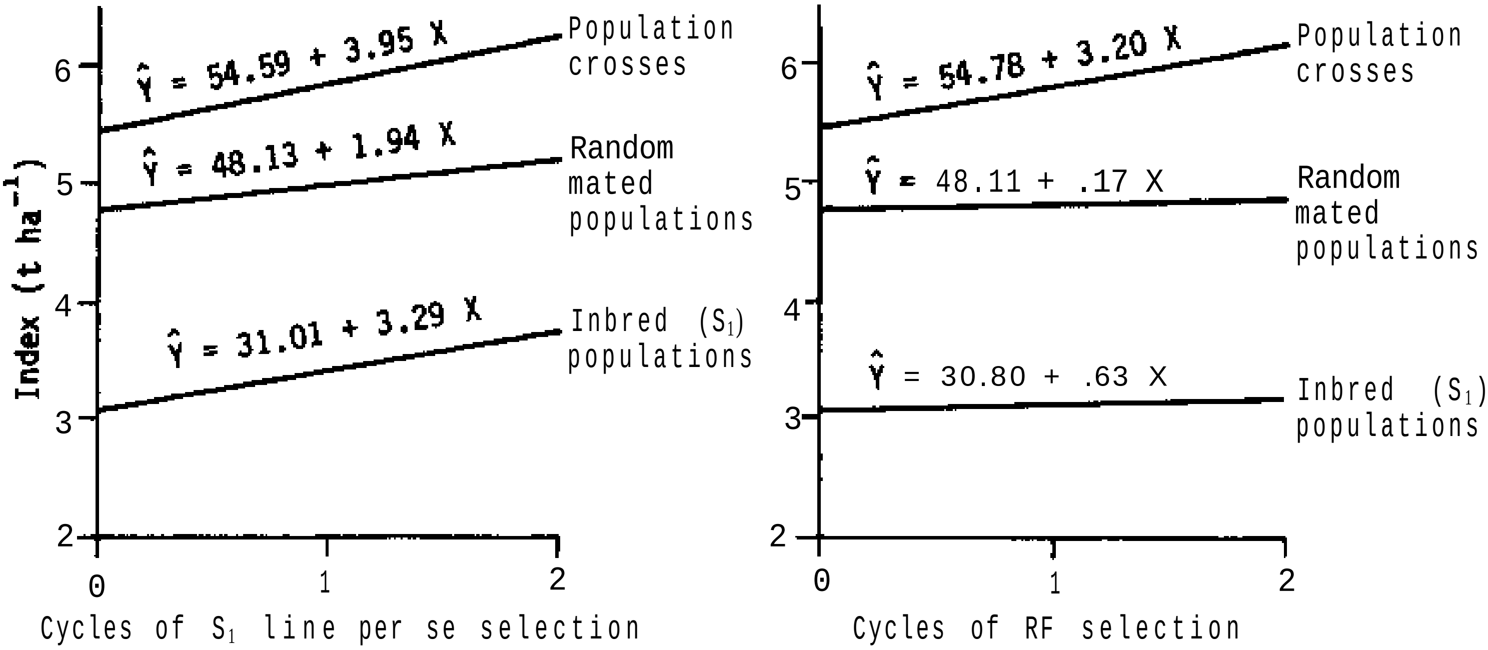


**Figure 5. Average response in index values to 2 cycles of selection.**

years and results have been summarized (Fig. 5). Each data point is an average of 160-480 plots (depending on the cycle or type of material). Thus, standard errors are quite small, and data points are estimated very precisely. Although the variety crosses have increased at similar rates for both $S_1$ per se and RFS selection, it is clear that these increases are due to different genetic changes. When the populations were tested as random-mated populations, $S_1$ per se selections increased more than the RFS selections. Thus, heterosis was increased more with RFS selection. Also, the inbred populations selected using the S, per se method increased more rapidly than the random-mated populations, resulting in a reduction in inbreeding depression. There was no change in inbreeding depression with RFS selection. These comparisons should give a reasonably accurate assessment of the relative advantages of these two methods, because total breeding effort is very similar in the two cases.

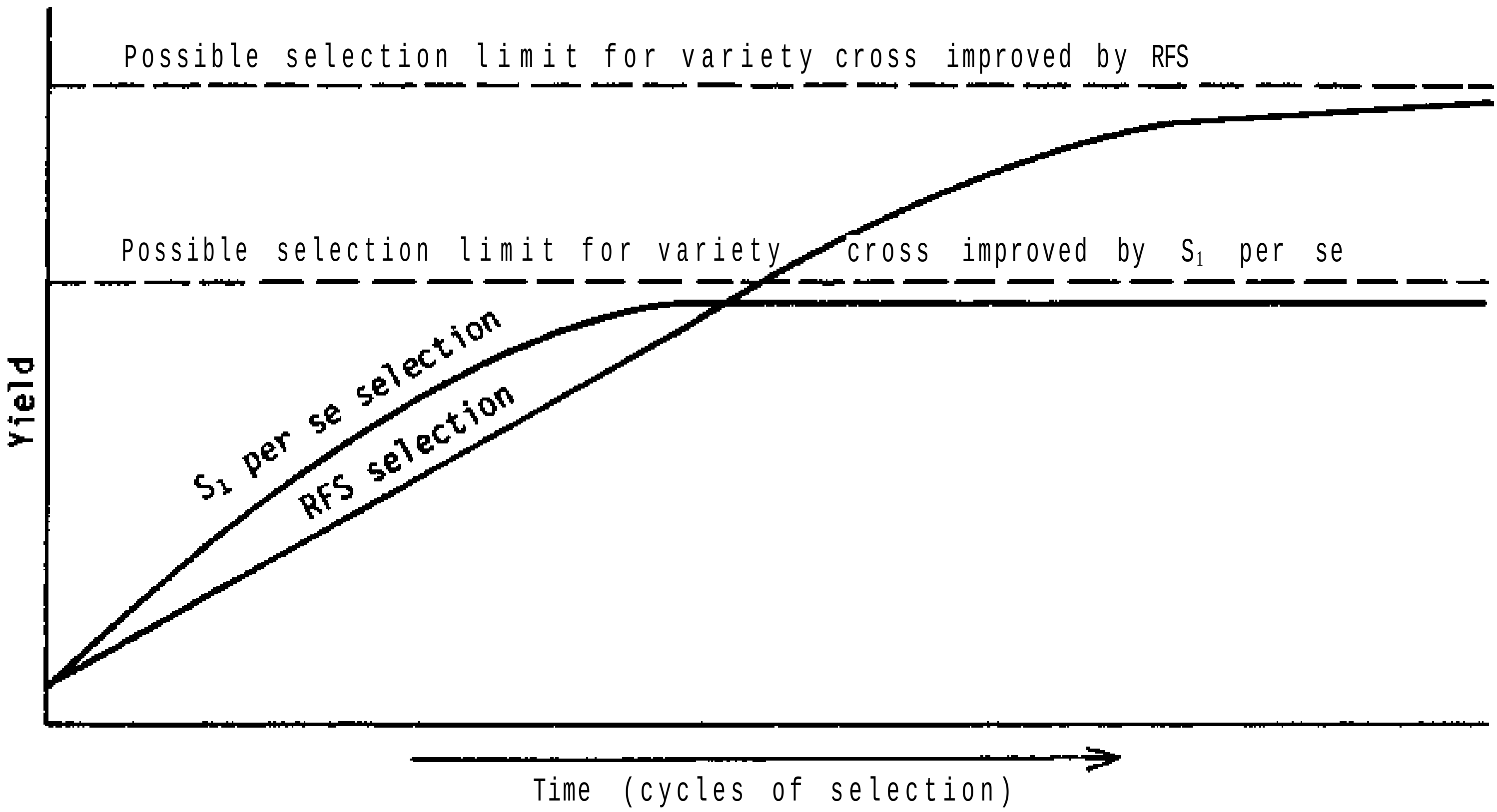


**Figure 6. Selection limits for reciprocal full-sib selection (RFS) and $S_1$ per se as imagined for the future.**

### What Does the Future Hold?

The authors believe that in maize S, per se will improve the variety cross as fast in early cycles (say 15 or 20) as RFS. However, RFS should result in a higher ultimate selection limit for the variety cross as shown in Figure 6. The results of the study just reported indicate that different genetic mechanisms are involved with the two methods. S, line per se seems to be improving the variety cross through changes involving loci that exhibit additive effects, while RFS seems to involve more of the nonadditive effects as expected from theory.

Continued selection based on selfed progeny may gradually reduce dominance effects. This has apparently occurred in crops that are largely self-pollinated. The corollary to this would be that if reciprocal recurrent selection were practiced between two populations of soybeans *[Glycine max* (L.)], or wheat *[Triticum aestivum* (L.)], or other self-pollinated crops, perhaps dominance relationships would gradually increase with a corresponding increase in heterosis. The heterosis presently seen in those crops is most likely due to additive x additive epistasis since inbreeding depression does not accompany the observed heterosis.

## Summary

The advantages and limitations of different methods of intrapopulation and interpopulation selection systems have been examined and the consequences of effective population size, selection intensity, and genotype * environment interaction discussed. Experimental evidence from a comparison of $S_1$ line versus reciprocal full-sib (RFS) selection in three populations of maize indicates that both were effective in increasing variety cross performance. But although $S_1$ was better at increasing self- and random-mated population yields, it is postulated that higher-yielding variety crosses ultimately would result from RFS.

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# Pearl Millet Hybrids

**H.R. Dave**[1]

***Abstract***

*Pearl millet is the important cereal crop in arid and semi-arid regions of the world, and is grown most widely in India. The availability of very wide genetic variability, its protogynous nature, and the existence of cytoplasmic male sterility have made this crop highly amenable to breeding improvement. In India, considerable progress has been made in the commercial exploitation of hybrids. HB 3 was the first hybrid and was very widely grown from 1968-1974. Subsequently its cultivation stopped because it became susceptible to downy mildew disease. Thereafter a series of hybrids on different male-sterile lines was released. The susceptibility of hybrids to downy mildew, and seed production problems are discussed. Hybrids such as BJ 104 and BK 560 were popular from 1978-1984, but are now being replaced by new hybrids. Incorporating disease resistance into pearl millet hybrids and the diversification and exploitation of genetic materials are discussed. Problems with commercial hybrid seed production are mentioned, and the suitability of parents in seed production programs is outlined.*

**Résumé**

**Hybrides de mil :** ***Le mil, importante culture céréalière des régions arides et semi-arides, est répandu en Inde. Son énorme variabilité génétique ainsi que la protogynie et l'existence de la stérilité mâle cytoplasmique le prête facilement à l'amélioration génétique. En Inde, l'exploitation commerciale des hybrides a fait beaucoup de progrès; le premier hybride HB 3 était largement cultivé de 1968 à 1974 lorsque sa culture, fut arrêtée à cause de sa sensibilité au mildiou. Une série d'hybrides issus de lignées mâles-stériles fut diffusée par la suite. La sensibilité des hybrides au mildiou ainsi que les problèmes liés à la multiplication des semences sont examinés. Les hybrides tels que BJ 104 et BK 560 étaient largement cultivés entre 1978 et 1984, ils sont en train d'être remplacés par de nouveaux hybrides. L'incorporation de la résistance aux maladies ainsi que la diversification et l'exploitation du matériel génétique sont également abordées. Les problèmes liés à la production commerciale des semences d'hybrides sont mis en lumière, en particulier le choix de géniteurs appropriés aux programmes de production.***

## Introduction

Pearl millet *(Pennisetum americanum)* is grown on more than 20 million ha in the world. It is the world's sixth most important cereal. In Africa and India, it is the principle grain crop of the semi-arid tropics, while in the USA it is one of the best annual summer forage crops for the drier regions.

Pearl millet, a short-day plant adapted to hot climates, is even more resistant to drought than sorghum. No other cereal grows so well in hot dry regions. Pearl millet yields reasonably well on poor, sandy soils on which most other crops fail (Arnon 1972).

In India, pearl millet is grown on about 11 million ha in the arid and semi-arid regions of the country. India grows nearly two-thirds of the world area of pearl millet, where it is the fourth most important food crop. It is grown chiefly in Rajasthan, Gujarat, Maharashtra, and Uttar Pradesh, which account for nearly 75% of the pearl millet area and production of the country. The pearl millet area in India has

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remained relatively stable at 11.5 million ha during the last 25 years, but the total productivity and, therefore, production has increased from 3.85 million t in 1960-65 to 5.91 million t in 1980-84, an increase of more than 50%. Similarly, the average productivity has increased from 340 kg $ha^{-1}$ to 512 kg $ha^{-1}$ (Table I) (Harinarayana 1985).

Since the release of high-yielding hybrids, the production and productivity of pearl millet has not only increased, but production has stabilized. However, in spite of the proven high-yield potential of hybrids, their impact on production in the country is by no means dramatic, primarily because they have not been widely adopted in the principal pearl millet growing areas such as Rajasthan, where hybrid coverage is only 10-20%. On the other hand, in Gujarat, where the coverage is more than 85%, there has been a spectacular increase in grain yield from 480 kg $ha^{-1}$ in 1966-67 to 1120 kg $ha^{-1}$ in 1984-85, which can be largely attributed to hybrids. With 1.1 t $ha^{-1}$ grown on 1.2 million ha, a 200% production increase is the result of the pearl millet hybrid era in Gujarat. The importance of the pearl millet crop in Indian agriculture, and the benefits from the use of hybrids, are amply demonstrated by production and productivity data over the last 25 years.

## History

Pearl millet breeding began in India in the early 1930s with an emphasis on grain production. Initially, open-pollinated populations were improved by mass selection. The selections were made on the basis of long, well-filled, compact heads, which ripened uniformly and yielded more grain. The improved populations were tested as varieties, e.g., C02, C03, AKP 1, AKP 2, RSJ, RSK, T 55, Babapuri, Nadiad 207, and S-28-15-2. Subsequently, mass selections from introduced African populations were released as varieties. S230 and Pusa Moti are two examples.

Prior to the availability of male-sterile lines, attempts were made in the early 1950s to exploit heterosis in pearl millet by building "chance" hybrids, mixtures of 40% hybrids and 60% parental genotypes. These hybrids were produced by planting equal proportions of parental inbred lines which flower at same time, and allow them to mate in isolation. These hybrids were released in India in the early 1950s, and outyielded the standard varieties by 10%. Chance hybrids did not become popular because of their limited productivity, narrow range of adaptability, and lack of seed production programs (Gill 1983).

The cytoplasmic male-sterile lines Tift 23A and 18A were bred by Burton in the USA (Burton 1958). In India, two more sources of cytoplasmic male sterility, L66A and L67A, were isolated at Ludhiana during 1961-62 (Athwal 1965). These sources were identified as different from Tift 23A (Burton and Athwal 1967). The three sources are designated as A,, originally identified in Tift 23A, $A_2$ identified in Tift L66A, and $A_3$ identified in Tift L67A (Burton and Powell 1968).

The use of cytoplasmic male sterility for Indian hybrid breeding started in 1962 with the introduction of Tift 23 A from the USA. The hybrids based on male-sterile lines were first tested in India in 1963.

The progress of hybrids in India is reviewed in this paper. Hybrid breeding and utilization can be divided into distinct phases based on seed parent used, release year, and disappearance of hybrids from commercial cultivation (Harinaryana 1977).

### First Phase

The first phase is characterized by the release of five hybrids, HB 1 to HB 5, during 1965-72 (Table 2).

Table 1. Area, production and productivity of millets.

| Crop | 1960-65 | 1965-70 | 1970-75 | 1975-80 | 1980-85 |
|---|---|---|---|---|---|
| Millets | | | | | |
| Area (ha x $10^6$) | 18.38 | 19.47 | 19.27 | 18.17 | 17.81 |
| Production (t x $10^6$) | 7.81 | 7.93 | 9.47 | 9.68 | 10.10 |
| Yield (kg ha") | 427 | 406 | 487 | 532 | 568 |
| Pearl millet | | | | | |
| Area (ha x $10^6$) | 11.33 | 12.31 | 12.34 | 11.07 | 11.55 |
| Production (t x $10^6$) | 3.85 | 4.51 | 5.61 | 5.16 | 5.91 |
| Yield (kg ha') | 340 | 365 | 447 | 465 | 512 |

Table 2. Early released hybrids in India.

| Hybrid | Bred at | Release year | Pedigree |
|---|---|---|---|
| Phase 1 | | | |
| HB 1 | Ludhiana | 1965 | Tift 23A x Bil 3B |
| HB 2 | Jamnagar | 1966 | Tift 23A x J 88 |
| HB 3 | Jamnagar | 1968 | Tift 23A x J 104 |
| HB 4 | Kanpur | 1968 | Tift 23A x K 560 |
| HB 5 | Kanpur | 1969 | Tift 23A x K 559 |
| Phase 2 | | | |
| NHB 3 | Delhi | 1975 | 5071A x J 104 |
| NHB4 | Delhi | 1975 | 5071A x K 560-230 |
| NHB 5 | Delhi | 1975 | 5071A x K 559 |
| PHB 10(HB 6) | Ludhiana | 1975 | Pb 111A x PIB 155 |
| PHB 14(HB 7) | Ludhiana | 1975 | Pb 111A x PIB 228 |
| GHB 1399 | Jamnagar | 1975 | 126D2A x J 1399 |
| Phase 3 | | | |
| BJ 104 | Delhi | 1977 | 5141A x J 104 |
| BK 560 | Delhi | 1977 | 5141A x K 560-230 |
| CJ 104 | Delhi | 1977 | 5054 A x J 104 |
| BD 111 | Delhi | 1977 | 5141A x D 111 |
| GHB 27 | Jamnagar | 1981 | 5141A x J 2002 |
| BD 763 | Delhi | 1982 | 5141A x D 763 |
| GHB 32 | Jamnagar | 1983 | 5141A x J 1188 |
| HHB 45 | Hisar | 1984 | 5141A x H 90/4-5 |
| COH 2 | Coimbatore | 1984 | 5J4IA x PT 1921 |
| CM 46 | Delhi | 1981 | 5054A x M46 |
| MBH 110 | Mahyco | 1981 | 2 x PL 2 |
| PHB 47 | Ludhiana | 1983 | Pb 111A x PIB 1234 |
| X 5 | Coimbatore | 1984 | Pb 111A x PT 1921 |
| MBH 118 | Mahyco | 1984 | 2 x PL 3 |
| Current Phase | | | |
| JCMH 451 | ICRISAT | 1986 | 81A x ICMP 451 |
| ICMH 501 | ICRISAT | 1986 | 834A x ICMP 501 |
| MH 182 | Pune | 1986 | 732A x PNBM 83099 |
| GHB 30[1] | Jamnagar | 1986 | 5054A x J 2002 |

1. For Gujarat.

The performance of HB 3 and HB 5 is given in Table 3.

Only HB 3 became popular, and it was extensively cultivated. This hybrid was successful in many Indian pearl millet-growing states from 1968-1973. HB3 was early maturing, had bolder grains and was well adapted to drought stress. These five hybrids averaged 75-88% more grain than did the check varieties. The other four hybrids did not become popular. When HB 3 succumbed to downy mildew in 1974, it was no longer cultivated, thus marking the end of the five hybrids with Tift 23A as the seed parent.

Table 3. Performance of first phase pearl millet hybrids HB3 and HB5 in all India trials.

| | Grain yield (kg ha$^{-1}$) | |
|---|---|---|
| Year | HB 3 | HB 5 |
| 1969-70 | 1310 | - |
| 1970-71 | 2150 | - |
| 1971-72 | 1790 | 1830 |
| 1972-73 | 1380 | 1420 |
| 1973-74 | 1420 | 1370 |
| 1974-75 | 1630 | - |
| Mean | 1610 | 1540 |

## Second Phase

The second phase started with the use of the male-sterile line 5071 A, which was bred at Delhi by mutational change from Tift 23A. It showed less downy mildew incidence in the seed crop, and its hybrids varied in their disease resistance.

Three hybrids had 5071 A as the seed parent (Table 2), but they did not become popular because of their low yields and their continued susceptibility to downy mildew. Within a year or two they were no longer cultivated.

During this second phase, an attempt was made to diversify the female background. Two hybrids bred at Ludhiana, PHB10 and PHB14 (later named HB 6 and HB 7), were released. These hybrids had the Ludhiana male-sterile line Pb 111A as the seed parent. In Gujarat, hybrid GHB 1399 (on male-sterile line 126D2A) was bred at Jamnagar and released.

Table 4. Performance of second phase pearl millet hybrids in coordinated trials.

| Year | Grain yield (kg $ha^{-1}$) NHB3 | NHB 5 | HB 6 | HB 7 | GHB 1399[1] |
|---|---|---|---|---|---|
| 1974-75 | 1420 | 1770 | 1960 | 1860 | |
| 1975-76 | | 1200 | 1100 | 1290 | 2460 |
| 1976-77 | 1330 | 1360 | | 1720 | 2120 |
| Mean | 1380 | 1440 | 1530 | 1620 | 2290 |

I. Irrigated.

The performance of these hybrids is presented in Table 4. All had good downy mildew resistance, however none of them were widely cultivated commercially, and they lasted 2-3 years. This marked the end of the second-phase hybrids.

## Third Phase

The third phase started with the use of two new downy mildew resistant male-sterile lines developed at Delhi from Tift 23A. These lines, 5141A and 5054A, had good downy mildew resistance and were widely used. These were the seed parents of hybrids such as BJ 104, BK560, and CJ 104, which became very popular and were widely cultivated (Table 2). The grain yield data and downy mildew incidence of these hybrids are shown in Table 5.

These hybrids were cultivated from 1977-84, but a high incidence of downy mildew on 5141A, and the resultant susceptibility in its hybrids caused it to be phased out as a hybrid parent in 1985. Moreover, CJ 104, which had 5054A as the seed parent, also became susceptible. The third phase of hybrid era is ending, as 5141A and its derivatives are no longer used.

During the latter part of this third phase, five hybrids were released which had three male-sterile lines as the seed parent other than 5141A (Table 2). The grain yield and downy mildew incidence of these hybrids is presented in Table 6. Two of these five hybrids were released by MAHYCO, a private company.

Table 5. Performance of third phase pearl millet hybrids in co-ordinated trials.

| Hybrids | Grain yield (kg $ha^{-1}$) 1977 | 1978 | 1979 | 1980 | 1981 | Mean | % BJ 104 | Downy mildew (%) 1977 | 1978 | 1979 | 1980 | 1981 | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BJ 104 | 2360 | 1920 | 2020 | 2080 | 2160 | 2110 | 100 | 8.3 | 9.8 | 13.7 | 8.7 | 8.1 | 9.7 |
| BK 560 | 2250 | 1890 | . | - | - | 2070 | 98 | - | 5.5 | - | 3.1 | - | 4.3 |
| BD 111 | 2440 | 1790 | - | - | - | 2120 | 100 | 1.1 | 3.7 | - | - | - | 2.4 |
| BD 763 | 2320 | - | 2170 | - | - | 2240 | 106 | 1.7 | - | 1.7 | - | - | 1.7 |
| GHB 27 | 2175 | 1840 | 2070 | 2100 | - | 2050 | 97 | 6.3 | 1.2 | 0.9 | 2.5 | - | 2.7 |
| GHB 32 | 2100[1] | 1950 | 2070 | 2150 | - | 2070 | 98 | 4.7 | 6.6 | 1.4 | 1.5 | - | 3.6 |
| COH 2 | - | 2050 | 2180 | 2290 | - | 2170 | 103 | - | 4.0 | 2.7 | 3.7 | - | 3.5 |
| Local | 1610 | 1490 | 1650 | 1510 | 1690 | 1590 | 76 | - | - | - | - | - | - |
| Susceptible control | | | | | | | | 93.5[2] | 67.9[2] | 42.12 | 58.5[3] | - | 65.5[3] |
| Trial mean | 2140 | 1880 | 2000 | 2110 | 2180 | 2060 | 98 | | | | | | |

1. From IPMHT-1
2. HB 3
3. NHB 3

Table 6. Performance of third phase pearl millet hybrids based on different male sterile lines in coordinated trials.

| Hybrid | Grain yield (kg ha$^{-1}$) | | | | | | | | % | Downy mildew (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | Mean | BJ 104 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | Mean |
| MBH 110 | - | 1970 | 2160 | 2550 | 2370 | 2420 | 2060 | 2260 | 111 | _ | 1.7 | 1.5 | 0.3 | 7.3 | 1.8 | 1.9 | 2.4 |
| MBH 118 | - | 2320a | 2140 | 7660 | 7470 | 7470 | 2170 | 2360 | 116 | _ | 4.6 | _ | 2.4 | _ | 2.1 | 5.6 | 3.7 |
| CM 46 | 2445 | 1790 | 1960 | 2070 | - | - | - | 2070 | 98 | 0.8 | - | 0.9 | 3.2 | _ | _ | - | 1.6 |
| X5 | - | - | - | - | 2270 | 2130 | 1910 | 2100 | 104 | - | . | - | - | 1.7 | 1.6 | 4.5 | 2.6 |
| BJ 104 | - | 1920 | 2020 | 2080 | 2160 | 2380 | 1620 | 2030 | 100 | - | 9.8 | 13.7 | 8.7 | 8.1 | 14.9 | 21.3 | 12.8 |
| Local | - | 1490 | 1650 | 1510 | 1690 | 2060 | - | 1680 | 83 | | | | | | | | |
| Susceptible control | | | | | | | | | | - | 67.9[1] | 42.1[1] | 58.5[2] | - | 61.8[2] | 58.9[2] | 57.8 |
| Trial mean | - | 1880 | 2002 | 2109 | 2184 | 2328 | 2049 | 2093 | 103 | | | | | | | | |

1. HB 3
2. NHB 3

### Current Phase

New hybrids were needed to replace 5141A and its hybrids. New hybrids using seed parents other than 5141A were released during 1981-84 (Table 2). They performed well agronomically and were downy mildew resistant, e.g., CM 46, PHB 47, MBH 110, X5, and MBH 118 are recommended for cultivation in the immediate future.

Four new hybrids, highly resistant to downy mildew with good productivity, were released in 1986 (Table 2). These hybrids are expected to have a longer life because they all have different seed parents, and both male and female parents are resistant to downy mildew.

## Problems in Hybrid Breeding

From the discussion of the different hybrid phases, it is evident that disease susceptibility is a major problem. It is downy mildew that has necessitated frequent changes in the most popular hybrids. The susceptibility of hybrids to downy mildew has diluted the impact of hybrids on Indian pearl millet production. The seed parents and their respective hybrids which were identified and released as resistant, have succumbed to downy mildew after 3-5 years of cultivation. Hybrids become susceptible to downy mildew because essentially they are a single genotype. Moreover, the hybrids released during the first three phases had a narrow genetic base which did not fully exploit the available genetic diversity. In the 20 hybrids released during the first three phases, male-sterile line 23A was used in five combinations, 5071A was used in three, and 5141A in eight. Thus, these three lines were seed parents of 16 of the 20 hybrids.

Similarly, the same pollinators were also repeatedly used in combination with different male-sterile lines. J 104 was used in four different hybrids, K 560-230 was used in three different hybrids, and K 559 in two.

The limited genetic resources used in the first three phases led to an early breakdown of downy mildew resistance. Diversification of hybrid breeding material is essential. Three different sources of cytoplasm, $A_1$, $A_2$, and $A_3$ are identified and available, but so far all male-sterile lines which have been used in released hybrid combinations are on $A_1$, cytoplasm. It may be necessary to exploit the other two cytoplasm sources. Work at the Punjab Agricultural University, Ludhiana, is investigating the use of new male-sterile lines which incorporate these other sources of cytoplasm. New male-sterile lines bred at different centers in India are at present showing a high degree of downy mildew resistance, and are being used to produce experimental hybrids. The restorer lines which are used as male parents, need to be diversified using material showing a high degree of downy mildew resistance. The present stock of restorer lines in use by different centers is promising and showing a high degree of downy mildew resistance.

So far the resistance in seed parents, restorer lines, and hybrid combinations has only been successful against downy mildew. The other two important diseases of pearl millet, ergot and smut, now need attention. Scientists at ICRISAT have bred some restorer lines with resistance to ergot and smut, but hybrids incorporating these have not reached advanced trials.

The plateauing effect of hybrid yield was observed in the late 1970s and early 1980s, and was of concern to all pearl millet breeders. It is encouraging to note that the yields of new test hybrids are not plateauing, and have substantially higher yields than the check hybrids.

Another problem with pearl millet hybrids is seed production. The two parents of the promising released hybrids should have synchronous flowering. The male-sterile line should be stable, and should have none or very few plants that shed pollen in seed production plots. Some hybrids could not be grown in India because of their seed production problems. Hence, the parents of promising or released hybrids should meet the requirements of seed production technology.

The genetic enrichment of nutritional quality, particularly protein content and amino acids, deserves greater attention.

The speed with which Indian breeders have developed high-yielding grain hybrids by using cytoplasmic male-sterile lines is a most remarkable plant breeding success story. The material under test and in the pipeline in India suggests that the future for pearl millet hybrids in India is still very bright.

## Acknowledgements

The author expresses his thanks to Dr. G. Harinarayana, Project Coordinator and gratefully acknowledges the wide use of data from the All India Coordinated Millets Improvement Project.

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# Breeding Pearl Millet Male-Sterile Lines

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### *Abstract*

*Numerous sources of cytoplasmic-genic male-sterility are now available in pearl millet. Although an understanding of the genetic control of male-sterility in pearl millet is far from clear, research indicates that it is due to an interaction between sterility-inducing factor or factors in the cytoplasm and multiple major genes and modifiers in the nucleus. Environmental factors, such as temperature and relative humidity, are also assumed to affect the expression of male-sterility. Tift $23A_1$ cytoplasm has been extensively used to breed diverse male-sterile lines at several leading research centers because of its more stable sterility across seasons and sites, and because there are a number of agronomically good lines that can be used as donors. Since the Tift $23A_1$, cytoplasm has been shown not to be associated with susceptibility to downy mildew, genetic diversification with this cytoplasm will continue to be a major objective in breeding male-sterile lines.*

*In most male-sterile breeding programs the common objectives will be to breed for dwarf plant height, early to medium maturity, large seeds, improved seed yield and combining ability, stable sterility, and appropriate combinations of resistance to diseases (downy mildew, smut, and ergot). Characterization of the nature and magnitude of cytoplasmic diversity should receive increased attention to identify alternative sources and systems to diversify the cytoplasmic base of male-sterile lines. Better understanding of the inheritance of male-sterility and the environmental factors affecting its expression will contribute significantly to the efficient utilization of diverse genetic materials in breeding male-sterile lines, as well as to the management of male-sterile lines under commercial production.*

### Résumé

**Sélection de lignées mâles-stériles du mil :** *Il existe plusieurs sources de stérilité mâle cytoplasmique-génique chez le mil. A l'état actuel de nos connaissances encore incomplètes, la stérilité mâle serait due à l'interaction entre un élément ou éléments provoquant la stérilité présent(s) dans le cytoplasme, d'une part, et de multiples gènes et modificateurs majeurs dans le noyau, d'autre part. Les facteurs environnementaux tels que la température et l'humidité relative auraient également un effet sur l'expression de la stérilité mâle. Plusieurs centres de recherche se servent du cytoplasme Tift $23A_1$ pour la sélection de différentes lignées mâles-stériles à cause de la stabilité de ce caractère dans l'espace et le temps et puisqu'il existe plusieurs lignées à bons caractères agronomiques pouvant servir de donneurs. Ce cytoplasme n'étant pas sensible au mildiou, la diversification génétique à partir de ce cytoplasme restera un objectif important dans la sélection de lignées mâles-stériles.*

*En général, la sélection visera à réduire la hauteur de la plante et la durée de la maturation à un cycle allant de précoce à moyen, à augmenter la taille des grains, tout en améliorant le rendement en grain et l'aptitude à la combinaison. D'autres objectifs sont une stérilité stable et une résistance multiple aux maladies (mildiou, charbon, ergot). L'intensification des études sur la caractérisation de la nature du*

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Submitted as CP 378 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

*cytoplasme ainsi que la détermination de l'amplitude de sa diversité permettront d'identifier d'autres sources et systèmes en vue de diversifier la base cytoplasmique des lignées mâles-stériles. Une meilleure compréhension de l'hérédité de la stérilité mâle et des facteurs environnementaux qui influencent son expression contribuera sensiblement à une exploitation efficace de la diversité génétique dans la sélection des lignées mâles-stériles ainsi que la gestion de ces lignées en production commerciale.*

## Introduction

The discovery of cytoplasmic-genic male-sterility often called cytoplasmic male-sterility and the development of male-sterile line Tift 23A, (Burton 1958, 1965) laid the foundation of the pearl millet *(Pennisetum americanum)* hybrid seed industry in India. The first commercial hybrid was HB 1. It was bred on Tift 23A$_1$ at the Punjab Agricultural University (PAU), Ludhiana, India, and it showed a 100% yield advantage over the open-pollinated check varieties (Athwal 1966). The success of male-sterile line Tift 23A, in producing high-yielding hybrids and their failure to last long due to downy mildew *(Sclerospora graminicola)* epidemics led to intensified research on genetic and cytoplasmic diversification of male-sterile lines, with particular emphasis on downy mildew resistance.

As a result, diverse, downy mildew resistant male-sterile lines, based on Tift 23A$_1$ cytoplasm, were bred. In the meantime, apparently two additional systems of cytoplasmic male-sterility were also discovered (Burton and Athwal 1967) and utilized for breeding male-sterile lines, mainly at PAU. Recent downy mildew epidemics on the most commonly used male-sterile line, 5141 A, and its hybrids which are under extensive commercial utilization has shown, once again, that large scale homogeneity of the genetic base is counter to the longevity of male-sterile lines and their hybrids. It is also clear that downy mildew is a major and unpredictably devastating disease of pearl millet hybrids. Recent research at ICRISAT has shown that ergot *(Claviceps fusiformis)* and smut *(Tolyposporium penicillariae),* although of secondary importance, can be more serious on hybrids than on open-pollinated varieties (Thakur et al. 1983a, 1983c), thus highlighting the need to breed male-sterile lines which also have resistance to ergot and smut.

Details of male-sterile breeding at various centers are not described in this paper as they have been extensively reviewed by Kumar and Andrews (1984). Instead, the approaches followed at the leading centers working on male-sterile lines are summarized, and the usefulness of various male-sterile lines in terms of their distinctness, use in hybrid production, and downy mildew resistance is evaluated. Although the treatment of the subject matter is based mostly on male-sterile breeding work done at Tifton, Georgia, USA, and in India, it is hoped that the principles and the materials described in this paper will find applications elsewhere.

## Genetic Diversification and Utilization of A$_1$ System Male-Sterile Lines

The A$_1$ cytoplasm of Tift 23A$_1$, has been extensively utilized in breeding a wide range of male-sterile lines (Table 1). At Tifton, four male-sterile lines were produced either by transferring single genes for specific traits into Tift 23A, and Tift 23B, or by backcrossing nonrestorers into Tift 23A$_1$ cytoplasm. Of these, mostly Tift 23A$_1$, and to some extent Tift 23DA$_1$, were used in India for hybrid production. Hybrids on Tift 23A$_1$ yielded more than those on Tift 23DA$_1$; five hybrids on Tift 23A$_1$ were released (Table 1) in quick succession between 1965-1972, but all went out of cultivation within about 5 years of their release due to high downy mildew susceptibility.

When hybrids on Tift 23A$_1$ succumbed to downy mildew, research efforts were intensified mainly at PAU and at the Indian Agricultural Research Institute (IARI), New Delhi, to diversify the genetic base of male-sterile lines in the A, cytoplamic system with high levels of downy mildew resistance. Seventeen male-sterile lines (Pb 111 A, Pb 101 A, and Pb 201A-Pb 215 A) which possessed high levels of downy mildew resistance were bred at PAU. They show considerable variability for tillering, head length, and compactness, and are of medium or mid-late maturity. Five of these have been involved in extensive hybrid testing. However, only one (Pb 111A) has successfully produced high-yielding hybrids, of which four have so far been released by the All India Coordinated Millets Improvement Project (AICMIP). Two of these (PHB 10 and PHB 14) were the first downy mildew resistant hybrids released in India (Gill et al. 1975).

| Table 1. Male-sterile lines of pearl millet released in India based on Tift $23A_1$ cytoplasm and grain hybrids. | | | |
|---|---|---|---|
| Research organization | Male-sterile lines | Hybrids[1] | Remarks |
| Coastal Plain Experiment Station, Tifton, Georgia, USA | Tift 23 $A_1$, Tift 23 $DA_1$, Tift 23 $DA_1E$, Tift 18A | HB I, HB 2, HB 3, HB 4, HB 5 | All hybrids on Tift $23A_1$ |
| Punjab Agricultural University, Ludhiana, India | Pb 111 A, Pb 101 A, Pb 20I-Pb 215A | PHB 10, PHB 14 PHB 47, X5 | All hybrids on Pb 111A |
| Indian Agricultural Research Institute, New Delhi, India | 5141 A, 5054 A, 3893 A, 3383 A, 5071 A, 5540 A, 5184 A | BJ 104, BK 560 BD 111, BD 763 CoH2, HHB 45, GHB 27, GHB 32 CM 46, CJ 104, NHB 3 | First 8 hybrids on 5141 A; next 2 on 5054A and the last one on 5071 A |
| ICRISAT Patancheru, India | 81 A, 833 A, 834 A, 841 A, 842 A, 843 A, 851 A, 852 A | ICMH 451, ICMH 501 | ICMH 451 on 81 A, ICMH 501 on 834 A |
| Maharashtra Hybrid Seeds Company, Ltd. Jalna, India | MSI, MS2, MS4-MS9, MS11-MS14 | MBH 110, MBH 118, MBH 130, MBH 131, MBH 136 | All hybrids on MS2 |

I. Hybrids and male-sterile lines not necessarily produced by the same research organization.

The work at IARI produced at least seven male-sterile lines (Table 1). However, only three (5054 A, 5071 A, and 5141 A) have good hybrid potential and downy mildew resistance (Pokhriyal et al. 1976). Male-sterile line 5071 A was used to reconstitute HB 3 as NHB 3 but it did not become popular because of its susceptibility to downy mildew. The most useful among these male-sterile lines was 5141 A on which eight hybrids were released by AICMIP during 1972-1984 (Table 1). Two hybrids (BJ 104 and BK 560) were widely cultivated in India and dominated the hybrid seed industry for about a decade. Two hybrids were released on 5054A but only one, CJ 104, became popular in the drier parts of Gujarat state due to its earliness (75 d to maturity). Male-sterile line 3383A is currently the highest-tillering male-sterile line and it also has a high level of downy mildew resistance. It has very thin heads and small seeds; empirical evidence shows that it is perhaps not a good general combiner.

Maharashtra Hybrid Seeds Company Ltd. (MAHYCO) at Jalna, India, initiated its male-sterile breeding work with S10A and SI0B, introduced from Serere, Uganda. $MS_2$ was the first successful male-sterile line bred from this stock on which two hybrids have been released by AICMIP; two others are promising and are likely to be released. Eleven additional male-sterile lines with different plant height, head size, and head compactness, but with larger seeds and improved seed set, have been bred by MAHYCO so far. Four of these are promising, and higher-yielding hybrids that have these male-sterile lines as seed parents are in advanced yield tests. MAHYCO has emphasized breeding for large seed size and early to medium maturity.

Starting in the late 1970s, seven male-sterile lines were bred at ICRISAT which have diverse plant height, maturity, tillering, head volume, and seed size. Two of these (81 A and 834A) are currently under extensive utilization in the hybrid programs in India. Two hybrids (ICMH 451 on 81A and ICMH 501 on 834A) yielded as high as the best check hybrid MBH 110 in AICMIP trials over years, and were released in 1986 for cultivation throughout India. The parental lines of these hybrids are currently being multiplied by various seed agencies. Because of initial concentration on 81A and 834A, other male-sterile lines have not been extensively tried in hybrid combination. There are indications that 833A and 852A have as good a general combining ability as 81A and 834A. Male-sterile line 841 A, selected from the residual variability for downy mildew resistance in 5141 A, compares well with the general combining ability of the latter and possesses much improved downy mildew resistance (Singh et al. 1987). Male-sterile lines 842 A and 843 A, bred jointly by the Fort Hays Branch Experiment Station, Kansas, USA, and by ICRISAT have large seeds (up to 12 g $1000^{-1}$) and mature early. The earliest male-sterile is 843A (42 d to 50% bloom) among all those currently available male-sterile lines in India, and it produces very early, short hybrids. However, it seems that due to downy mildew susceptibility, its use in hybrid production will be very restricted and it will be of negligible commercial value in downy mildew endemic areas.

At present, the major emphasis in India is to breed medium-maturity male-sterile lines (time to bloom, 45-55 d), primarily for two reasons:

- most breeding materials (including composites and synthetics used to produce restorer lines) belong to the medium maturity class and offer a wide range of genetic diversity, and
- the medium maturity class perhaps represents currently the most productive group of materials.

With the extensive use of germplasm from Togo and Ghana and breeding materials from the Fort Hays Branch Experiment Station, a wide range of male-sterile lines in the early maturity group are expected in the near future. For plant height, the emphasis is shifting towards dwarf male-sterile lines. Dwarf lines are considered important because they are, in general:

- less prone to lodging even under the intensive management conditions of seed production,
- are easy to stabilize for height,
- easy to recover in crosses,
- provide an option to produce hybrids with a wide height range, and
- make more efficient use of pollen from restorers in hybrid seed production plots.

## Cytoplasmic Diversification of Male-Sterile Lines

Enormous differences in downy mildew incidence among male-sterile lines based on Tift $23A_1$ cytoplasm indicate that the cytoplasm is not associated with downy mildew susceptibility, and that it is nuclear gene resistance which is important. Experimental evidence confirms this assumption (Kumar et al. 1983). Thus, at present, there is no need to be alarmed about the vulnerability of Tift 23A, cytoplasm to downy mildew. However, in the long run, the large scale and continuous use of a single cytoplasm source runs the risk of it becoming vulnerable to existing or unforeseen diseases. Hence, there is a need to diversify the cytoplasmic base of male-sterile lines. The cytoplasmic diversification should encompass other sources of cytoplasm within the A, system, as well as other cytoplasms in different systems.

In 1961, a cytoplasmic male-sterile line was identified at PAU (Athwal 1961) in a very late-maturing genetic stock, IP 189. The sterile plants were pollinated with different sources of maintainers and the male-sterile line finally produced was called CMS 66A (L 66A). In 1962, male-sterile plants were observed at PAU in a population originating from a natural cross of a stock possessing pearly amber grains. The cytoplasmic male-sterile line bred using this source was called CMS 67A (L 67A) (Athwal 1966). Burton and Athwal (1967) compared the relationships between the cytoplasms of Tift $23A_1$, L 66A and L 67A in experiments conducted at Tifton and Ludhiana and concluded that these three sources represented three different systems of cytoplasmic male-sterility. Several male-sterile lines were produced with these new cytoplasms. Burton and Athwal (1969) produced Tift $239DA_2$ by backcrossing Tift 239DB into L 103A (an $A_2$-system male-sterile line). At PAU, nine male-sterile lines were bred: (Pb 301A-Pb 309A) with $A_2$ cytoplasm and four male-sterile lines (Pb 401A-Pb 403A and Pb 405 A) with $A_3$ cytoplasm. Most of these male-sterile lines are resistant to downy mildew and have quite diverse phenotypic characters. A high-yielding hybrid (PHB 108) has recently been identified on Pb $405A_3$. It yielded as much as the best check hybrid MBH 110 in the AICMIP hybrid trials in 1984 and 1985.

Several other sources of cytoplasmic male-sterility have recently been reported. Cytoplasmic male-sterility has been identified in four pearl millet accessions from the ICRISAT genetic resources collection (S. Appa Rao, ICRISAT, personal communication) and there are indications that they resemble the $A_3$ system. None of these, however, has become stable for sterility: under selfing, partial fertility is observed in some plants which have 1-10 grains per head. Two other sources of cytoplasmic male-sterility have been reported (Appadurai et al. 1982, Aken'Ova and Chheda 1981), but it has not been conclusively shown whether they are different from the other existing systems. Marchais and Pernes (1985) have recently reported an interesting source of cytoplasmic male-sterility discovered from a cross between a wild relative of pearl millet *[Pennisetum violaceum* (Lam.) L. Rich = *P. americanum* ssp. *monodii]* and a landrace cultivar (Tiotande) from

Senegal. This source is reported to be different from all the existing systems. In a general survey of the germplasm and breeding lines using this male-sterile line, Marchais and Pernes (1985) showed that the frequency of restorer alleles was generally low in the cultivated millets, whatever their origin, and very high in wild millets. This points clearly to the immediate utility of this cytoplasm in male-sterile breeding and the utility of wild species which have a high frequency of restorers for breeding pollinations.

Studies of diallel $F_1$ hybrids among several A and B lines, all incorporating Tift $23A_1$ cytoplasm, did not clearly show that a maintainer of a given male-sterile line was necessarily a maintainer on the other male-sterile lines (Table 2). This shows that there is perhaps a continuum between different cytoplasmic systems which involves complex genetic mechanisms of multigenic inheritance confounded with modifying genes and environmental factors. Field evaluation of cytoplasmic diversity based on the fertility response of F, hybrids between cytoplasm sources and a set of inbreds may, therefore, suffer from these confounding effects as shown in sorghum (Ross and Hackerott 1972, Conde et al. 1982). Thus biochemical techniques such as those used in sorghum, in conjunction with field tests (Conde et al. 1982), may be quite valuable to characterize the nature and magnitude of cytoplasmic diversity in pearl millet.

## Genetics of Cytoplasmic Male-Sterility

Burton and Athwal (1967) studied the genetics of cytoplasmic male-sterility by crossing Tift $23A_1$, L 66A, and L 67A with each of their maintainers and restorers of Tift 23A,. Based on the fertility/ sterility of F, hybrids in nurseries grown at Tifton and Ludhiana, it was proposed that:

- cytoplasmic male-sterility results from the interaction of a specific recessive gene, ms, in the homozygous condition with sterility-inducing factors in the cytoplasm, and
- different single genes in recessive form are responsible for male-sterility in different cytoplasmic systems.

The genetic model proposed for male-sterile lines, maintainers, and restorers used in their studies is summarized in Table 3. Burton and Athwal (1967) recognized the possible role of modifiers and environmental factors in the maintenance of sterility and restoration of fertility. Siebert (1982) studied the genetics of fertility restoration and suggested there were two dominant complementary genes and a modifier for the A, system, and two dominant duplicate factors for the $A_2$ system. It has also been suggested that the maintenance of sterility of a new cytoplasmic system discovered by Marchais and Pernes (1985) from *P. violaceum* cytoplasm is controlled by three independently inherited recessive genes.

Several progenies derived from B $^{x}$ R crosses in pearl millet when tested on two male-sterile lines (843A and 81 A) did not conform to monogenic or digenic inheritance (Table 4). This means that there are more than two major genes involved in the maintenance of sterility, or that there are modifier genes involved. Considerable variability in the expression of sterility in $A_1$ (Tift $23A_1$) x B crosses has been

Table 2. Fertility/sterility of (AxB) $F_1$ hybrids[1].

| Female parent | Male parent | | | | | | |
|---|---|---|---|---|---|---|---|
| | 842B | 843B | 81B | 5I41B | 834B | IIIB | PT732B |
| 842A | S[2] | F[3] | S | F | F | F | F |
| 843A | F | S | S | -[4] | F | F | F |
| 81A | S | S | S | S | F | S | F |
| 5141A | F | F | S | S | F | F | F |
| 834A | F | F | F | F | S | F | F |
| 111A | F | F | S | F | F | S | F |
| PT 732A | F | F | F | F | F | F | S |

1. ICRISAT Center data: 1985 rainy season.
2. S = Sterile hybrid.
3. F = Fertile hybrids.
4. - = Not involved in this study.

Table 3. Fertility-sterility in (AxB) and (AxR) $F_1$ hybrids across three cytoplasmic systems and the genetic constitution of B and R lines.[1]

| Male parent | Female parent | | | | | |
|---|---|---|---|---|---|---|
| | $23A_1$ | $L66A_2$ | $L67A_3$ | Genetic constitution | | |
| 23 $B_1$ | S | F | F | $ms_1ms_1$ | $MS_2MS_2$ | $MS_3MS_3$ |
| $L66B_2$ | S | S | F | $ma_1ms_1$ | $ms_2ms_2$ | $MS_3MS_3$ |
| $L67B_3$ | S | S | S | $ms_1ms_1$ | $ms_2ms_2$ | $ms_3ms_3$ |
| $T13R_1$ | F | S | S | $MS_1MS_1$ | $ms_2ms_2$ | $ms_3ms_3$ |
| $L4R_1$ | F | S | S | $MS_1MS_1$ | $ms_2ms_2$ | $ms_3ms_3$ |
| L6R | F | F | F | $MS_1MS_1$ | $MS_2MS_2$ | $MS_3MS_3$ |

1. Modified from Burton and Athwal (1967). B lines have normal (N) cytoplasm; A lines have sterile (A) cytoplasms.

Table 4. Frequency of maintainer progenies in (BxB) and (BxR) crosses when tested on two male-sterile line testers.[1]

| Cross | Tester | No. of progenies Total | R | B | Others[2] | B (%) |
|---|---|---|---|---|---|---|
| (BxB) Cross[3] | 81 A | 85 | 0 | 69 | 16 | 81 |
| | 843 A | 64 | 6 | 12 | 46 | 19 |
| (BxR) Crosses[4] | 81A | 46 | 43 | 0 | 3 | 0 |
| | 843A | 34 | 29 | 0 | 5 | 0 |

1. Based on two seasons' data at ICRISAT Center.
2. Includes those progenies which were not consistently restorer (R) or maintainer (B) in both seasons.
3. Progenies from two populations on tester 81A and four populations on tester 843A.
4. Progenies from two populations on each tester.

observed. Forty nine $A_1 \times B$ crosses involving six A lines with Tift 23 $A_1$ cytoplasm, one with PT 732 A (probably non-$A_1$) cytoplasm, and their respective maintainers were studied for pollen shed and seed set (under selfing) at ICRISAT Center (Table 2). The pollen shed and seed set data were in good agreement: F,s shedding pollen gave good seed set and the $F_1$s producing no pollen failed to set seed under selfing. This study showed that:

- the maintainer of a given A, system male-sterile line was not necessarily a maintainer on the other A, system male-sterile lines;
- all the A, system maintainers except 834B were maintainers on 81 A, and 81B was maintainer on all the A, system male-sterile lines except 834 A; and
- 834B and PT 732B were restorers on other male-sterile lines except on their own respective male-sterile lines (Table 2).

These points imply the possible involvement of multiple major genes and modifiers in determining the male-sterility.

Studies in sorghum show that inheritance patterns of cytoplasmic male-sterility vary widely from one group of materials to the other. For instance, Stephens and Holland (1954) postulated more than two pairs of genes whereas Maunder and Pickett (1959) presented evidence for a single gene control. Based on pollen viability studies, Pi and Wu (1961) found indications of three types of genetic control: single gene control in five crosses, two gene control in two crosses, and complex inheritance in another two crosses. Alam and Sandal (1967) also found evidence for single gene control in three crosses, two gene control in two crosses, and three gene control in one cross in sudangrass *(Sorghum vulgare var. sudanense)*. In an extensive study in sorghum, Appadurai and Ponnaiya (1967) found cytoplasmic male-sterility under single gene control only in 4 out of 11 crosses; in the remaining 7 crosses, the inheritance appeared to be rather complex.

## Breakdown of Male-Sterility

A few heads shed pollen from the nodal tillers of Tift 23A, (Rao 1969). Burton (1972) made detailed studies of fertile sectors in Tift $23A_1$ heads and observed that the reversion to fertility could be due to nuclear mutation from recessive maintainer allele (ms) to dominant restorer allele (MS), as well as cytoplasmic mutation from sterile (A) to normal (N) cytoplasm. Further studies showed that about 97% of such reversions to fertility are mutations from (A) cytoplasm to (N) cytoplasm, and only about 3% are nuclear mutations from ms to MS allele (Burton 1977). Such reversions were observed both in A, and $A_2$ system male-sterile lines. Clement (1975) studied four male-sterile lines and found all reversions to fertility were mutational changes in the cytoplasm. He also observed up to 30-fold differences in reversion rates between lines (0.03/100 heads in ASM 3 to 1.02/100 heads in ASM 7), indicating the effect of genetic background on the stability of sterility-inducing factors in the cytoplasm. Singh and Laughnan (1972) found in maize that reversions to fertility were all due to changes in cytoplasm from S type to N type, and that there were large differences among genotypes for the rates of such changes.

Thus, it is clear that more than 97% of the reversions to fertility in male-sterile lines are due to changes in the cytoplasm from the sterile to the normal state. These changes would simply produce B-line equivalents, which would cause no problem by pollinating the plants of A-line. However, the reverted fertile plants in A-lines should be rogued to insure pure A-line stock at harvest for subsequent seed increase and hybrid seed production. The reversions to fertility due to nuclear mutations from ms to MS allele, although very rare, can cause considerable problems not only by contaminating A-line plants (whose progenies will also be fertile) but also by contaminating B-line plants, which in turn would no longer serve as maintainers. Limiting the number of generations increased from breeder seeds and timely roguing have been recommended as the best possible solutions to produce high quality A-line seed for hybrid production (Burton 1977). There is some evidence to show that higher temperatures and low relative humidity lead to a breakdown of male-sterility in pearl millet (Reddy and Reddy 1970, Saxena and Chaudhary 1977). Thus, multiplication of seed of male-sterile lines in areas with lower temperatures (<30°C) and high relative humidity are likely to significantly reduce the problem of pollen shedders in male-sterile lines.

## Breeding for Disease Resistance

### Downy Mildew Resistance

The longevity of some very promising and widely used male-sterile lines (Tift $23A_1$ and 5141 A) in the Indian hybrid program was severely reduced by downy mildew susceptibility. Thus, downy mildew resistance continues to be a major objective in male-sterile breeding. Several attempts made to induce resistance or to exploit residual variability for resistance in the susceptible male-sterile lines with high general combining ability have met with varying degrees of success.

At IARI, Tift 23B was irradiated with gamma rays and subsequent selection of progeny produced 5071 A, (Murty et al. 1975) which had short-lived resistance to downy mildew. Male-sterile line 81A was bred by irradiating Tift 23DB and selecting the progeny in the disease nursery at ICRISAT. In tests in the disease nursery at ICRISAT Center (Kumar et al. 1984), 81A showed *<2%* downy mildew as compared to 100% in Tift $23A_1$. Under high disease pressure, 81A had 8% downy mildew as compared to 97% in the susceptible check hybrid NHB 3 (Table 5).

The exploitation of residual variability for downy mildew resistance in the otherwise susceptible but promising male-sterile lines and their maintainers has also produced resistant lines with negligible changes in phenotypic characteristics. Selection in Tift $23A_1$ and Tift 23B produced resistant male-sterile line Pb 204A at PAU (Gill et al. 1981). Selection in susceptible 5141A produced Pb 211A at Ludhiana and 841A at ICRISAT Center. Pb 211A had 17% downy mildew as compared to 1% in 841A and 28% in unselected original stock of 5141 A. (S.D. Singh, ICRISAT, personal communication). Selection in three susceptible male-sterile lines and their maintainers (AKM 2021/BKM 2021, AKM 2026/BKM 2026, AKM 2068/BKM 2068) bred at the Fort Hays Branch Experiment Station, Kansas, USA, was undertaken at ICRISAT Center. The selection was most effective in AKM 2021/BKM 2021 which produced male-sterile line 842A with 1% downy mildew (Table 5) as compared to about 35% in the AKM 2021/BKM 2021. The selection was least effective in AKM 2026/BKM 2026 (D.J. Andrews, University of Nebraska, personal communication).

Table 5. Downy mildew incidence in male-sterile lines in downy mildew nursery, ICRISAT Center, rainy season 1984.

| Male-sterile line | No. of plants Total | No. of plants DM infected | Downy mildew (%) | Status |
|---|---|---|---|---|
| 81A | 264 | 20 | 8 | AICMIP release 1986 |
| 833A | 277 | 1 | >1 | AICMIP use since 1983 |
| 834A | 272 | 0 | 0 | AICMIP release 1986 |
| 841A | 245 | 3 | 1 | AICMIP use since 1984 |
| 842A | 114 | 1 | 1 | AICMIP use since 1983 |
| 843A | 173 | 20 | 12 | AICMIP use since 1983 |
| 852A | 380 | 2 | <1 | AICMIP test in 1985 |
| 111A | 249 | 4 | 2 | AICMIP release, early 70s |
| 5141A | 329 | 153 | 47 | AICMIP release, early 70s |
| NHB 3 | 255 | 249 | 97 | - |

K.N. Rai and S.D. Singh, personal communication.

At ICRISAT, the hybridization between B-lines with high general combining ability and varying levels of downy mildew resistance has recently produced a large number of maintainer progenies which have shown high levels of resistance in preliminary tests. These progenies at present form a very diverse base to breed male-sterile lines of various maturity and phenotypes. Of the several accessions that showed high levels of stable resistance in multilocational tests over years, two (700651 and P 7) were crossed with 843B to transfer the genes for stable resistance into 843B. The derived, agronomically elite B-lines will be tested multilocationally for resistance in disease nurseries and, if the resistance is high and stable, the lines will be utilized further in the male-sterile breeding programs.

### Smut Resistance

Recent studies have shown that a high level of smut resistance in one parent is generally adequate to produce smut-resistant hybrids (Table 6). Smut resistance is now available in agronomically elite

Table 6. Smut severity (%) in $F_1$ hybrids between susceptible (S) x resistant (SRL) lines.

| (S x R) $F_1$ hybrids | No. of hybrids | Number of hybrids in smut severity class | | | |
|---|---|---|---|---|---|
| | | <1 | 1-5 | 6-10 | >10 |
| 81B x SRL | 46 | 23 | 12 | 1 | 10 |
| 843B x SRL | 43 | 41 | 2 | 0 | 0 |
| 843A x SRL | 46 | 32 | 10 | 1 | 3 |

1. All the smut-resistant lines (SRL) were either free or had <1% smut; A and B lines had 32-70% smut severity.

lines and composites with formidable genetic diversity. These will be used to breed resistant pollinators to produce resistant hybrids, even in combination with the existing male-sterile lines, all of which are highly susceptible to smut. However, smut-resistant, male-sterile lines will increase the usefulness of existing pollinators (most of which are susceptible to smut) to produce resistant hybrids. The hybridization between 843B (a large-seeded, early-maturing, $d_2$ dwarf B-line) and smut-resistant lines has generated a wide range of maintainer progenies which have shown <5% downy mildew and smut in preliminary tests. Following this initial success, several resistant lines have now been crossed with 843B to further diversify the genetic base in the breeding program for smut-resistant, male-sterile lines.

## Ergot Resistance

There is evidence that ergot resistance is governed by polygenic recessives (Thakur et al. 1983b). Therefore, ergot-resistant hybrids cannot be bred unless both hybrid parents possess resistance (Table 7). There is further evidence that the source of resistance in both hybrid parents should be as similar as possible to insure a high level of resistance in hybrids (Rai and Thakur, ICRISAT, personal communication). An ergot-resistant line, ICMPE 134-6-9 (a maintainer on 81A), was converted into a male-sterile line. Like many other ergot-resistant lines, it is tall and matures late. Preliminary tests have not shown this male-sterile line to have high hybrid potential. The ergot-resistant lines are not very diverse, hence crossing this male-sterile line with currently available ergot-resistant pollinators is unlikely to exhibit an improved hybrid yield. This calls for the genetic diversification of the male-sterile lines and pollinators while breeding ergot-resistant hybrid parents.

Ergot-resistant lines (ERL) have been crossed with 843B, a $d_2$- dwarf, early-maturing, large-seeded maintainer line with a high general combining ability. The $F_2$ populations and backcross populations [(843B x ERL) x ERL] are at present being screened to select short ($d_2$), large-seeded, early-maturing, and ergot-resistant plants. Breeding ergot-resistant, male-sterile lines is obviously a slow process, since the polygenically-inherited resistance is available in agronomic backgrounds which are generally neither very diverse nor very promising.

## Rust Resistance

Numerous sources of rust resistance have now been reported (ICRISAT 1985). However, an $S_2$ progeny

Table 7. Ergot severity (%) in testcross hybrids based on ergot-resistant pollen parents and ergot-susceptible and ergot-resistant seed parents; ICRISAT Center Ergot Nursery.

| Year | Female parent | No. of F, hybrids | Percentage of hybrids in ergot severity class | | | |
|---|---|---|---|---|---|---|
| | | | <10 | 10-20 | 21-50 | >50 |
| Susceptible seed parents | | | | | | |
| 1980 | IIIA | 189 | 0 | 0 | 0 | 100 |
| | 5054A | 216 | 0 | 0 | 0 | 100 |
| | 5141A | 237 | 0 | 0 | 0 | 100 |
| Resistant seed parents | | | | | | |
| 1982 | ER $F_6$ | 49 | 92 | 8 | 0 | 0 |
| | $SC_2$(R)-5-4 (LES)[2] | 55 | 45 | 29 | 20 | 0 |

1. ER = Ergot resistant.
2. LES = Low Ergot Susceptible.
Source: R.P. Thakur and B.S. Talukdar, personal communication.

selected from IP 2696 has recently been identified as having a single dominant gene for rust resistance (Andrews et al. 1985). Further studies have shown this resistance to be stable across locations in India (ICRISAT 1985). Taking advantage of this simple genetic control, programs are underway at ICRISAT Center to introduce it into potential B-lines for breeding rust-resistant, male-sterile lines.

A male-sterile line, 852A, showed a very high level of rust resistance in a nursery at ICRISAT Center. This line is also highly resistant to downy mildew (Table 5) and a very good general combiner. If found stable across locations, the resistance from 852B will be used extensively in the male-sterile breeding program.

## Breeding Methods

### Breeding Maintainer Lines

Three essential features of a B-line considered useful for conversion into a male-sterile line are:

- high general combining ability,
- ability to produce a completely sterile $F_1$ hybrid on a male-sterile line when tested across locations and seasons, and
- ability to produce adequate pollen for the maintenance of an A-line under varying seed production conditions.

The evaluation for these traits is generally undertaken when the B-lines have become highly homozygous. Depending on the agroecological conditions at the location where the hybrids based on a male-sterile line will be cultivated, selection for numerous traits (e.g., downy mildew resistance, maturity, and plant height), are made in preceding generations. Selection for several other characters would seem quite desirable. These include peliminary evaluation for sterile $F_1$ hybrids made on an A-line to discard those which are not nonrestorers, and selection for high tillering, head volume, head compactness, medium to large seed size, moderate dormancy, resistance to grain weathering, good ear exsertion, lodging resistance, and good seed set. This comprehensive list of traits does not exclude consumer quality traits and resistance to other diseases, if these form part of a male-sterile breeding program.

Hard data do not exist to provide guidelines whether to follow recurrent selection or a classic pedigree breeding program. At the moment it seems that various forms of pedigree breeding used by almost all the major breeding programs have proved quite effective in producing and maintaining a wide range of useful, diverse B-lines. Recurrent selection to breed B-lines initially started with three composites in 1975 at Punjab Agricultural University, Ludhiana. These composites, however, have not been sufficiently exploited to breed B-lines. Because two of these composites have a narrow genetic base, all three have recently been merged, and another 30 B-lines added to widen the genetic base of the resulting composite.

In the long term, it would appear sensible for any breeding program to pursue both methods, but with the emphasis on pedigree breeding.

#### Combining Ability of Maintainer Lines

During generation advance, mild selection pressure is exerted at each inbreeding stage for the performance per se of the progenies. Although phenotypic performance is important, what matters more within the framework of agronomic acceptability, is the general combining ability of the B-lines. The published records do not show that B-lines in any pearl millet breeding program were tested for combining ability before embarking on their conversion into male-sterile lines. This explains to a large extent why many male-sterile lines bred after 5141A was released have not shown any better hybrid potential than 5141A.

Topcross tests have been recommended as the most practical approach to survey the combining ability of lines when the number of lines under test is too large (Simmonds 1979). No "universal" broad-based tester in pearl millet has yet been found. Limited data available at present show that combining ability of lines may largely depend on the tester (first author's unpublished data), and that perhaps the average of general combining ability estimates based on 3-4 broad-based testers may be much more reliable.

#### Conversion of Maintainers into Male-Sterile Lines

Maintainers are converted into male-sterile lines by conventional backcross breeding in which a maintainer is used as a recurrent male parent and a male-sterile line as a nonrecurrent parent. At least six backcrosses are required to insure acceptable similarity between maintainers and male-sterile lines. Where the maintainers and the donor male-sterile lines (source of sterile cytoplasm) are very different, 1-2 additional backcrosses may be required to achieve acceptable phenotypic similarity between the B- and A-line. Segregation and attendant genetic variation within the progenies in backcross series are expected. This would provide an opportunity for phenotypic selection of individual plants resembling the phenotype of maintainer line. Phenotypic selection and maintaining A/B pairs during the backcrossing will accelerate the conversion process.

## Future Directions

**Breeding.** Breeding early or medium-maturing male-sterile lines with short plants, medium to large seeds, and a good balance between tillering and head volume should form the primary objectives in most breeding programs. Early male-sterile lines would be particularly useful to breed hybrids intended to be grown in areas with likely terminal drought stress or intended to fit in multiple cropping systems. Increasing the yielding ability of male-sterile lines per se, improved general combining ability, and high levels of stable downy mildew resistance (for downy mildew endemic areas) should be an integral part of any male-sterile breeding program. Although of secondary importance, incorporating smut and ergot resistance should also be attempted to mitigate the yield losses from these two head diseases.

Cytoplasmic Diversity. Since evidence suggests there is no relationship between Tift $23A_1$ cytoplasm and downy mildew, genetic diversification with Tift 23A, cytoplasm can continue. However, to avoid any catastrophic diseases from cytoplasmic uniformity, alternative sources or systems of cytoplasmic male- sterility should be utilized. Various sources of cytoplasms currently available should be characterized for the nature and magnitude of cytoplasmic diversity through the application of biochemical techniques. At the same time, the search should continue for alternative sources of cytoplasm in accessions and in segregating populations derived from divergent crosses. Attempts should also be made to induce cytoplasmic male-sterility as already reported in pearl millet (Burton and Hanna 1982) to diversify the cytoplasmic base of male-sterile lines.

**Environmental Factors.** The inheritance of cytoplasmic male-sterility and fertility restoration under varying environmental conditions should be studied. The effects of environmental factors, particularly temperature regimes and humidity levels, on the breakdown of male-sterility should also be examined.

Isonuclear Lines. Isonuclear lines should be created and used to study the effects of different sources and systems of cytoplasmic male-sterility on various plant characters and disease incidence.

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# Discussion

Discussion following the paper on genetic diversity in pearl millet covered reasons for the wide diversity of African genetic resources (diverse climates and agricultural systems); the maintenance and use of that diversity by selfing, sibbing, and cluster bagging (200 plant minimum); the widespread usefulness of certain specific germplasm sources, and use of other diversity that exists in wild relatives.

The performance of improved varieties under traditional management in farmers' fields was the primary topic following the paper on landrace improvement. Evidence has shown no advantages to new varieties under such conditions (compared to trials using improved management), and it was concluded that improvements in management would have to accompany, or even precede, new varieties). It was confirmed a reasonable objective to breed new varieties which perform as well as traditional ones under no-input management, but which respond well to improved management.

After the paper on recurrent selection methods, the discussion covered the choice of testers for use in several reciprocal recurrent selection schemes in the context of the theoretical and practical effects of using elite or poor inbreds as testers. The role of linkage blocks in the determination of actual gains in response to recurrent selection which are not fully accounted for in genetic models was discussed.

The discussion of the paper on hybrids in India focused on the reasons for low adoption rates of hybrids in stress environments. Adoption has been high (85%) in Gujarat because of an intensive initial extension effort, and the better performance of hybrids in the drier areas, as well as in more favorable climates. Lack of adoption elsewhere was considered a result of insufficient education of the farmers, insufficient seed supplies (but not the cost of seed), and to the common necessity of resowing, often several times.

Following the final paper dealing with breeding male-sterile lines, the discussion dealt mainly with the problem of downy mildew susceptibility. Early male-steriles (and pollinators) were not thoroughly tested for downy mildew resistance, but even though 5141A had been tested, it subsequently became susceptible. Greater genetic diversity of male-sterile lines was considered a necessity, but the greater vulnerability of single-cross hybrids will probably remain. India has a sufficiently large research, extension, and seed production capability to exploit hybrids, but the African countries of the Sahel do not, and therefore the genetic stability of open-pollinated varieties may be preferable. There was also discussion on whether the present classification of male-sterile cytoplasm, which originated in the 1960s, is valid. Current evidence suggests a more complicated picture.

# Biological Factors Affecting Pearl Millet

# Facteurs biologiques affectant le mil

**O. Sidibe**

La presente session consacree aux facteurs biologiques affectant le mil examinera cinq communications relatives aux trois principaux domaines concernant la pathologie, Tentomologie et la microbiologic du sol.

La contrainte majeure au developpement de la production du mil en Afrique de l'Ouest et en Inde sont les maladies. Leur incidence varie selon les conditions eco-climatiques, les regions et les annees.

Parmi les maladies les plus import antes, il faut noter le mildiou *(Sclerospora graminicola)* dont l'importance est plus grande en Afrique de l'Ouest qu'en Inde. Avec I'introduction des hybrides en Inde, dans les annees 1970, le mildiou et Tergot *(CJaviceps fusiformis)* sont devenus des facteurs limitants importants en milieu reel.

Apres le mildiou et Tergot, il faut souligner le charbon (*Tolyposporium penicillariae)* qui est tres important dans certaines zones agro-ecologiques d'Afrique de l'Ouest et de l'Inde.

En Afrique australe, nos connaissances sur les maladies du mil sont limitees. Mais compte tenu des conditions eco-climatiques, la baisse importante des rendements est attribuable aux parasites precites.

Dans des conditions de basses temperatures particulierement apres la floraison, la rouille *(Puccinia purpurea)* pourrait etre egalement un s6rieux probleme en Afrique orientale et australe et en Inde.

Pour ce qui est des insectes ravageurs, leur importance n'est plus a demontrer et tout paysan marquera son inquietude sur les degats qu'ils causent. Aussi bien pour les maladies que pour les insectes, leur importance economique n'est pas encore bien connue, mais l'incidence elevee et la nature des degats indiquent Timportance de certains d'entre eux, par exemple la mineuse de Tepi *(Raghuva albipunctella)* et le foreur des tiges *(Acigonia igncfusalis).*

C'est egalement Toccasion d'attirer l'attention sur d'autres facteurs biologiques qui reduisent considerablement la production du mil dans nos pays. II s'agit des mauvaises heroes, des sauteriaux, des criquets, des oiseaux, des gerboises, des bacteries et des virus. II est aussi necessaire de determiner Timportance economique de chaque facteur ou groupe de facteurs biologiques, car leur incidence varie d'une zone agro-ecologique et d'une annee a Tautre.

Enfin, il faut noter Tutilisation des microbes des zones de la rhizosphere en vue d'augmenter les rendements. C'est un nouveau domaine d'investigation pour le mil bien qu'il soit connu que certaines bacteries du sol fixent l'azote atmospherique et les mycorhizes augmentent la disponibilite du phosphore. Sur ce point, il faut souligner les importants travaux realises en Inde dont les resultats sont en cours de vulgarisation en milieu paysan.

De meme les nombreuses etudes et recherches sur les parasites n'ont pas permis d'elaborer des paquets de recommandations susceptibles d'interesser le paysan qui tiendraient compte de tous les aspects socio-economiques et de protection des ecosystemes et de Tenvironnement. A cet effet, Tapproche multidisciplinaire preconisee par la lutte integree et I'intensification de la formation et de Tinformation donnees aux vulgarisateurs pourraient contribuer a resoudre le probleme.

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## Moderator's Overview

# Biological Factors Affecting Pearl Millet

**O. Sidibe**[1]

This session includes five papers concerning three main areas of pathology, entomology, and soil microbiology.

Diseases cause much damage to pearl millet crops in West Africa and India. Disease incidence varies according to the ecoclimatic conditions, region, and year.

Downy mildew *(Sclerospora graminicola)*, a major disease, is more prevalent in West Africa than in India. After the introduction of hybrids in India in the 1970s, it has been noticed that mildew and ergot *(Claviceps fusiformis)* seriously reduce pearl millet yield. Smut (*Tolyposporium penicillariae)* is another disease that is common in certain agroecological zones of West Africa and India.

There is not much information on the disease situation in East and southern Africa. It has been observed, however, that in similar ecoclimatic conditions, these diseases are responsible for substantial yield losses here.

In West and southern Africa, and in India, rust *(Puccinia purpurea)* can become a serious problem under low-temperature conditions, particularly after flowering.

Insect pests like spike worm *(Raghuva albipunctella)* and stem borer *(Acigona ingefusalis)* cause a lot of damage. As in the case of crop diseases, the economic importance of pests has not yet been accurately determined.

Other yield-reducing pests that should be considered are weeds, grasshoppers, locusts, birds, and jerboas. Bacteria and viruses can cause serious diseases. The economic importance of each of these factors or group of factors should be determined since their incidence varies each year from one agroecological zone to another.

The use of microbia in the rhizosphere for yield increase is a relatively new area of research, although it has been well known that certain soil bacteria can fix atmospheric nitrogen in the soil and that mycorrhizae increase phosphorus availability. The significant work done in India on the subject is being applied in farmers' fields.

Many studies have been carried out but have not yet resulted in any solutions suitable to farmers, which also consider socioeconomic aspects and protection of the ecosystems. The multidisciplinary approach recommended for integrated control and intensified training and information given to extension agents could provide a solution to the problem.

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# Biology and Epidemiology of Downy Mildew of Pearl Millet


**H. S. Shetty**[1]



## Abstract

Sclerospora graminicola *is an important pathogen on pearl millet, prevalent wherever the crop is cultivated in the semi-arid tropics. The primary inoculum source is seed or soil, but the secondary spread is by airborne sporangia. Sexually produced oospores can survive under dry conditions for more than 5 years. Asexual propagules are ephemeral and fragile. Their production, liberation, deposition, and germination are greatly influenced by environmental factors, as are penetration, infection, and disease development. Epidemiological studies indicate that dew formation is the most important factor that governs disease development. In addition, disease incidence positively correlates with relative humidity and maximum temperature.*

S. graminicola *is an obligate parasite. Axenic growth (culture in artificial medium) of the fungus has not been possible thus far. The fungus was cultured in association with its host tissue callus (dual culture) and the life cycle was completed successfully in vitro. Inoculated seeds and systemically infected shoot tips of the host are good source materials to establish the dual culture on a semi-synthetic medium. The dual culture technique can be utilized to screen host cultivars against downy mildew reaction. Vegetative mycelium of* S. graminicola *is coenocytic. During sporogenesis nuclei migrate to sporangiophores and sporangia to form multinucleate structures. Zoospores formed from sporangia are uninucleated. There is no nuclear division in the zoospores, sporangia, and sporangiophores. However, nuclear divisions are common in the germ tubes of zoospores during germination.*

## Résumé

**Biologie et épidémiologie de mildiou chez le mil : Sclerospora graminicola** *est un important pathogène du mil qui sévit partout où cette plante est cultivée dans les zones tropicales semi-arides. Les semences ou le sol servent de source primaire d'inoculum; les sporanges véhiculés par le vent sont responsable de la diffusion secondaire du pathogène. Les oospores produites par voie sexuelle peuvent résister en conditions sèches pendant plus de cinq ans. Les propagules asexuées sont éphémères et fragiles; leur production, diffusion, dépôt et germination sont influencés en grande mesure par les facteurs environnementaux, tout aussi bien que la pénétration et l'infection par le pathogène et l'évolution de la maladie. D'après les études épidémiologiques, la rosée est l'élément le plus important dans le développement de la maladie. Il y a une correlation positive entre l'humidité et la température maximale, d'une part, et l'incidence de la maladie, d'autre part.*

**S. graminicola** *est essentiellement un parasite. Son développement axène en milieu artificiel n'est pas encore possible. Le champignon était élevé en association avec un cal du tissu hôte (culture double); le cycle de vie était achevé in vitro. Les semences inoculées et les sommets des pousses ayant subi une infection systémique offrent un excellent matériel pour l'établissement de cette culture double dans un milieu semi synthétique. Cette technique sera utile à cribler les cultivars pour leur réaction au mildiou. Le mycélium de*



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*S. graminicola est cénocytique. Pendant la sporogenèse, les noyaux se déplacent aux sporangiophores et aux sporanges afin de former des structures multinuclées. Les zoospores issues des sporanges sont uninuclées. Les zoospores, les sporanges et les sporangiophores ne présentent pas de division nucléaire, qui se produit cependant dans les tubes germinaux des zoospores pendant la germination.*

## Introduction

Downy mildew of pearl millet *(Pennisetum americanum)* is incited by *Sclerospora graminicola* (Sacc.) Schroet., which is the type species of the genus.

Although *S. graminicola* has been recognized as an important pearl millet pathogen since the early part of this century, it received relatively little attention until the early 1960s. Even today international comparative research on the biology and epidemiology of this pathogen and the disease it causes is needed to expand control techniques.

Comprehensive reviews of research on the disease up to 1976 are available (Nene and Singh 1976, Safeeulla 1976b), but information on the inoculum sources, climatic influence, and the disease cycle has been misunderstood so that the epidemiology of the disease has been seriously misinterpreted. In this paper, current knowledge on the origin and distribution, survival of the infective propagules, sporulation, dispersal and infectivity, dual culture, and cytology of the pathogen are presented and discussed.

## Geographic Distribution

*S. graminicola* is widely distributed in the temperate and tropical areas of the world, including Europe, the Middle East, Africa, and Asia. Although the fungus has been reported as occurring in the USA, it has not been found in pearl millet in that country. Since its discovery by Schroeter (1879), it has been recorded in more than 20 countries (Safeeulla 1976b). Thus far there is no report of the fungus in South America and Australia. The principal host of *S. graminicola* is pearl millet, which originated in Africa (Harlan 1975, Brunken et al. 1977). Information on the most frequent sources of resistance to 5. *graminicola* (Williams and Singh 1979) supports a hypothesis of African origin with dissemination to other countries possibly by seedborne inoculum. However, it is also possible, but less likely, that the pathogen originated in indigenous Indian grasses, and moved to pearl millet when this crop was introduced from Africa. The present widespread occurrence in Africa would then be explained by its introduction long ago on plant products from India, with the many resistance sources among African pearl millet merely reflecting a long period of coevolution in regions with a wide range of host variability (Williams 1984). On the contrary, Shaw (1981) suggested that *S. graminicola* has a temperate origin because it is circumpolar on species of *Setaria*, and that it has become adapted to plants in tropical habitats, particularly pearl millet. He also believes 5. *graminicola* to be not only primitive, but to have been circumpolar on the Paniceae since Pleistocene times because it has coevolved in many locations with species of *Setaria*, *Panicum*, *Chaetochloa*, and *Pennisetum*. Shaw also said that *S. graminicola* has occurred in Africa since that continent was much more temperate, evolving and adapting to the changing climate along with its host.

## Inoculum Sources

Pearl millet is an annual crop, but the nature of the perennation of the pathogen during the off-season was not clearly understood. The obligate nature rules out the possibility of it perennating on the straw, and the fragile nature of the sporangium makes it unsuitable for survival for more than a few hours. Logically, wild hosts, the seed, and soilborne oospores are the sources of inoculum for the recurrence of the disease year after year.

### Wild Hosts

About 14 species of graminaceous plants belonging to eight genera are known to be susceptible to 5. *graminicola* (Safeeulla 1976b). The role of wild hosts in offering sporangial inoculum each growing season to the fresh crop is not yet clear. However, Suryanarayana (1965) made some observations on 5. *graminicola* occurring on *Setaria verticillata* (Linn.) P. Beauv, a common annual grass found during the rainy season. He made a detailed study and observed abundant production of oospores and sporangia on this common Indian grass, which raises the possibility of *S. verticillata* serving as an alternative host for downy mildew of pearl millet.

## Seed and Soilborne Inoculum

The seed or soilborne inoculum acts as a primary inoculum source to cause the first expression of the disease in a host population by infecting the seedlings. Severely infected young seedlings mostly die within 30 d without producing oospores. Michelmore et al. (1982) reported heterothallism in *S. graminicola* which indicated that if compatible mating types colonize the same host's tissue, oospores are produced even in 12-day-old seedlings. Perhaps compatible mating types are not colonizing the same leaf during the early growth period of the host seedlings. But plants which express disease symptoms about 20 d after sowing due to soilborne oospores, seedborne inoculum, or secondary infection by airborne sporangia (Reddy 1973, Subramanya et al. 1982), produce millions of sporangia during earlier growth periods (Figs. 1 and 2). However, towards the end of the growing season, they give rise to numerous oospores in the infected leaves, which are perennating structures. The oospores produced in the leaves get mixed with soil or seeds to initiate the disease in the next season. The airborne sporangia can infect the unfertilized florets during the heading stage of the crop, and this might lead to the mycelium establish-

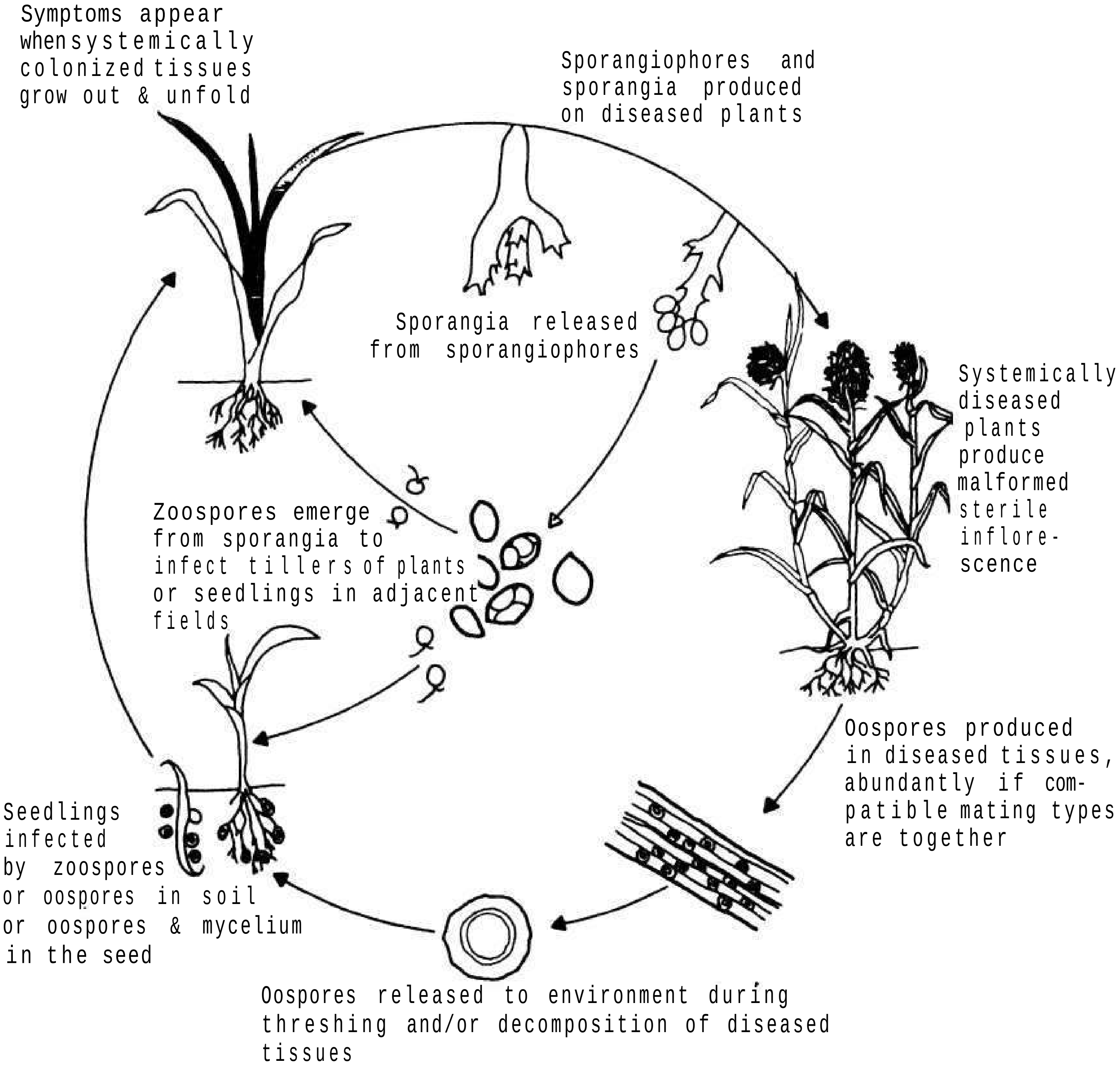


**Figure 1. Disease cycle of pearl millet downy mildew.**

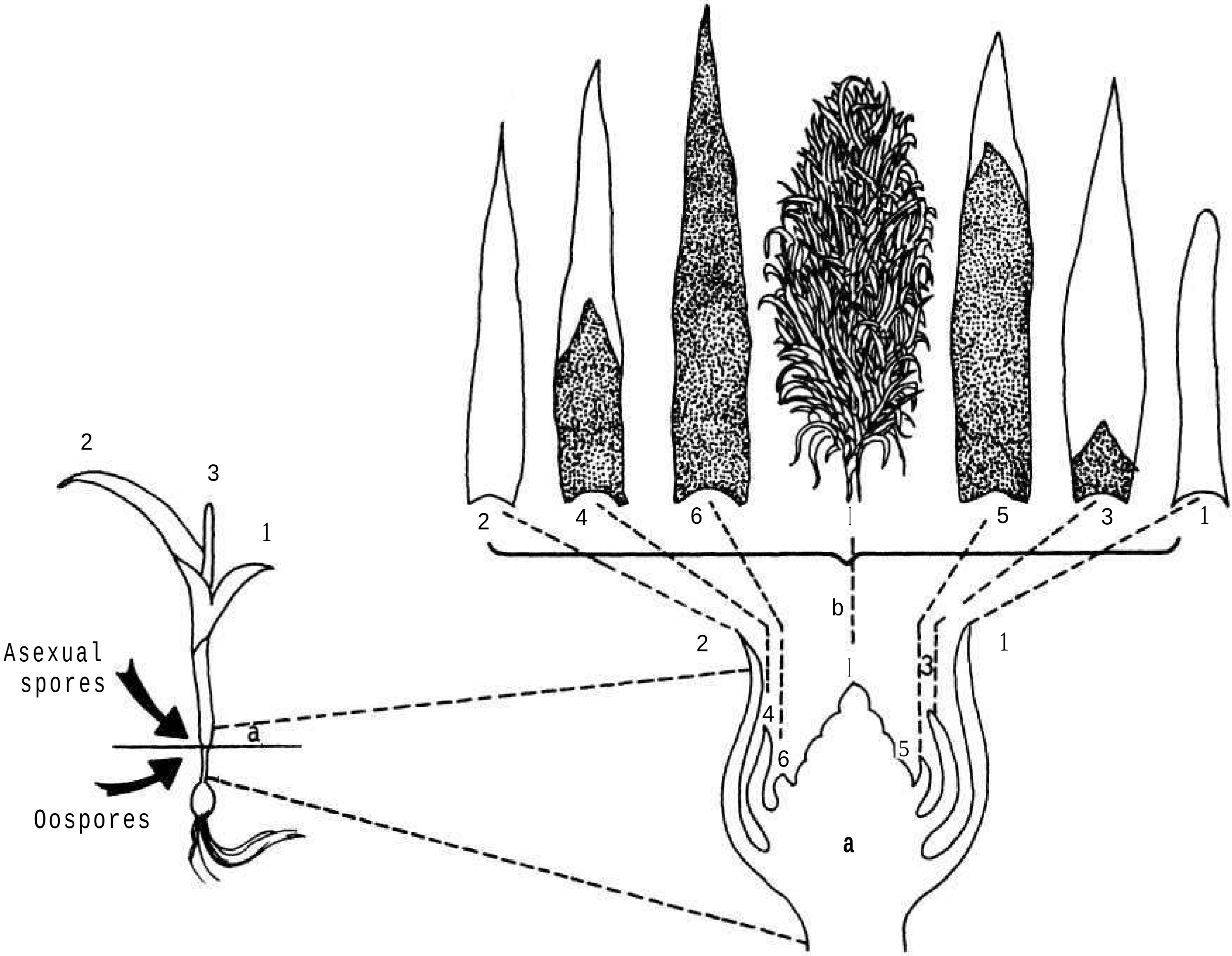


**Figure 2. Progressive development of leaf symptoms in pearl millet colonized by *Sclerospora graminicola* (a) the pathogen colonizes the growing point of a seedling; (b) the tissues differentiated after colonization appear systematically diseased when the organs subsequently grow out and unfold.**

ment in the seeds (Subramanya et al. 1981). This establishment might also be due to systemic infection. As such seeds apparently look healthy, they might be able to initiate the disease in the next season. As a consequence, it is important to realize that seed produced in the partially malformed heads are known to contain internally borne mycelium. Although seeds on such heads are usually not selected for seed purposes, florets infected by sporangia do not look any different from those which are not infected, so seed from them could easily be selected unknowingly for planting.

## Seed as Inoculum Source

Conflicting reports about the seedborne nature of downy mildew in pearl millet have generated a lot of interest among pathologists. There are many reports on the association of the pathogen with the seed to serve as a primary infection source, in addition to oospores present in the soil (Arya and Sharma 1962, Suryanarayana 1962, Singh and Pushpavathi 1965, Tiwari and Arya 1966, Sundaram et al. 1973, Safeeulla 1976b). There are conflicting reports about mycelium in the embryonic tissue. Shetty et al. (1980b) reported that HB 3 race invariably showed downy mildew mycelium in seed tissues, but the Mysore local race did not infect the pearl millet seed. It is likely that the pathogen prevalent in the areas where the seeds were collected belongs to a race which does not infect the seed. Shetty et al. (1977, 1978, and 1980a) demonstrated the seedborne and seed-transmitted nature of 5. *graminicola* in pearl millet seeds. They demonstrated that inoculum may be present in pearl millet seeds either as external oospores, or in the form of internal dormant mycelium. The standard procedures for detecting seedborne inoculum of *S. graminicola* were evolved by Shetty et al. (1978). Oospore inoculum on the seed surface was detected by using the washing method and mycelial infection by the modified embryo count procedures. Out of 93 seed samples obtained from different sources, 59 were surface contaminated with oospores whose viability was checked by the tetrazolium chloride (TTC) test.

Although mycelial infections were detected in all parts of the seed tissue, tests conducted by Shetty et al. (1980a) indicated that only the mycelium present in the embryo takes part in causing seedling infection. A direct correlation was observed between the percentage of infected embryos and percentage of plants that expressed symptoms (Shetty et al. 1980a). However, Williams et al. (1980) questioned whether the surface sterilization technique used actually killed oospores on the seed surface.

### Soilborne Oospores as Inoculum Source

Large numbers of oospores are produced in downy mildew-infected plants which can easily get incorporated in the soil during natural shredding of the crop or during harvesting.

The survival of oospores in soil has been investigated by several workers, with details provided by Nene and Singh (1976). Oospore survival in soil is reported from 8 months to 10 years. In the absence of a reliable and repeatable technique for germinating oospores, all tests for oospore longevity are based on the infectivity test. The TTC test (Shetty et al. 1978) can be very effectively employed to determine viability of oospores during storage. However, Williams et al. (1980) were of the view that the TTC test is unreliable to determine the viability of *graminicola* oospores.

Several workers claim to have germinated oospores of *S. graminicola* under laboratory conditions. Hiura (1930), Evans and Harrar (1930), Chaudhri (1932), Tasugi (1933), and Suryanarayana (1956), reported the production of germ tubes from the germinating oospores, while Pande (1972), Safeeulla (1976b), and Sundaram and Gurha (1977) reported the indirect germination of oospores in the sense that no germ tubes were produced from such germinating oospores. However, the author has repeated all existing techniques to germinate oospores, in addition to several other methods, but with little success.

Commonly, all oospores from a particular source do not germinate at the same time. Safeeulla (1976b) noticed that five successive crops grown on soil containing oospore inoculum (added at the beginning) were infected. The importance of host factors in stimulating oospore germination has been realized in several downy mildew pathogens (Kaveriappa 1973, Pratt 1978, Shetty and Safeeulla 1980). Specific host factors for oospores to germinate rule out the possibility of controlling the disease by crop rotation. Even avoiding cultivation of this staple crop for 1 -2 years may be of no use because soilborne oospores can remain infective for several years.

It is possible to isolate soilborne oospores by flotation methods, but no correlation can be made between disease severity and oospore density in the soil. Pratt (1978), who worked on *Peronosclerospora sorghi (*Weston & Uppal) C.G. Shaw came to a similar conclusion. This low correlation between oospore densities and disease incidence may be due to the percentage of oospores in the soil that are viable and able to germinate, and the secondary spread of the disease due to airborne sporangia.

## Infectivity of Soilborne Oospores

It is generally agreed that oospores have a higher infection rate after weathering, and that 1-year-old oospores infect at a higher rate than fresh oospores or those more than 1 year old. Early workers believed that oospores have a dormant period. However, Safeeulla (1976b) reported that newly formed oospores infected 55% of the plants. Borchhardt (1927), Chaudhury (1932), Suryanarayana (1952, 1963), I A R I (1955, pp. 87-99), and Bhandar and Rao (1967), all of whom tested the viability of the oospores, incorporated them into the soil and observed the disease. Siddiqui and Gaur (1978) observed that oospores coated on seed and incorporated in the soil infected plants. However, after the initiation of systemic infection from the oospores often insufficient care has been taken to prevent secondary infection. So high incidences of infection have been found. The author's study demonstrated that the plants which received both oospore and sporangial inocula were 68% diseased, but those which received only oospore inoculum showed 31% disease incidence and those which received only sporangial inoculum showed 36% disease incidence (Subramanya et al. 1982).

The airborne behavior of oospores of 5. *graminicola* has not been reported thus far. It is possible, however, that wind plays an important role in dislodging oospores from shredding leaves and disseminating them to neighboring areas. It is also possible that whirlwinds, common in the semi-arid tropics during April and May, carry oospores from field to field. Dissemination would be effective because the off-season fields would be free of crops, and oospores and oospore-laden debris are dry and light. Frederiksen and Rosenow (1967) and Rajasaab et al. (1979) reported the airborne nature of *P. sorghi* oospores.

## Secondary Infection

The progress of the disease in a single season initiated by primary inoculum sources depends on recurring infection cycles involving secondary inoculum. Once the host becomes infected, it produces several crops of sporangia which cause secondary infection in the same season.

*S. graminicola* produces sporangia in large numbers under humid conditions. Much work has been done on the influence of environment on sporulation (Weston 1929, Safeeulla and Thirumalachar 1956, Suryanarayana 1965).

The author's work on this pathogen has shown that sporulation isinfluenced by several factors. The process of sporulation can be classified into two phases: inductive and formative. During the inductive phase, the pathogen in the host tissues prepares itself for asexual reproduction. The formative phase begins when the sporangiophores start emerging from the stomata, and continues up to the dissemination of the sporangia. Environmental factors, particularly humidity, can influence sporulation during the formative phases, while temperature can influence sporulation both during the inductive and the formative phases. Sporulation can occur between 14 and 30°C (Safeeulla 1976a). No sporulation was observed below 12°C or above 30°C, and sporulation was maximum at 23°C and 100% RH. It was also evident that at low temperatures (< 23°C), the time required for sporangia production was longer than at 23°C. The night temperature at Mysore (South India) during the cropping season ranged from 20-25°C. At all these temperature profiles, sporulation can occur within 4-6 h. Maximum sporulation was observed at 100% RH, but very little at 70% RH. The duration of the inductive period was almost the same at all RH profiles, but at 100% RH, the formative phase was as short as 2 h 25 min. With RH decreased to 80%, the duration of the formative phase increased. Probably the desiccation at low RH and a high rate of metabolic activity are responsible for the delay in sporulation at low RH and higher temperature.

Free water on the leaf surface inhibits sporulation of *S. graminicola,* but Safeeulla and Thirumalachar (1956) observed the proliferation of sporangiophores. Under such conditions, the absence of free aeration might be responsible for the inhibition of sporulation.

Some of the author's experiments have also demonstrated that prior exposure of the leaves to light is a must for sporulation. Infected leaves from plants stored in darkness for 12 h failed to sporulate. A minimum 2-hour exposure to light prior to incubation at 24°C, 100% RH in darkness, was essential for infected leaves to sporulate. However, with the increase in exposure duration, the number of sporangia produced per unit area also increased. This indicates that the photosynthates produced during the period of light exposure are utilized for the actual phase of sporulation, which obviously needs high nutrition for the process of wall and protoplast synthesis (Subramanya 1984).

Under favorable conditions Safeeulla (1976b) recorded the production of 35 000 sporangia $cm^{-2}$ on the infected leaf and as many as 11 crops of sporangia formed on successive nights.

Melhus et al. (1927) found that sporangia are forcibly discharged up to 2.5 m from the sporangiophores. Twisting of sporangiophores during the process of liberation of sporangia into air has not been observed so far. Sporangial liberation can occur continuously at 24°C, 100% RH, and darkness. However, the effect of varying temperatures and light on spore liberation has not been studied. After liberation, some sporangia may fall to the ground and some may be carried by moving air (Fig. 3).

The sporangium remains airborne after take off from the sporangiophores until it gets deposited on a substratum. The viability of the sporangium is determined by temperature, humidity, and wind speed. Analysis of weather at Mysore indicated that, during most of the year, nights are best suited for sporulation. Most days have a high RH (above 95%) between 00:00 and 06:00, with a temperature of 20-24°C, and a wind speed of 20-160 m $min^{-1}$. Subramanya and Safeeulla (1981) showed that at 98% RH, 22°C, and 50 m $min^{-1}$ wind speed, about half of the sporangial population can remain viable for more than 1 h and at least some of the sporangia will be viable for 6 h. At night time extremes for temperature and RH in Mysore during the cropping season,

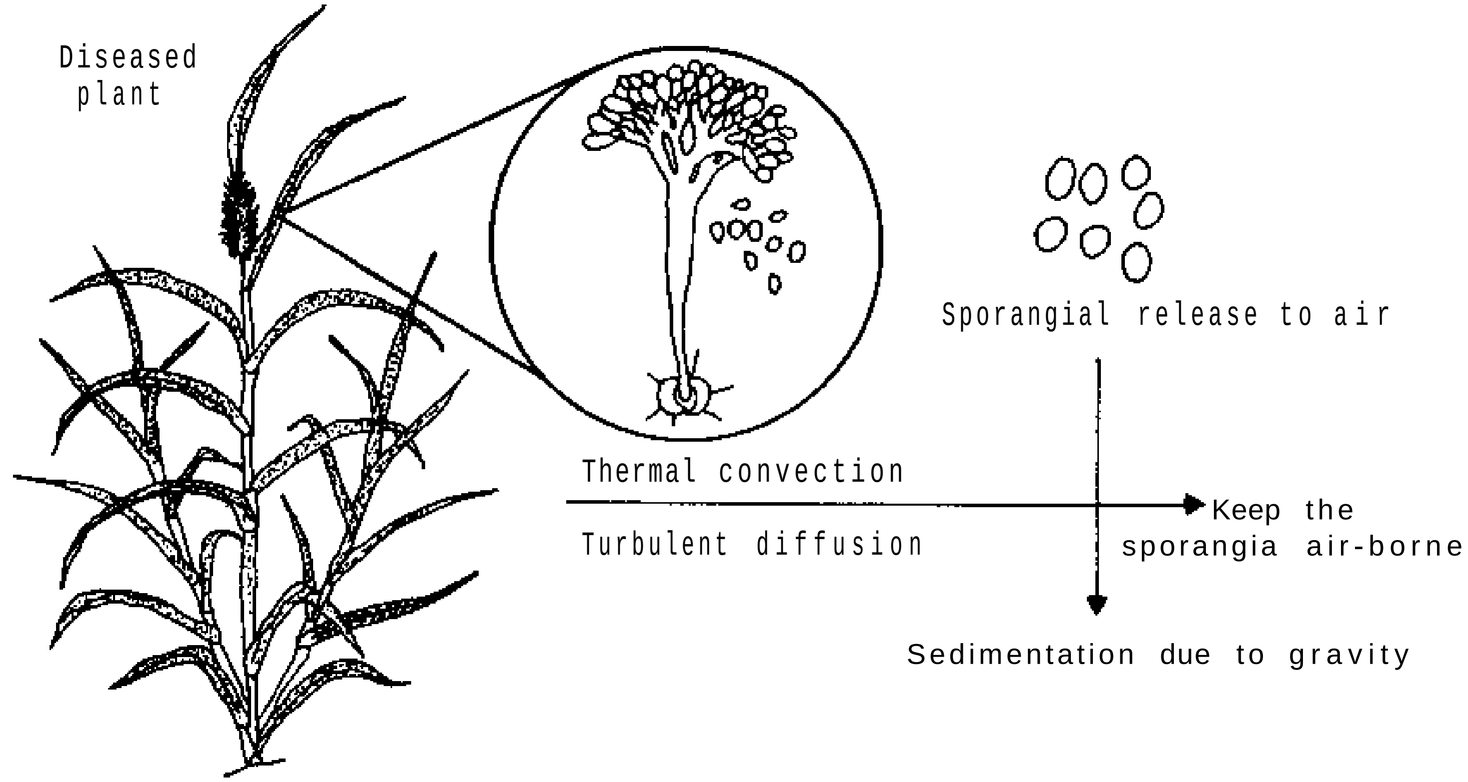


**Figure 3. Air-borne state of *Sclerospora graminicola.***

at least a few of the sporangia will be viable for 2.5-6.0 h. At a wind speed of 50 m $min^{-1}$, the sporangia can travel over 3 km in an hour and still be viable.

Further, the environmental conditions best suited for sporulation are also best suited for efficient dispersal. Subramanya (1984) demonstrated that during the hottest nights of the year (April), the sporangia could remain viable for 3 h 15 min and the half-life was 1 h. Even at this range, the viable sporangia can travel at least 1 km. Singh and Williams (1980) observed the spread of the inoculum up to 340 m in the rainy season, but the disease spread only up to 80 m from the inoculum source in the postrainy season. Mayee and Siraskar (1980) observed the spread of the disease up to 2 km. Obviously, there is wide variation in the distance the pathogen can spread by air, perhaps due to the nature of the inoculum source and the weather. Heavy inoculum sources and favorable weather place more sporangia in the air, with more moved from the source.

The fate of sporangia which fall to the ground after take off from the sporangiophores was not known until recently. Safeeulla (1976b) speculated that these sporangia may liberate zoospores in the wet soil, which in turn may infect healthy plants through the roots. This is important because zoospores can very effectively infect through roots. Ramesh (1981) observed that the sporangia can germinate in the soil and produce zoospores which can survive, move against gravity in the soil, and remain infective up to 5 h. This shows that sporangia/zoospores deposited on the soil may act as a secondary source of inoculum, causing infection in the seedling stage of the plant during the rainy season.

Zoospores exhibited a strong affinity towards host plant roots, and less affinity towards the nonhost roots. The complete process of infection starting from zoospore germination, formation of the appressorium and infection peg, further development in the epidermal cells of the host, and subsequent colonization, was observed in host plant roots. In nonhost monocotyledenous plants, although the fungus penetrated the epidermis, it failed to colonize the root tissue (Subramanya et al. 1983).

Reddy (1973) established the airborne nature of the sporangia, but details such as horizontal and vertical diffusion of sporangia in the air have not been worked out. Shenoi (1976) observed maximum deposition of conidia of *P. sorghi* at the tips of the sorghum leaves. Sporangia may also be deposited at the leaf tips of pearl millet plants. At Mysore, dew periods of 2-8 h in a day are frequent (Shenoi and Ramalingam 1979), and dew deposited on the leaves can act as a germination medium for sporangia on the leaves to liberate the zoospores. The zoospores swim towards the leaf whorl of the plant to cause infection (Subramanya et al. 1982) (Fig. 4).

As a rule, sporangia germinate by producing

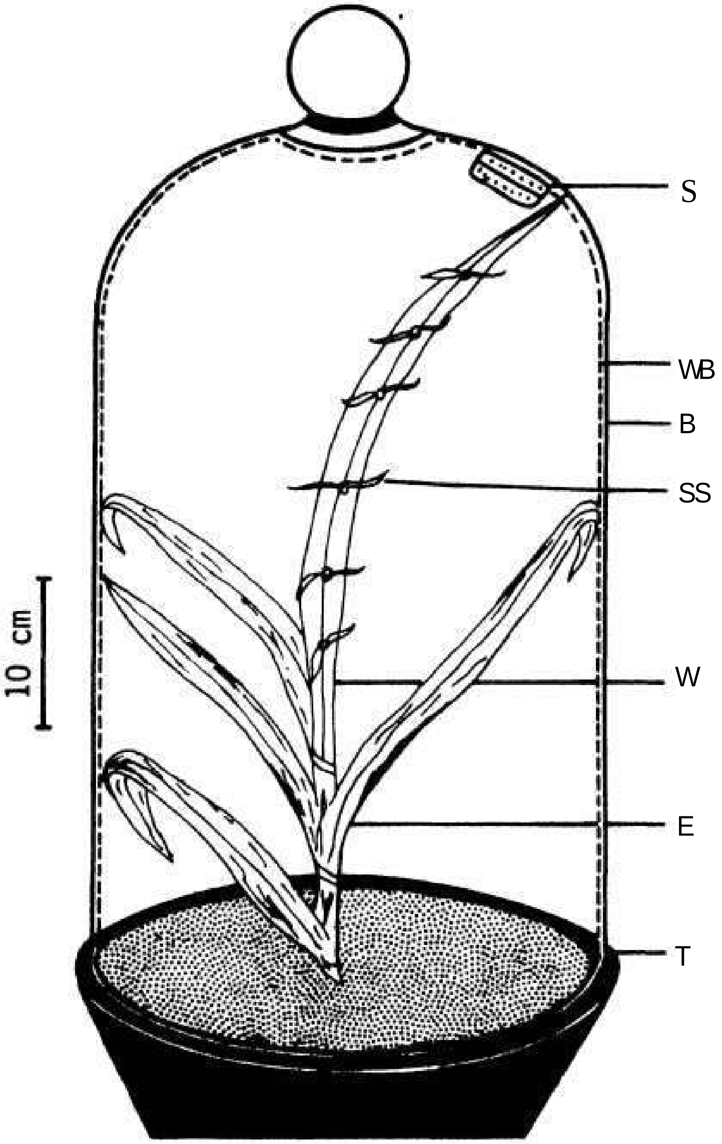


**Figure 4. Figure assembly to demonstrate the movement of zoospores on the leaf surface (S = sporulating leaf, WB = wet blotter, B - belljar, SS = susceptible seedling, W = whorl, £ = Excised plant, T = trough).**

zoospores (Hiura 1935, Suryanarayana 1965, Safeeulla 1976b), but occasionally, production of the germ tube has been noted. Hiura (1935) reported that the pathogen from Italian millet had a minimum sporangial germination temperature of 5-7°C, an optimum of 18°C, and a maximum of 30-35°C. Melhus et al. (1927) noticed that an isolate of *S. graminicola* from *Setaria viridis* (Linn.) P. Beauv had an optimum temperature requirement of 17-18°C for sporangial germination. Suryanarayana (1965) noticed that sporangia germinate readily in drops of distilled water, liberating 3-8 zoospores. The formation and liberation of zoospores from sporangia took 35-180 min. Only the fully mature sporangia germinated, but none however, germinated directly to produce germ tubes. Safeeulla et al. (1963) noted that sporangia of *S. graminicola* from pearl millet germinated at 18-29°C, with an optimum of 24-25°C, while Suryanarayana (1965) reported 22-23°C as optimal. Germination tests with sporangia in both light and dark germinated at 80-90% (Suryanarayana 1965). Researchers seem to agree that sporangia require free water for germination. Production of 3-8 zoospores (Suryanarayana 1965) and 3-11 zoospores (Bhat 1973) from a sporangium have been noted, however Shetty and Ahmed (1981) reported 1-3 zoospores produced from the sporangia of the HB 3 race of *S. graminicola.*

Zoospores produced by germinating sporangia, which normally swim for 30-60 min, undergo encystment leading to retraction of the flagella, and then germinate by producing germ tubes. Appressorium production by the germ tubes when they are still in water suspension has been noted (Safeeulla 1976b). Suryanarayana (1965) noticed that germinated zoospores swim freely at 16-22° C. At higher (near 32° C) and lower (4°C) temperatures, movement stops and they are presumed dead since no activity resumes when returned to favorable conditions.

The mode of infection of pearl millet plants by zoospores has only recently been studied because the importance of zoospores in causing secondary infection was not understood. Studies have shown that roots, root hairs, coleoptiles, and the base of young and emerging leaves still present within the whorl are the infection courts for zoospores to infect pearl millet plants (Subramanya et al. 1983).

Often the germinated zoospores produced an appressorium from which a tube-like infection peg developed. The infection peg gave rise to a primary vesicle which developed into intercellular mycelium (Subramanya et al. 1983). Bhat (1973) noticed the unidirectional movement of the zoospore germ tubes toward the roots, indicating the prevalence of a chemotactic stimulus. In studies on the biology of systemic infection, the aggregation of infecting zoospores at a single infection site has been noted (Subramanya et al. 1983). Zoospores have been observed entering leaves through stomata. Very often more than two zoospores entered through one stomata, and soon after entering the substomatal chamber they produced both primary and secondary vesicles. From the secondary vesicles thread-like infection hyphae originated and developed as intercellular hyphae.

Not much work has been done to understand the factors influencing the infection process. It is quite likely that temperature, humidity, dew period, tissue susceptibility, and inoculum load influence the infection process. Studies have indicated that although infection can occur at 90% and 95% RH, 100% RH is best to produce maximum infection at 23 ± 1°C. A dew period of about 2 h is enough to cause infection, but about a 6-hour dew period is necessary at 23°C for maximum infection.

Inoculation with single zoospores of 2-day-old NHB 3 pearl millet seedlings did not produce infection. Five zoospores was the minimum needed to infect a seedling. The infection percentage increased with an increase in the number of zoospores, however the percentage infection remained constant beyond a concentration of 100 zoospores per seedling. The incubation period also decreased with increased inoculum concentration. Disease expression began in 8-20 d depending upon the zoospore concentration. Disease intensity increased with increased inoculum load, and became constant beyond 20 000 zoospores $ml^{-1}$ (Ramesh 1981).

## Tissue Culture Studies

Tiwari and Arya (1967) reported the establishment of *S. graminicola* on pearl millet callus by placing systemically infected tissues of a head on modified White's medium. Tiwari and Arya (1969) reported axenic growth of *S. graminicola,* and maintained the saprophytic growth of the fungus for two subsequent subcultures which later perished. Shaw and Safeeulla (1969), Safeeulla (1976b), and Bhat et al. (1980) established dual cultures of *S. graminicola* by inoculating the healthy host callus with asexual inocula on modified White's medium. The fungus grew on the medium up to a short distance from the callus, however they failed to get axenic fungus growth. Prabhu (1985) used three different basal media to find the most suitable one to establish the host callus and *S. graminicola.* Among them, Murashige and Skoog basal medium (1962) best supported initiation and growth of dual cultures. Although cultures were initiated on the modified White's medium, a lot of reddish brown secretions exuded into the medium inhibiting further growth of the callus and the fungus. In Linsmaier and Skoog medium (1965), the growth and development of the callus were not satisfactory. In the author's study the stem tip of pearl millet produced a fleshy type of callus, but the young inflorescence produced a nodular type. From the downy mildew-infected stem tip and inflorescence of pearl millet, the callus developed within a week and the mycelia appeared directly on the callus after 20-25 d. The growth of 5. *graminicola* mycelium was profuse on fleshy type callus. The mycelium of *S. graminicola* was aseptate, coenocytic with irregular wavy walls. It remained intracellular at the beginning and later became intercellular.

In the early stages, the mycelia appeared beaded, but later changed into the characteristic downy mildew type. The mycelium was dense in the peripheral region of the callus with spores absent in the central region. After profuse growth of the mycelium, asexual spores were produced, but shapes and sizes varied from the normal ones produced on the infected leaf surface. Subsequently, asexual spore production decreased with the initiation of oogonial and antheridial structures. The mycelial growth on the host callus usually produced oospores for about 50-55 d (Prabhu 1985).

Morphology of the oospores produced on callus tissue is similar to that produced on infected tissues of pearl millet grown in soil. The healthy callus of pearl millet placed in contact with the infected ones showed infection within 3 d. The 2-day-old pearl millet seedlings brought in contact with *S. graminicola* on callus for 24 h expressed downy mildew disease symptoms 1 week after transfer to sterilized soil. Subculturing the healthy callus is necessary once a month to retain strong growth, and the fungus will grow on the vigorously growing callus. Maintained like this, the fungus retained its virulence over 5 years without any change.

## Establishment of *S. graminicola* Dual Culture on Host Callus Tissue

In most cases, healthy callus tissues were infected by the asexual propagules of the pathogen. In some cases, the S. *graminicola-infected* meristematic tissue of the pearl millet plant was used for raising dual cultures (Prabhu 1985). Prabhu (1985) used very young pearl millet seedlings to raise dual cultures after infecting them with asexual propagules. In this study, the seeds of highly susceptible pearl millet hybrid, NHB 3, were surface sterilized with 0.1% of $HgCl_2$ for 5 min followed by thorough washings in sterilized distilled water. The seeds were placed on sterile moist blotters in sterilized petri plates and incubated at 20 ± 1°C for 24 h. The next day, richly sporulating pearl millet leaves were brought from the field and washed well in sterilized distilled water to remove the old spores. Under aseptic conditions, the sporulating leaf surface was swabbed with cotton soaked in 1% chlorine solution followed by washing in sterilized distilled water. Leaves were air dried and incubated for 6 h in the dark at 100% RH. On the heavily sporulating leaves, under sterile conditions, young seedlings with just emerging radicle and plumule were placed in contact for 4-5 h. They were transferred to the Murashige and Skoog medium with growth supplements containing culture flasks and incubated at 20 ± 1°C in alternating 12 h dark and light (5000 lux) cycles. After 3 d, the callus initiated from the hypocotyl region of seedlings. In 6 d, white downy mildew mycelia were observed on the callus, which could be subsequently maintained (Fig. 5). This technique can be used successfully to screen host cultivars for susceptibility to downy mildew infection, to study the infection processes of the various host-parasite interfaces with the electron microscope, and also can be easily used to study the host range of a biotrophic pathogen in vitro (Prabhu 1985).

The tissue culture technique to determine the viability of the internally seed borne mycelium of *S. graminicola* in pearl millet seeds has been detailed by Prabhu et al. (1983). The callus originated from the hypocotyl region of the seedling, and the mycelium expressed on the callus, should have originated from embryonic tissue. Sometimes, the primary callus turned brown at the initial stages, but after subculturing on the same medium some of them developed healthy secondary callus, which supported a clear network of mycelial growth. This technique is very useful where a small quantity of valuable seed material needs to be tested for internally-borne downy mildew inoculum without loss of the seeds. Plantlets from the callus tissue can be raised to save the germplasm. This tissue-culture technique can also be used in quarantine laboratories to detect downy mildew or other biotrophic organisms associated with seeds.

Many techniques have been developed to maintain the inoculum of downy mildews. Culture on excised leaf pieces was tried by Singh (1970), who floated diseased maize leaf pieces infected with *Sclerospora rayssiae* var. *zeae* Payak & Renfro in sucrose with 20 ppm kinetin to produce "a good harvest" of sporangia. For *Sclerospora sorghi,* Kenneth (1970) used 60-200 ppm benzimidazole and obtained sporulation continually for 7 d. Gale et al. (1975) reported the cryogenic storage of *S. sorghi* conidia to maintain the inoculum. Intact seedlings were used to maintain the various populations of maize downy mildews using the monospore culturing method (Dogma 1974). The dual culture system can be used safely to maintain the inoculum and different isolates and pathotypes of *S. graminicola* without sophisticated laboratory facilities. No in vitro studies on the chemical control of the downy mildew pathogen have been conducted except with downy mildew on grape, where dual cultures were used to demonstrate the systemic and curative properties of metalaxyl on downy mildew (Lee and Wicks 1982). Similar studies can be extended to pearl

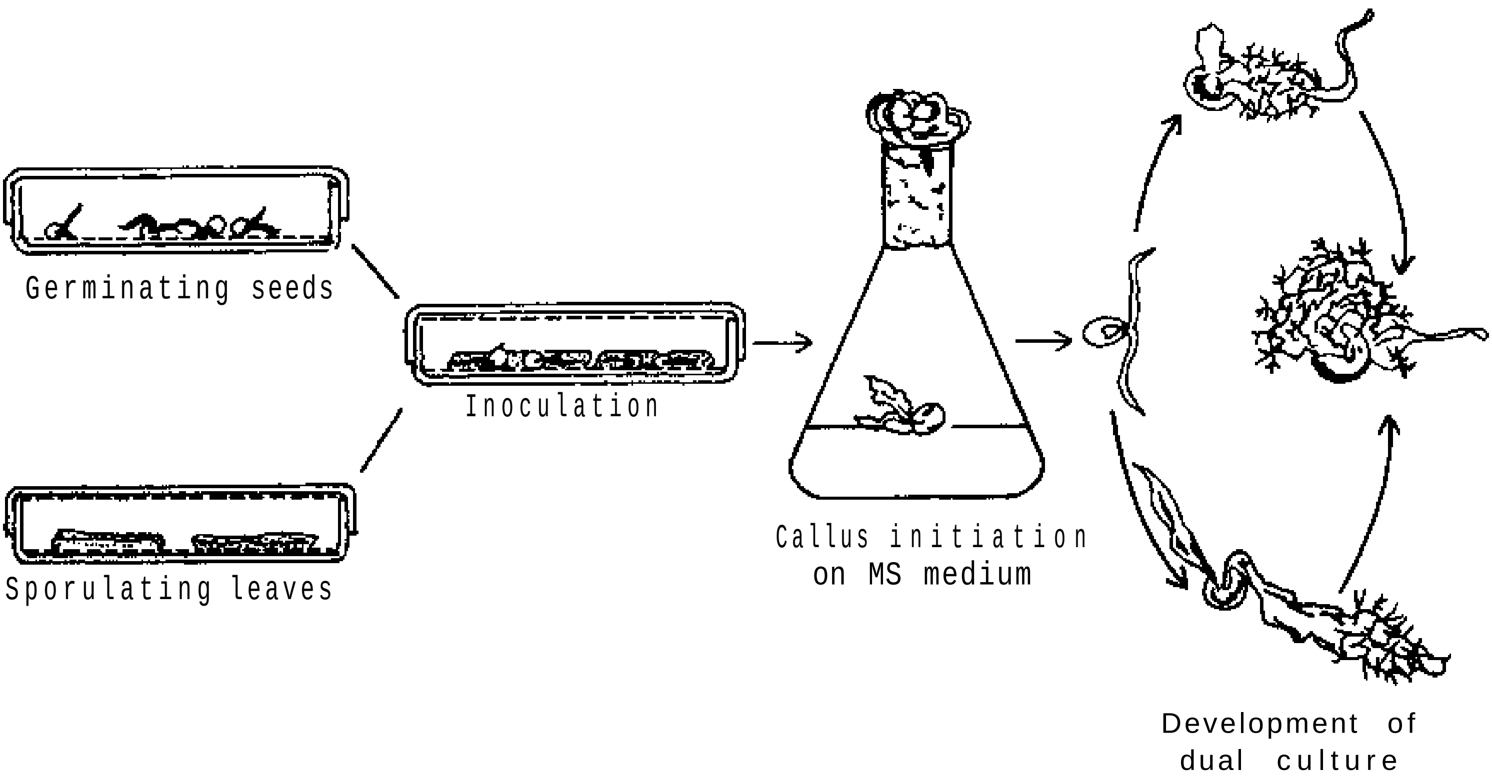


**Figure 5. Seedling inoculation technique to culture *Sclerospora graminicola* on pearl millet callus.**

millet, to study penetration and the effect of systemic fungicides. Plantlets have been successfully regenerated in the laboratory from dual cultures (Prabhu 1985). Plants from such cultures were transferred to soil and tested for their reaction to the downy mildew pathogen, and the test indicated that the plants were resistant to downy mildew. Further research is in progress. In addition, the behavior of susceptible and resistant pearl millet callus was studied on media mixed with different concentrations of downy mildew diseased leaf extract containing Sg-toxin. The callus on the medium with Sg-toxin turned black, whereas the medium with healthy extract supported callus growth. This work is continuing.

## Cytology

Nuclear behavior of the inductive fungus and formative phases was studied cytologically by fixing the material in Farmer's solution and staining with acetocarmine and iron haematoxylin. When the knob-like sporangiophore structures began to emerge from stomata, nuclei migrated into them from hyphae located in the leaf tissue. There was a great rush of nuclei to gain entry into the branches of sporangiophores. As a result, the nuclei often appeared thread-like. Once nuclei entered into the sporangiophores, the nuclei regained their normal shape. Subsequently, the nuclei from the sporangiophores migrated into the sporangia as soon as they were formed. Three to five nuclei entered each sporangium. Sometimes up to 13 nuclei were observed in each sporangium. All the nuclei were functional and a zoospore was formed around each nucleus. Zoospores were liberated from the sporangium through an opening in the region of the papilla and the liberation process was over within 5-10 min. There was no nuclear division in the zoospores, sporangia, and sporangiophores. When released from the sporangium the uninoculated zoospores moved forward and rotated on their axes. They were of different shapes and sizes. The zoospore wall was more distinct after the contents were emptied into the germ tube. There is a 30-45 min time lapse between the formation of germ tubes and migration of nuclei into them. Some of the germ tubes were without nuclei. When appressoria were developed, nuclei occupied the apical region of the germ tube. Nuclear divisions are common in the germ tubes of zoospores (Safeeulla 1976b).

Differences in nuclear contents of sporangia of 5. *graminicola* were observed in the two different pathogenic races reported by Shetty and Ahmed (1981). The number of nuclei in the sporangia of the pathogenic race occurring on NHB 3 varied from 2-5, with 2 most frequent. In contrast, the number of nuclei in the sporangia of the pathogenic race occurring on Mysore pearl millet cultivar Kalukombu varied from 3-13. Six was most frequent, but in no case was the number less than three. The nuclei were smaller and more or less round. This study suggests that the nuclear cytology may be race dependent in *S. graminicola.*

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# Problems and Strategies in the Control of Downy Mildew

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*Abstract*

*Downy mildew (DM) continues to be a major threat to pearl millet production in Africa and Asia. In India, heavy losses due to DM caused the withdrawal of several novel genotypes. Considerable progress has been made in the development of screening techniques and identification and utilization of host-plant resistance. The systemic fungicide metalaxyl has been highly effective in controlling infection by soil-, seed-, and airborne inoculum. Although variability in the pathogen, within and between continents has been demonstrated, sources of stable resistance have been identified. Cultivation of disease-resistant varieties, use of metalaxyl if resistance fails, coupled with roguing of infected plants are recommended for long-term control. Identification of durable resistance, basic genetic studies on the host and pathogen, and studies on the resistance mechanism(s) should be research priorities.*

**Résumé**

**Problèmes et stratégies de la lutte contre le mildiou :** *Le mildiou reste une menace importante à la culture du mil en Afrique et en Asie. En Inde, plusieurs nouveaux génotypes ont été retirés de la production à cause des pertes considérables dues au mildiou. Cependant, le perfectionnement des techniques de criblage ainsi que l'identification et l'exploitation de la résistance des plantes-hôtes ont fait de grands progrès. Le fongicide systémique métalaxyl s'est montré très efficace pour maîtriser l'infection transmise par le sol, les semences ou le vent. Malgré la variabilité du pathogène à travers les continents, on a identifié des sources de résistance qui restent stables. Pour la lutte à long terme, on préconise l'utilisation des variétés résistantes et de métalaxyl en cas de non fonctionnement de la résistance, accompagnée de l'élimination des plantes atteintes par la maladie. Les priorités établies pour la recherche sont : l'identification d'une résistance durable, des études génétiques de base sur la plante-hôte et le pathogène et sur le(s) mécanisme(s) de résistance.*

## Introduction

Downy mildew (DM), caused by *Sclerospora graminicola* (Sacc.) Schroet., is the most widespread and destructive pearl millet *(Pennisetum americanum)* disease. It is grown for grain and forage on about 26 million ha in the tropical and subtropical areas of Africa and the Indian subcontinent (FAO 1983). The disease has been reported in more than 20 countries (Safeeulla 1976) and is a major factor limiting the full exploitation of high-yielding improved cultivars in India. In India, DM epidemics caused substantial yield losses in F, hybrids from 1970-1976 (Safeeulla 1976), and again in 1983 and 1984 (S.D. Singh, ICRISAT and D.P. Thakur, Haryana Agricultural University, personal communication). Losses of 10-60% of the pearl millet harvest have also been reported in various African countries: Mozambique

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Submitted as CP 377 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

(Decarvalho 1949), Nigeria (King and Webster 1970), and Tanzania (Dogget 1970).

During the past decade progress has been made in understanding the biology and epidemiology of the disease, identifying host-plant resistance, and in developing alternative control measures. However, the disease continues to be a major problem. In this paper, the known control measures are summarized, and strategies and research priorities for long-term control are proposed.

## History

*S. graminicola* was first reported on pearl millet in India by Butler (1907). Although the disease is established throughout most pearl millet-growing areas, higher disease incidence and losses were reported only in poorly drained, low-lying areas (Butler 1918, Mitra and Tandon 1930). Epidemics were never reported until 1970. With the traditional cultivars and cultivation methods, the disease remained sporadic. The discovery of cytoplasmic genetic male sterility in pearl millet (Burton 1958) encouraged the production of F, hybrids. Tift 23A, a male-sterile line from Georgia, USA, was imported and a hybrid breeding program began. The first pearl millet hybrid (HB 1) was released for commercial production in India in 1965, followed by HB 2 and HB 3. In 1971, a severe DM epidemic caused heavy losses (AICMIP 1973). This was followed by many epidemics (Safeeulla 1976, Thakur et al. 1978). In West Africa, the disease can reduce yields, although epidemics have not been reported.

### "Breakdown" of Resistance: Causes and Consequences

In India "breakdown of resistance" primarily occurred in hybrids. All early hybrids were based on Tift 23 A, which was bred in the USA in the absence of DM. After its introduction into India, neither this line nor the resultant hybrids were tested for disease susceptibility. No pearl millet diseases were important during that period, so the significance of *S. graminicola* was underestimated. With the large scale cultivation of these hybrids, the pathogen, which had been sporadic, began to multiply and gradually oosporic inoculum accumulated in the soil. With environmental conditions suitable for downy mildew and widespread cultivation of uniformly susceptible cultivars, severe and widespread DM epidemics began in 1971. Unfortunately, these hybrids continued to be cultivated despite their known susceptibility to DM (Pokhriyal et al. 1976).

There were three consequences of resistance breakdown: withdrawal of several of the hybrids, yield reductions, and an increase in the pathogen inoculum. After the introduction of HB 1 there was a gradual increase in pearl millet yields. HB 1 was replaced by HB 2 and later by HB 3. In 1970-71, India harvested a record grain production of 8 million t (AICMIP 1973). In 1971-72, a DM epidemic occurred and the yield dropped to 4.6 million t (Fig. 1). Following the epidemic some new cultivars were released and cultivated widely; however, total yield levels never reached the record 1970-71 level. The resultant oosporic inoculum build-up in the fields posed a major threat to the survival and continuation of even local cultivars, which were previously considered to be highly resistant.

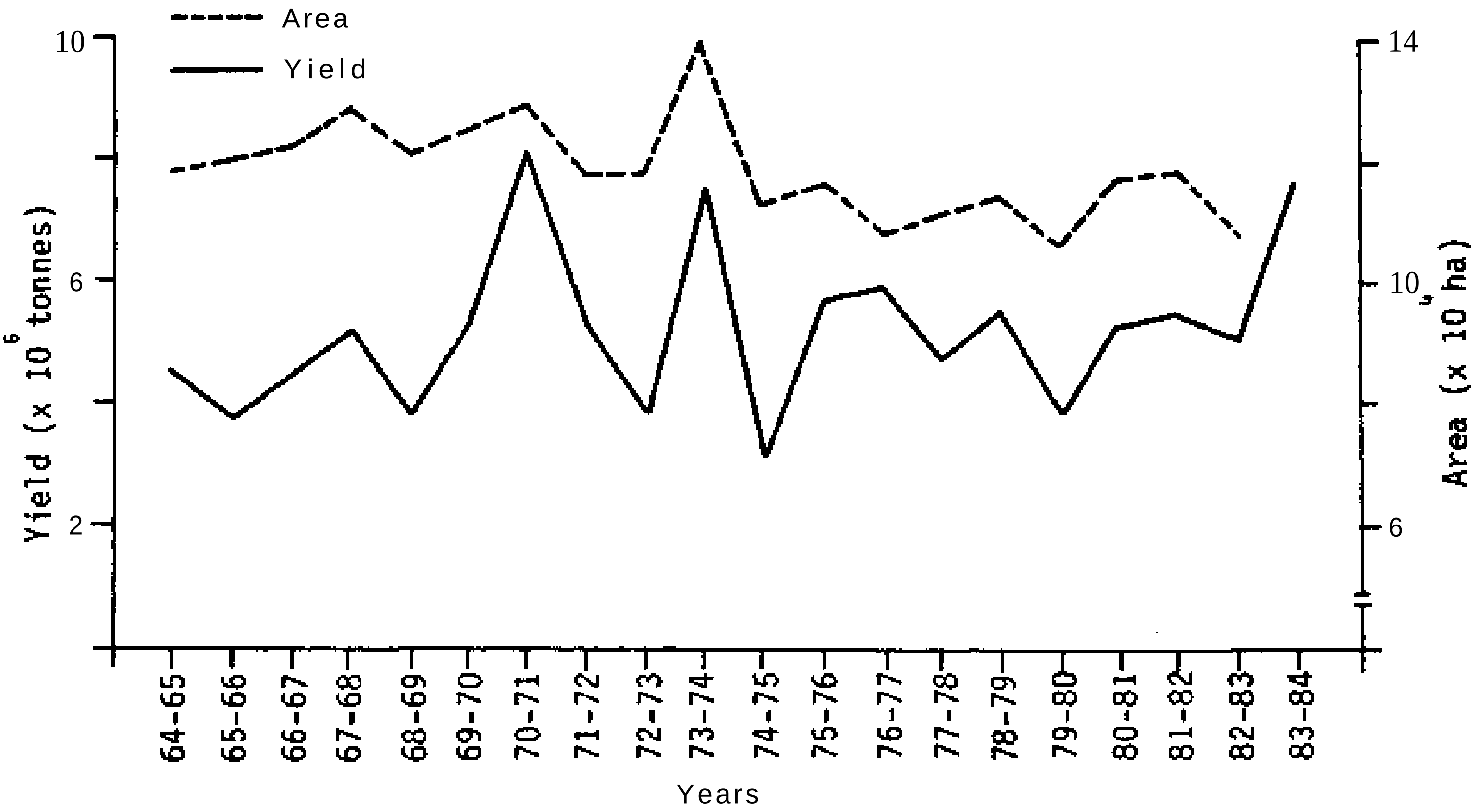
## Pathogenic Variability

### Pathotypes on Different Host Genera

The pathogen was first described as *Protomyces graminicola* on *Setaria verticillata* by Saccardo in 1876. It was renamed as *S. graminicola* by Schroeter in 1879 (Ullstrup 1973). The pathogen was reported on *S. viridis* by Farlow in 1884, and later on pearl millet and several other crops (Bhat 1973). However, the pathogen isolates infecting different hosts appear to be highly host-specific. For example, oospores from *S. italica* failed to infect pearl millet and vice versa, (Uppal and Desai 1932, Singh and Luther 1981). In another study, a pearl millet isolate from ICRISAT Center did not infect 23 hosts belonging to 11 genera previously reported as hosts (Singh and Williams 1979a). In one report, however, the pathogen from *S. italica* was reported to infect pearl millet and vice versa (Safeeulla 1976). Although these isolates may be morphologically similar, they do vary in pathogenicity. To clarify these differences, some nomenclatural changes, such as a *Setaria* pathotype and pearl millet pathotype, have been suggested to reflect the distinct pathogenic differences within this species (Williams 1982, 1984).

### Variability on Pearl Millet

The first report of intervarietal differences in susceptibility to *S. graminicola* was made by Bhat (1973). He found that NHB 3, highly resistant at Mysore,




Source: Agricultural Situation in India

**Figure 1. Pearl millet production in India (1965-84).**

was highly susceptible at other places in India. Similar observations were made on other pearl millet genotypes by Girard (1975) in West Africa and by Shetty et al. (1981) in India. Support for differences in the susceptibility was provided by results from the International Pearl Millet Downy Mildew Nursery (IPMDMN), which has been evaluated annually since 1976. In these nurseries, certain entries were considerably more susceptible at some locations in West Africa than at locations in India, although there were also entries that possessed location nonspecific resistance (Table 1). To ascertain whether these differences were genetic or environmental, a project funded by the Overseas Development Administration (ODA) was initiated at the University of Reading. In a series of experiments conducted from 1980-1985 (Ball 1983, Bali and Pike 1983, Bali and Pike 1984, Idris and Ball 1984, and Ball et al. In press), collections of *S. graminicola* from West Africa proved quantitatively more pathogenic than those from India, and among West African collections, the collections from Nigeria were the most aggressive. This clearly supports the view that pathogenic variation exists in *S. graminicola,* and the differences are not just environmental.

Two more interesting reports on the variability in *S. graminicola* are available. Singh and Singh (In press) reported that NHB 3, which showed a high susceptibility at Durgapura, India, up to 1977, showed a high degree of resistance at this location after 1981, but at other locations in India it continues to be highly susceptible.

A different form of variability was demonstrated in a Zambian collection (Ball et al. In press). This collection was able to overcome the stunt reaction of BJ 104, which was exhibited by all other collections from West African countries and India.

The pathogen survives through the production of sexually produced oospores which are therefore genetic recombinants. Furthermore, it is heterothallic with two mating types (Michermore et al. 1983, Idris and Ball 1984). The pathogen populations, therefore, are dynamically variable and adaptable. However, many sources of stable resistance have been identified (ICRISAT 1985). Recently Ball et al. (In press) have provided evidence that one line, 111B, bred in India, after multiplication for two seasons in a downy mildew nursery in India was equally resistant to all collections, including some from West Africa. Further expansion of the multilocational testing program to identify stable resistance sources could be recommended.

Table 1. Differential and stable downy mildew reactions of certain entries in India and Nigeria.

| | (Mean) Downy mildew score | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Indian location[1] | | | | | | Nigerian locations | |
| Entry | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| E 298-2-1-8 | <1 | 0 | 0 | 0 | <1 | 8 | 7 | 4 |
| WC-8220 | 6 | <1 | 0 | 2 | <1 | 7 | 10 | 8 |
| MPP-714-Sel 1 | <1 | 3 | 2 | 4 | <1 | 7 | 6 | 9 |
| 700780 | 1 | <1 | 4 | 5 | 0 | 4 | 34 | 63 |
| 700792 | 2 | 0 | 2 | 3 | 0 | 4 | 32 | 54 |
| 700335 | 8 | 4 | 3 | 2 | 6 | 15 | 49 | 73 |
| Mean[2] | 2 | 3 | 3 | 3 | 3 | 11 | 24 | 22 |
| 7042 Susc. control | 48 | 70 | 60 | 15 | - | 60 | 98 | 98 |

1. Locations: 1. Hisar 2. Jamnagar 3. Ludhiana 4. Pune 5. Patancheru 6. Mysore 7. Samaru and 8. Kano.
2. Location mean for entries.

## Influence of Plant Maturity and Environment?

Environment and developmental stage of the host may influence the course of an epidemic. In a congenial environment, a severe epidemic may develop if an inoculum supply is available to young seedlings (Singh and Gopinath 1985). The senior author has seen disease-free crops of BJ 104 in some fields, while in other fields in the same area the crop was completely devastated by downy mildew. This may have been caused by the emergence of the crop at a time when there was a favorable environment and inoculum from an earlier crop was available. The disease-free crop may have emerged at a time when the environment was unsuitable for the production of sporangia. This could be one reason why BJ 104 has remained almost DM free in some parts of India, even though the cultivar is highly susceptible to infection by sporangia.

# Control Measures

Control methods are designed to reduce soil- and seedborne oosporic inoculum and secondary spread within and among crops. The following methods have been used.

### Cultural Controls

The basic principles of cultural control are sanitation and manipulation of the environment to the advantage of the host and disadvantage of the pathogen. Four techniques have been studied: sanitation, planting date, roguing, and nutrition.

### Sanitation

Use of disease-free seed and management of infected debris after harvest are essential to reduce the primary inoculum in the field. Claims have been made that the disease is transmitted by internally seedborne mycelium (Sundaram et al. 1971, Shetty et al. 1977, Thakur and Kanwar 1977a), and also by oospores adhering to the seed surface (Thakur 1983). Although the internal seedborne nature of this disease is not entirely agreed upon by researchers, a procedure to prevent introduction of new variants of *S. graminicola* into India was devised jointly by the Indian Council of Agricultural Research (ICAR) and ICRISAT. In this process:

- seed is surface sterilized with $HgCl_2$ (0.1%) for 10 min followed by washing in several changes of distilled sterile water,
- surface-sterilized seed is heated at 55°C for 10 min, and
- the seed is then treated with Metalaxyl at 2 g a.i. $kg^{-1}$ seed.

This procedure, however, cannot be applied to larger seed quantities.

Collecting and burning infected leaf debris after harvest, or plowing to bury debris will help reduce oospore buildup in the soil. These practices, although effective, are not being used by farmers in India.

## Early Planting

If the crop emerges at a time when conditions for the production of sporangia are unfavorable, or before sporangial inoculum levels have built up, for instance very early in the season, then the crop may escape infection, or have only a low disease incidence from infection by soilborne oospores. Conversely, a crop planted when sporangia are abundant will be severely affected (Chahal et al. 1978b). However, because of the unpredictability of environmental conditions following late planting, adjusting the planting date to avoid high DM pressure is an impractical control method.

## Roguing

No collateral hosts are known to harbor *S. graminicola* which attacks pearl millet. Therefore the removal and destruction of DM-infected plants can reduce the spread of disease-causing sporangial inoculum within the same season (Thakur and Kanwar 1977b, Singh and Williams 1980) and oospore buildup in the soil for following seasons. Roguing infected plants prior to oospore formation has been recommended (Kenneth 1977, Thakur 1980). This practice is used to control *Peronosclerospora maydis* in South Sumatra (Tantera 1975), and DM on sugarcane and maize in Taiwan (Sun et al. 1976).

In the absence of collateral hots, roguing could provide effective control. However, success will depend on the willingness and cooperation among farmers, timely availability of labor, expertise in identifying diseased plants at an early stage, and governmental support.

## Nutrition

Research on the possible relationship between downy mildew infection and nitrogen or phosphorus, added to either the soil or plants, has produced contradictory data. (Deshmukh, et al. 1978a, Singh 1974, Singh and Agarwal 1979) Further work, with soil analyses prior to fertilization, is necessary.

## Chemical Controls

Systemic as well as nonsystemic fungicides have been used. Because the disease is seedborne, soilborne, or airborne, fungicides have been applied to seed, soil, and growing plants.

### Nonsystemic Fungicides

Trials resulted were contradictory; some workers hae obtained positive results (Suryanarayana 1965; Thakur and Kanwar 1977c; AICMIP 1970-1976), while others failed to obtain good control (Ramakrishnan 1963, Singh 1974). The reasons for failure of protective fungicides were their inability to control systemic growth of the pathogen, to withstand frequent rains, and to protect enlarging roots and plumules from oospore infection after their application to seed.

### Systemic Fungicides

A new era for chemical control of oomycete fungi began with the acylalanine fungicides (Urech et al. 1977). Seed treatment with metalaxyl at 1-2 g a.i. $kg^{-1}$ of seed has given excellent control of DM in maize, sorghum, and pearl millet (Venugopal and Safeeulla 1978, Exconde and Molina 1978, Frederiksen 1979, Schwinn 1980, Williams and Singh 1981, Singh 1983b, Dang et al. 1983). As a seed treatment, it controls soil- and seed-carried inoculum, and is absorbed by the seedlings, protecting them from sporangial infection. In highly tillering crops like pearl millet, however, the efficacy of the fungicide is reduced as plants grow. Foliar applications of metalaxyl have cured diseased plants (Singh and Williams 1979b, Singh et al. 1984).

Metalaxyl at 31 ppm a.i. cured greenhouse plants, but a higher concentration was needed for field-grown plants. Although plant age did not affect recovery, head length was reduced if diseased plants were sprayed prior to panicle development (Singh et al. 1984).

### Limitations to Metalaxyl Use

Phytotoxic effects of metalaxyl seed treatment expressed as reduced seed germination have been demonstrated; however, only at higher than recommended rates of application, e.g., >2 g a.i. $kg^{-1}$ of seed (Singh 1983b). Cultivars differ in their sensitivity. The seed treatment formulation (SD 35) is particularly toxic. It is suggested, therefore, that cultivars be evaluated for their sensitivity prior to large-scale seed treatment.

Metalaxyl may become ineffective with time probably because of its narrow spectrum of activity. There are already reports of a decline in its effectiveness against certain Phycomycetes (Reuveni et al. 1980, Bruin and Edgington 1981).

### Host-Plant Resistance

Use of resistant cultivars is the best method to control this disease. Considerable progress has been made in the development of screening techniques, identification of sources of resistance, and breeding of resistant cultivars.

### Screening Techniques

Field screening. A field screening technique that mainly utilizes sporangia as the infection propagules has been developed (Williams et al. 1981). This technique has three components:

- infector rows (inoculum donors) planted in advance as a mixture of 2-3 susceptible genotypes;
- test rows planted after 40-50% plants in the infector rows develop the disease; and
- indicator rows (susceptible genotype) which indicate the level of disease pressure.

Perfo-spray irrigation is applied in the early evening as needed to encourage high night-time relative humidity for sporangial production and infection, especially during early growth of test material. The technique was developed:

- to provide uniform inoculum distribution,
- to inoculate naturally throughout the susceptible period,
- to minimize chances of escape,
- to utilize both types of inocula (oospores and sporangia), and
- to provide opportunities for breeding activities in the same season, field, or both.

This technique is being used twice a year at the ICRISAT Center and has been adopted by many researchers in India and West Africa. Some of the resistant sources identified using this technique have been stable across hot-spot locations in India and West Africa.

**Laboratory Screening.** To detect escapes from field screening and to conduct pathological studies, various laboratory and greenhouse inoculation techniques, have been developed. Singh and Gopinath (1985) described one such technique: potted seedlings in the coleoptile stage (<10 mm above ground) are inoculated using a microsyringe. A drop of inoculum placed at the tip of the seedling flows down to the base covering most of the above-ground surface area. The inoculated seedlings are marked to differentiate them from those that may emerge later. Under favorable conditions, >90% of the susceptibility of a genotype is expressed within 15 d after inoculation.

### Sources of Resistance

At ICRISAT Center, 3163 accessions from the Genetic Resources Unit originating from more than 20 countries in the major millet growing areas of the world were screened. A total of 428 accessions with high levels of resistance and which flowered in 45-60 d at ICRISAT Center, were further evaluated, and 48 single plant selections made. Progenies of these were highly resistant and agronomically acceptable. These selections will serve as the major source of DM resistance for future breeding in India. In addition, many sources of resistance have been identified in India by other workers (Chahal et al. 1975, Dass and Kanwar 1977, Chahal et al. 1978a, Deshmukh et al. 1978b, Appadurai et al. 1978, Shinde and Utikar 1978, Thakur and Dang 1985).

Sources of Stable Resistance. With the help of the cooperators in India and West Africa, the IPMDMN began in 1976. Each year 45 entries from breeders and pathologists are evaluated at DM hot-spot locations in India and Africa. More than 50 sources of stable resistance, primarily originating in Nigeria, have been identified (Table 2).

## Utilization of Resistance

At ICRISAT Center resistant sources are being utilized, particularly in the hybrid program. SDN 503, P 7, 700516, P 310, and 700651 are being used in the pollinator project, while resistance from P 7 and 700651 is being transferred into hybrid seed parents. Figure 2 shows the basic scheme for the identification and utilization of resistance.

In the population improvement project, progenies of composites are tested and selected in the DM nursery. The levels of DM resistance in the composites have increased substantially, so incorporation of resistance from other sources is currently not

Table 2. Downy mildew (DM) reactions of 26 entries and standard susceptible controls included in the IPMDMN trial for 2-9 years and at all locations of testing in India and Africa.

| Entry | Origin | Mean DM severity (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 |
| SDN 503 | Nigeria | 1 | 1 | 3 | 3 | 8 | 9 | 8 | 1 | 2 |
| P7 | Mali | 6 | 2 | 3 | 3 | 9 | 6 | 6 | 3 | 3 |
| 700251 | Nigeria | 3 | 2 | 2 | 1 | 9 | 6 | 6 | 4 | - |
| 700516 | Nigeria | 2 | 3 | 2 | 1 | 7 | 5 | 3 | 3 | - |
| 700651 | Nigeria | 1 | 3 | 4 | 1 | 10 | 6 | 4 | 3 | - |
| SDN 347-1 | Nigeria | 5 | 3 | 4 | 3 | - | - | - | - | - |
| BJ 104 | New Delhi | - | 14 | - | 13 | 21 | 10 | 17 | - | - |
| EB 18-3-1 | ICRISAT | - | - | 2 | 1 | 7 | 2 | - | - | - |
| IP 1930 | ICRISAT | - | - | - | 2 | 8 | 2 | 1 | 2 | 2 |
| EB 83-2 | ICRISAT | - | - | - | 2 | 6 | 5 | 3 | 4 | 1 |
| MPP 7147-2-1 | New Delhi | - | - | - | 1 | 7 | 5 | 6 | 4 | 4 |
| E 298-2-1-8 | ICRISAT | - | - | - | - | 5 | 3 | 4 | 3 | 1 |
| 700546 | Nigeria | - | - | - | - | 7 | 6 | 7 | 5 | 1 |
| 700512 | Nigeria | - | - | - | - | 6 | 3 | 3 | 5 | 4 |
| SDN 714 | Nigeria | - | - | - | - | 6 | 6 | 4 | 5 | - |
| IP 2058 | Nigeria | - | - | - | I | 9 | 8 | 5 | - | - |
| P 310-17 | Mali | - | - | - | - | - | - | - | 1 | 1 |
| P 472-1 | Mali | - | - | - | - | - | - | - | 1 | 2 |
| P 473-4 | Mali | - | - | - | - | - | - | - | 3 | 1 |
| P 2672-6 | Niger | - | - | - | - | - | - | - | 4 | 3 |
| IVC-P 78-2 | ICRISAT | - | - | - | - | - | - | - | 6 | I |
| IVC-P 8004-2 | ICRISAT | - | - | - | - | - | - | - | 8 | 2 |
| NELC-H79-4 (Original) | ICRISAT | - | - | - | - | - | - | - | 6 | 3 |
| SSC-BB 78-4 (Reconstituted) | ICRISAT | - | - | - | - | - | - | - | 2 | 2 |
| (B282 X 3/4 E B-100) -11-9-2-2 | ICRISAT | - | - | - | - | - | - | - | 6 | 1 |
| (F4FC 1436-4-3-2 x J104 ST)-1-1-5) | ICRISAT | - | - | - | - | - | - | - | 8 | 1 |
| Location mean for entries | | - | 9 | 7 | 5 | 4 | 11 | 6 | 7 | 6 |
| Suceptible controls | | | | | | | | | | |
| 7042 | Chad | - | - | - | 58 | 63 | 68 | 44 | 64 | 44 |
| J 1593 | Jamnagar | - | 28 | 14 | 8 | 17 | 15 | - | - | - |

needed. Two open pollinated varieties, WC-C75 and ICMS 7703, have been released for cultivation in India. WC-C75 has been cultivated by Indian fanners since 1982, and is now grown in nine states on several hundred thousand ha. There is yet no report of its resistance becoming ineffective.

## Development of Resistance

Susceptibility to DM gradually builds up if a cultivar is grown for several years. In the past, several pearl millet cultivars were withdrawn in India because of their susceptibility to DM. Research at ICRISAT Center has shown that such cultivars could be resurrected by selecting for resistance from variability within the lines. This was demonstrated in a landrace from Chad in 1982 (Singh, ICRISAT, personal communication) and also for parents of hybrid BJ 104 (Singh 1983a). Lines thus selected have shown high levels of DM resistance at several locations in India (Table 3). The selected parental lines (841A and ICMP 84814) of BJ 104 are phenotypically sim-

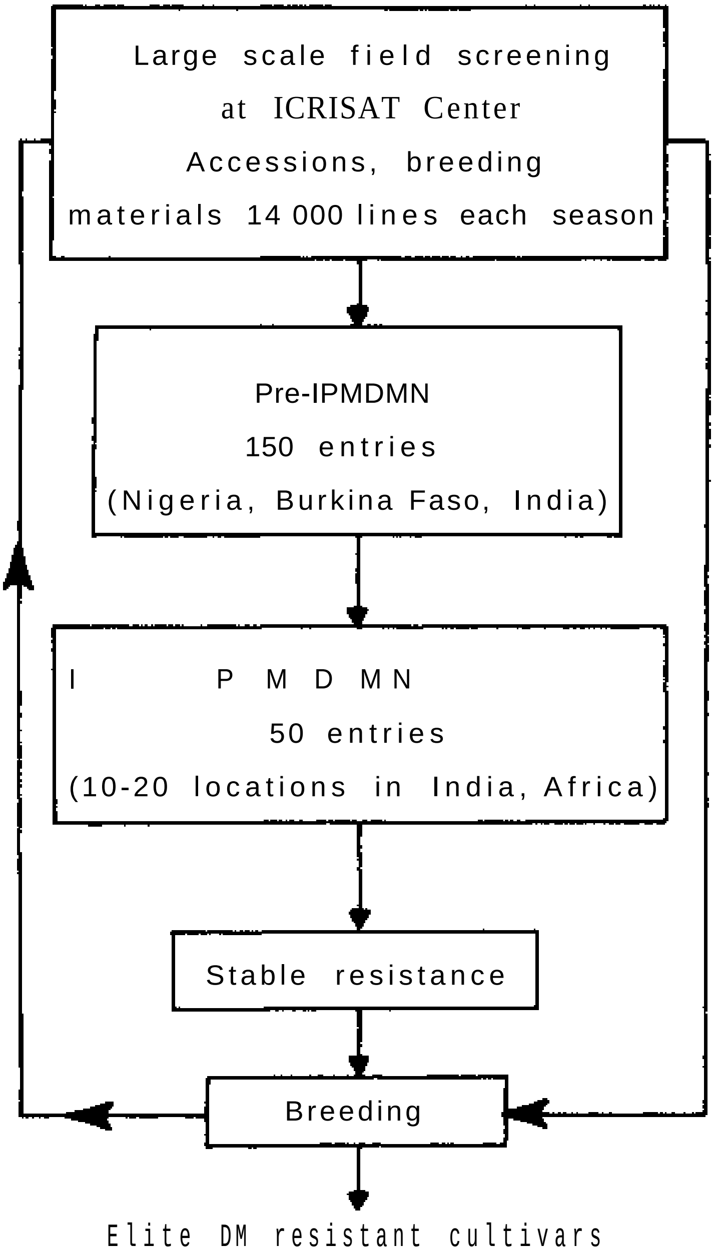



**Figure 2. Basic scheme for the identification and utilization of downy mildew resistance.**

Table 3. Downy mildew (DM) reactions of three lines reselected for DM resistance at several locations[1] in India.

| Entry | Test year | DM severity (%) locations[1] 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 241A1 | 1983 | 0 | 0 | 0 | 0 | 0 | 0 | <1 | 9 | - |
| ICMP 84814 | 1984 | 12 | 0 | 1 | - | - | 2 | 8 | 13 | 3 |
| 7042 | 1982 | 11 | | 0 | 0 | 4 | 7 | 4 | 9 | 0 |
| 7042[2] | | 64 | 4 | 33 | 30 | 63 | 92 | 57 | 67 | 52 |

1. Locations: 1. Aurangabad 2. Durgapura 3. Jamnagar 4. Coimbatore 5. Hisar 6. Patancheru 7. Ludhiana 8. Mysore 9. Kovilpatti
2. Mean of 3 test years.

iliar to the original parental lines and the hybrid (ICMH 84814) based on these lines is similar in yield and other characteristics to BJ 104 (Table 4). However, 841A differs significantly from 5141A for several characters, most notably for time to 50% flowering, height, head length, and individual grain mass (Table 4).

### Inheritance of Resistance

Little is known about the model of inheritance (Nene and Singh 1976). In some cases the resistance was demonstrated to be controlled by one or two dominant genes (Appadurai et al. 1975, Singh 1974, Gill et al. 1975, Gill et al. 1978), while in others it was reported to be controlled polygenically and by additive and nonadditive gene effects (Singh et al. 1978, Basavaraj et al. 1980, Shinde et al. 1984). The overall mode of inheritance is unclear because the parents used in these studies were heterozygous, the pathogen populations were highly variable, and inoculation procedures were generally not standardized.

Homozygous parents for susceptibility and resistance and uniform inoculum should be used in inheitance studies. Laboratory screening such as the newly-developed, seedling-inoculation technique (Singh and Gopinath, 1985) will be useful.

## Strategies for Control

Availability of resistant cultivars, an effective systemic fungicide, and cultural practices provide opportunities for the long-term management of this disease.

### Host-Plant Resistance

Growing one cultivar over a large area should be avoided. Cultivars should be specified for particular areas, and there should be several cultivars in given areas. Success, however, will depend on the genetic differences among the cultivars. Another approach would be to use gene deployment over time. This approach is based on the principle of host specificity. It is likely that pathogenicity and consequently the oospore population of the pathogen may increase if a genotype is grown for a long period. Conversely, the pathogenicity may decline if the specific host is withdrawn from cultivation. This particular phenomenon has been observed with NHB 3, at Durgapura in Rajasthan (Singh and Singh In Press).

Table 4. Comparison of BJ 104 and 5141A with their downy-mildew resistant counterparts, ICMH 84814, and 841A, ICRISAT Center, rainy season 1985.

| Entry | Tillering (no) | Time to 50% flowering (d) | Plant height (cm) | Head length (cm) | Head mass ($kg\ ha^{-1}$) | 1000 grain mass (g) | Grain yield ($kg\ ha^{-1}$) |
|---|---|---|---|---|---|---|---|
| ICMH 84814 | 2.8 | 44 | 127 | 15.9 | 2800 | 6.9 | 2100 |
| BJ 104 | 3.8 | 42 | 111 | 16.3 | 3000 | 6.5 | 2100 |
| 841A | 3.1 | 53 | 106 | 15.0 | 1600 | 5.8 | 1100 |
| 5141A | 3.3 | 51 | 96 | 11.5 | 1600 | 4.9 | 1000 |
| Mean[1] | 2.4 | 44.4 | 120.0 | 15.8 | 3000 | 6.8 | 2100 |
| S.E. | ±0.2 | ±0.5 | ±2.1 | ±0.4 | ±275 | ±0.22 | ±200 |

1. Mean of 17 entries including 13 reconstituted hybrids that were evaluated in the trial.

Open-pollinated cultivars in which every individual is genetically different provide another opportunity to keep the disease under control. Due to their heterogeneity, such cultivars will have a buffering effect against DM. They are unlikely to be disease-free, but they will not develop the disease in epidemic proportions for several years. ICRISAT is putting major emphasis on open-pllinated varieties. In Africa, where hybrids are not currently being grown for various reasons, open-pollinated cultivars will be the most appropriate genotypes for DM control.

## Fungicides

Metalaxyl is a powerful tool to control DM in pearl millet. Although the inefficacy of metalaxyl has been reported for some other diseases, it can still be used effectivewly for control of downy mildew of pearl millet if the strategies for its use are carefully worked out. The best strategy would be to keep the fungicide in reserve, for use only if the resistance breaks down unexpectedly.

## Cultural practices

Of the many cultural practices known, only roguing infected plants soon after their detection is strongly recommended. This should be done even if other control methods, including resistant cultivars, have been used.

# Research Priorities

### Durable Resistance

Cultivation of varieties over a large area for many years is the only method to detect the durability of resistance. Stability (multilocational tests), has been suggested as one method which might predict durability (Johnson 1984), but which whould need testing over time. Moreover, durable resistance to systemic diseases like DM in which a plant can be either diseased or healthy, should be viewed differently from leaf spots and rusts. Therefore, to make the resistance durable, a system must be identified in which the pathogen can parasitize each plant without adversely affecting its yield.

### Basic Genetic Studies

With the available knowledge of variation in the pathogen population, frequencies of virulence genes need to be assessed. Likewise genes for resistance in the host should be determined. To utilize the identified resistance by the appropriate breeding procedures, the pattern of inheritance should be studied.

### Nature of Resistance

Resistance may operate before or after penetration. During the prepentration stage, spore germination may be inhibited due to certain chemicals, or there may be barriers to penetration by mechanical or physiological factors. After penetration, several factors, including incompatability, reduced colonization, and sporulation (slow mildewing) may stop and/or delay disease development. All these aspects need to be studied. Research is needed to identify lines with reduced colonization and sporulation, and to further improve these traits by appropriate selection methods.

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# Problems and Strategies in the Control of Ergot and Smut in Pearl Millet

**R.P. Thakur[1] and S.S. Chahal[2]**


### Abstract

*Ergot and smut are the most important floral diseases of pearl millet. These are more serious and damaging in* $F_1$ *hybrids than in open-pollinated varieties because protection by pollination is more effective in varieties than in hybrids. Both pathogens are primarily soilborne and infect the crop at flowering through the stigmas. These diseases become more severe when flowering occurs during wet weather.*

*The most effective and economical control of ergot and smut is host-plant resistance. Effective field-based screening techniques are available to identify resistance. Lines with high levels of resistance to smut are available. Resistance to ergot, rarely detected in accessions of the ICRISAT world collection of pearl millet, has been bred by pedigree selection. Resistance stability is determined by international multilocational testing. Stable resistant lines, for ergot and smut, and lines that have combined resistance to ergot, smut, and downy mildew have been produced. In cooperation with breeders, resistant lines are used to breed hybrids and varieties. Varieties with high levels of smut and downy mildew resistance and high grain yields comparable to standard varieties have already been bred and are under All India Coordinated Millets Improvement Project (AICMIP) testing. In the near future, high-yielding hybrids and varieties, with resistance to ergot and possibly with resistance to smut and downy mildew as well, may be bred.*

*Euture research efforts are needed to understand more about the biology and epidemiology of the pathogens; variations in the pathogen populations and existence of different pathotypes or races; mechanisms and genetics of resistance; identification of newer sources of resistance that can be easily manipulated in resistance breeding; and multilocational testing of resistant lines, particularly in Africa.*

### Résumé

**Problèmes et stratégies de la lutte contre l'ergot et le charbon chez le mil :** *L'ergot et le charbon sont les principales maladies de l'inflorescence du mil. Ils sont plus graves chez les hybrides* $F_1$ *que chez les variétés à libre pollination puisque la protection offerte par la pollination est plus efficace chez les variétés que les hybrides. Ces pathogènes sont transmis par le sol et atteignent la plante à travers les stigmates à l'époque de la floraison. L'incidence est plus élevée lorsque la floraison coïncide avec les pluies.*

*La résistance des plantes-hôtes offre le moyen le plus efficace et économe de lutter contre l'ergot et le charbon. Il existe d'efficaces méthodes de criblage au champ pour identifier cette résistance ainsi que des lignées à forte résistance au charbon. La résistance à l'ergot rarement repérée chez les accessions de la collection mondiale à l'ICRISAT, est obtenue par sélection généalogique du matériel. La stabilité de la résistance est établie par des essais multilocaux à l'échelle internationale. Ce processus a permis de produire des lignées résistantes à l'ergot et au charbon ainsi que des lignées qui associent la résistance à toutes ces deux maladies à celle au mildiou. Cette résistance est utilisée dans la création des hybrides et des variétés par*



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Submitted as CP 376 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

*les sélectionneurs. Les variétés à haut niveau de résistance au charbon et au mildiou ainsi qu'à rendements élevés en grain comparables aux variétés normales sont déjà mises au point et subissent actuellement les essais par le projet coordonné indien d'amélioration des mils (AICMIP). On s'attend également à la création prochaine des variétés et hybrides à haut rendement résistants à l'ergot, et, éventuellement, au charbon et au mildiou.*

*Les recherches à poursuivre devraient permettre de mieux comprendre la biologie et l'épidémiologie des pathogènes, les variations à l'intérieur des populations et l'existence des différents pathotypes ou races, les mécanismes et la génétique de la résistance, l'identification des autres sources de résistance faciles à manipuler pour la sélection, et enfin les essais multilocaux des lignées résistantes, en particulier en Afrique.*

## Introduction

Ergot *(Claviceps fusiformis* Loveless) and smut *(Tolyposporium penicillariae* (Sacc.) Schoet.) are the two major floral diseases of pearl millet *(Pennisetum americanum)* worldwide. Although pearl millet is a crop of ancient origin, its diseases have been recorded only in the 20th century, with most published information from India. These have been reported from almost every country in Asia and Africa where pearl millet is grown (Ramakrishnan 1971, Rachie and Majmudar 1980). Smut is reported to occur also in the USA (Wells et al. 1963). In India, smut was first reported in the 1930s (Ajrekar and Likhite 1933) and ergot in the 1940s (Thomas et al. 1945). For the first time ergot appeared in epiphytotic proportion in Maharashtra in 1957 (Bhide and Hegde 1957) and smut in some parts of Uttar Pradesh and Haryana in 1967 (Bhowmik and Sundaram 1971).

These diseases, although known for a long time to occasionally be serious on pearl millet in parts of Africa, have not always been properly recorded and studied due to lack of technical personnel, particularly plant pathologists, a situation which prevails even today. Presently ergot and smut are considered next to downy mildew *[Sclerospora graminicola]* in importance in India and many African countries. There are, however, areas where one disease is more important than others in different years depending on amount and distribution of rainfall during the crop season.

In the late 1960s, commercial cultivation of hybrids in India, based on cytoplasmic male-sterility, produced a dramatic grain yield increase of about 70% over traditional varieties. The national production of pearl millet almost doubled within 3-4 years. A major epidemic of downy mildew in 1971 destroyed a large hectarage of the most popular hybrid, HB 3, and pearl millet production suffered a major setback (Safeeulla 1977). With the large-scale cultivation of single-cross hybrids, it also became apparent that these hybrids, as a class, are more susceptible to ergot and smut than open-pollinated varieties. Both ergot and smut infections occur through emerging stigmas, more successfully in the absence of pollen. Rapid pollination prevents or reduces infection by both ergot and smut pathogens (Thakur and Williams 1980, Thakur et al. 1983a). The pollination-induced resistance operates more effectively in open-pollinated varieties, which have more variability in flowering time, than in single-cross hybrids in which flowering is more synchronous.

There are no reports on yield loss due to ergot and smut in pearl millet based on well-planned disease surveys in farmers' fields. However, results from experiment stations have indicated a yield loss of 58-70% in hybrids with 62-76% ergot severity (Natarajan et al. 1974), and 54% in a variety, WC-C75, and 65% in a hybrid, BK 560, under artificial disease pressure (R.P. Thakur, ICRISAT, personal communication). Ergot, in addition to directly reducing grain yield, adversely affects quality by contaminating the grain with the neurotoxic, alkaloid-containing sclerotia which render it unfit for consumption. Bhowmik and Sundaram (1971) reported 50-75% of the crop infected with smut in different farmers' fields with damage ranging from a few scattered sori in a head to 100% loss of grains.

In recent years, with increasing efforts to breed hybrids and varieties with higher grain yields, ergot and smut have become very significant. If the advantage of high grain yield potential of new cultivars has to be realized, these diseases must be kept under control. This paper presents a brief review of the biology, epidemiology, and disease cycles of ergot and smut as related to the development of various control measures; discusses various steps involved in host-plant resistance; and finally suggests future research.

## Biology, Epidemiology, and Disease Cycle

### Ergot

The causal organism of ergot was known as *C. microcephala (W*allr.) Tul. until 1967 when Loveless created a new species, *fusiformis* based on samples from several countries in Africa (Loveless 1967). Studies from India (Siddiqui and Khan 1973a; Thakur et al. 1984) have confirmed the findings of Loveless and now *C. fusiformis is* the most accepted nomenclature for the pathogen which causes ergot on pearl millet.

Reproduction in *C. fusiformis is* both asexual and sexual. Conidia germinate readily by producing one to several germ tubes which bear macroconidia and secondary or microconidia (Ramakrishnan 1971, Siddiqui and Khan 1973a). Macroconidia are fusiform and microconidia globular, and both are unicellular and hyaline. Macroconidia from fresh 'honeydew' produced on infected inflorescences germinate within 16 h at 25°C (Thakur et al. 1984,Chahal et al. 1985). Macroconidia from fresh 'honeydew' are usually more infective than microconidia (Thakur and Williams 1980, Chahal et al. 1985).

The sexual phase of the fungus initiates from sclerotia formed in the infected florets in place of grains after the honeydew phase. Sclerotia are dark-brown to black with variable shapes and sizes. They germinate to produce ascospores, the sexual spores of the fungus. Sclerotial germination in the laboratory and field has been reported with varying success (Loveless 1967, Prakash et al. 1981, Thakur et al. 1984). On germination, sclerotia produce stipes that bear globular capitula. Numerous pyriform perithecia are embeded in the peripheral somatic tissue of the capitula. In the perithecium, asci are interspersed with hyaline paraphyses emerging through the ostiole. Asci are long, hyaline, and operculate with a narrow base. Each ascus contains eight ascospores which are long, hyaline, nonseptate, and thin walled. The fungus can easily be cultured on Kirchoffs medium and optimum growth occurs at 25°C. The growth is initially mycelial and macroconidia are produced 7-10 d after incubation and microconidia a few days later (Thakur et al. 1984).

Infection takes place through stigma (Prakash et al. 1980, Thakur and Williams 1980). However, Reddy et al. (1969) observed infection through the ovary wall as well. It has now been clearly demonstrated that infection occurs only through stigma and once pollination occurs infection is prevented (Thakur and Williams 1980, Willingale and Mantle 1985). The fungus invades florets through stigma and colonizes the ovaries within 3-4 d. The ovaries are completely replaced by interwoven fungal hyphae and conidia within 10 d, and sclerotia become visible within 20-25 d after inoculation.

The most important factor in ergot epidemiology is weather conditions at the flowering stage of the crop. High relative humidity (70-100%), overcast skies with reduced sunshine hours, frequent rain showers, and cooler nights (18-20°C) are conducive for ergot development (Ramaswamy 1968, Siddiqui and Khan 1973b, Arya and Kumar 1982, Gupta et al. 1983). Rainfall distribution during flowering also influences the ergot severity (Chahal and Dhindsa 1985).

The pathogen survives in sexual and asexual forms during the off-seasons. Conidia retain their viability up to 13 mo under storage (Ramakrishnan 1971, Thakur 1983). In several field and greenhouse studies sclerotial germination coincided with flowering in pearl millet and ascosporial infection was demonstrated (Thakur et al. 1984). The intensity of disease development and spread depends on the prevailing weather conditions during the flowering period, the susceptibility level of the cultivar, and the amount of initial inoculum.

Pollination reduces ergot infection by inducing stylar constriction (Willingale and Mantle 1985). Withered stigmata prevent infecting hyphae from entering the ovary (Thakur and Williams 1980, Willingale and Mantle 1985). This phenomenon of pollination-protection often prevents or delays ergot epidemic in pearl millet.

The disease cycle in ergot begins with sclerotia left in the field after harvest and/ or sclerotia mixed with planting seed at the time of threshing (Sundaram 1975, Thakur et al. 1984). Following rain showers, sclerotia germinate and release ascospores, which then settle on emerging stigmas and initiate infection. In addition to ascosporial infection, conidia in the sclerotial cavities may also serve as a primary source of inoculum (Thakur 1983). Honeydew becomes visible within 6-7 d of ascosporial infection. The secondary disease cycle within a crop initiates from macro- and microconidia in the honeydew (Siddiqui and Khan 1973b). These are disseminated by splashing rains, wind, and physical contact with healthy inflorescences. A role for insects in ergot transmission has also been reported (Sharma et al. 1983, Verma and Pathak 1984).

In addition to several collateral hosts reported for the ergot pathogen (Ramakrishnan 1971), *Panicum* *antidotale* (Thakur and Kanwar 1978) has recently been reported from Haryana and *Cenchrus ciliaris* (Singh et al. 1983) from Rajasthan (India). These may serve as both primary and secondary sources of inoculum in these areas.

### Smut

The causal organism of smut is generally known as *Tolyposporium penicillariae Bref,* but Vanky (1977) created a new genus, *Moesziomyces,* for this fungus based on sori without columella, and spores with surface ornaments appearing as irregular meshes firmly agglutinated in sporeballs. Chahal and Kumar (In press) confirmed Vanky's observations on the morphology of the fungus, and agreed with his classification.

The fungus reproduces both asexually and sexually. Sporidia, produced on promycelia or basidiophores, are the sexual spores. These can further reproduce by budding, and are the infective spores. These are hyaline, single-celled, and vary from 8-25 $\mu$m. Teliospores are produced in smut sori from dikaryotic mycelial cells in the infected florets. A matured sorus contains numerous sporeballs of teliospores. These are brown, globose to subglobose with a thick exospore wall and measure 7.0-12.5 $\mu$m. Individual teliospores germinate by producing a typical four-celled promycelium. Sporidia are borne either laterally or terminally on the promycelium. In some cases they are produced on pointed branches and form chains or clusters. The teliospores do not separate readily and germination is usually scanty. The maximum germination of teliospores aggregated in sporemass occurs at 30°C (Rao and Thakur 1983) and no resting period is necessary for germination (Ajrekar and Likhite 1933, Bhatt 1946).

The fungus can easily be cultured on potato-dextrose agar, potato agar, and carrot agar and grows well at 30-35°C. In culture it produces sporidia without mycelial growth. When the culture is kept at 10°C for a longer time, intercalary and terminal chlamydospores are formed (Rao and Thakur 1983).

There are no reports on biotypes or races in this fungus. Research at ICRISAT Center has indicated cultural and pathogenic variations within single spore cultures obtained from a single isolate (R.P. Thakur and K.V. Subba Rao, ICRISAT, personal communication).

Bhatt (1946) studied and described the infection process in detail: hypha penetrates the flower through the stigma and reaches the upper ovary wall, traversing the entire length of the style without lateral spread. The mycelium is binucleate, inter- and intracellular, exhibiting slight branching with two-to four-lobed haustoria. The hypha advances downward through the ovary wall and finally invades the ovule. Before all the tissue is involved, the walls of the hyphae begin to gelatinize to form the sporeballs.

In the field, teliospores in soil or crop residues, or adhering to seed, serve as primary inoculum. They germinate to produce sporidia which become airborne and cause infection through young, emerging stigma (Bhatt 1946, Vasudeva and Iyengar 1950). Smut sori, larger than the normal grain, become visible 2 weeks after infection. The sori are initially shiny green, but later turn brown and rupture to release millions of dark brown teliospores. High relative humidity (>80%) and an average temperature of 30°C favor smut development.

Secondary spread of the disease within a crop is minimal because of a prolonged latent period (2 weeks) by which time flowering is almost complete. Pollination prevents infection by the smut pathogen (Thakur et al. 1983a). A late flowering crop can be infected by the inoculum from the infected crop in an adjacent field. The infection intensity, however, depends on weather conditions, wind direction, and the susceptibility level of the cultivar.

## Control Measures

The various control measures for pearl millet ergot and smut can be grouped into chemical, cultural, biocultural, and host-plant resistance.

### Chemical Control

Since both ergot and smut are strictly soil- and airborne diseases, control by seed-dressing fungicides is not possible. Pearl millet is a high tillering crop of the rainy season, and therefore use of fungicides as sprays has major economic and technical limitations for farmers. However, several fungicides used in experiments to control these diseases are summarized by Thakur (1984) for ergot and by Rachie and Majmudar (1980) for ergot and smut, but none is economical for use by farmers.

### Cultural Control

Cultural controls are an attempt to decrease the primary inoculum level in the soil. Deep plowing of fields immediately after harvest helps bury sclerotia to prevent germination (Sundaram 1975).

Ergot is usually more severe on late-sown cultivars (Singh and Singh 1969, Thakur 1983), perhaps due to more conducive weather at flowering. But a late-sown crop usually yields poorly even in the absence of diseases, and therefore is not a useful control measure. Intercropping pearl millet with mungbean produced less ergot (2-7%) than in the sole crop of pearl millet (21-32%) (Thakur 1983). The dense leaf canopy of mungbean probably intercepts ascospores from reaching the inflorescences and thus reduces ergot infection.

Use of sclerotia-free seed helps reduce primary inoculum level. This can be done by hand picking with the help of a gravity separator (Nicholas 1975), or by immersing contaminated seed in 10% common salt solution (Nene and Singh 1976) to separate sclerotia floating at the surface. However, there is no efficient method available to separate sclerotia from seed on a larger scale.

## Biocultural-Pollen Management

In several field experiments it was clearly demonstrated that ergot in $F_1$ hybrids can effectively be controlled (79.5% reduction in ergot) by strategically planting a less-susceptible, early-maturing line as a pollen donor to the hybrid (Thakur et al. 1983d). An experiment at Hisar in north India (Thakur 1983) produced similar results. This approach for ergot control, which is based on pollination-induced resistance seems to have promise, but needs wider testing before being recommended to farmers. This practice can effectively reduce smut infection as well.

## Host-Plant Resistance

Resistant cultivars are the most effective and economical means to control disease. Development of a resistant cultivar involves:

1. Development of an effective field-based screening technique.
2. Identification of resistance sources by screening and breeding lines.
3. Determination of resistance stability through multilocational testing.
4. Understanding the genetics and mechanism(s) of resistance.
5. Utilization of resistance to breed disease-resistant cultivars.

Researchers have made significant progress in understanding host-plant resistance to ergot and smut.

## Ergot

An effective, field-based, screening technique has been developed (Thakur et al. 1982): bagging the panicles at the boot stage, inoculating the protogynous inflorescences with aqueous suspension of conidia from honeydew, rebagging immediately after inoculation, and irrigating by overhead sprinklers to maintain the high relative humidity necessary for ergot infection and development. Plants are scored for percentage ergot severity 20 d after inoculation (Thakur and Williams 1980) and resistant plants with good selfed seed are selected. This technique is precise, effective, and may be easily transferable. It is used twice each year during the rainy and postrainy seasons at ICRISAT Center, and only during the rainy season at Punjab Agricultural University (PAU), Ludhiana, and other locations in India.

A large number of accessions and breeding lines have been screened at ICRISAT Center since 1975, but lines with satisfactory levels of ergot resistance have not been detected. Ergot-resistant lines have, however, been developed by intermating less susceptible plants and selecting the resistant progenies under high disease pressure for several generations following pedigree and recurrent selection (Gill et al. 1980, Chahal et al. 1981, Thakur et al. 1982). At the Punjab Agricultural University (PAU), Ludhiana, this program began in 1977 following recurrent selection in the full-sib progenies of 11 inbred lines with less susceptibility. The frequency of resistant plants (<5% ergot severity) has increased from 2.5 in 1977 to 77.1% in 1984 (S.S. Chahal, PAU, personal communication). The progenies of these plants need to be evaluated at other locations to test the resistance stability.

Stability of ergot resistant lines has been tested (Thakur et al. 1985) through a multilocational International Pearl Millet Ergot Nursery (IPMEN). Several lines have shown high levels of ergot resistance across-location in India and West Africa over years (Table 1).

Ergot-resistant lines developed at ICRISAT Center were also screened for smut and downy mildew resistance, and many ergot-resistant lines have shown combined resistance to ergot, smut, and downy mildew (Table 2).

Table 1. Performance of some selected ergot-resistant lines in the International Pearl Millet Ergot Nursery (IPMEN) at one location in West Africa and six locations in India over 2-4 yrs (1981-84).

| | Mean ergot severity (%)[2] at locations[3] | | | | | | |
|---|---|---|---|---|---|---|---|
| Entry[1] | SMR | ABD | JMN | ICR | LDH | NDL | MYS |
| ICMPE 13-6-27 | 3 | 1 | 2 | 2 | 3 | 3 | 1 |
| ICMPE 13-6-30 | 1 | 1 | 2 | 2 | 4 | 2 | 4 |
| ICMPE 134-6-25 | 1 | 1 | 1 | 1 | 2 | 1 | 1 |
| ICMPE 134-6-34 | 1 | 1 | 1 | 1 | 2 | 1 | 1 |
| ICMPES 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 |
| ICMPES 2 | 1 | 2 | 1 | 1 | 1 | 2 | 5 |
| ICMPES 23 | 1 | 2 | 1 | 2 | 2 | 2 | 3 |
| ICMPES 27 | 1 | 1 | 1 | 1 | I | 1 | 1 |
| ICMPES 28 | 1 | 5 | 1 | 3 | 1 | 6 | 8 |
| ICMPES 32 | 1 | 15 | 2 | 4 | 2 | 1 | 8 |
| Susceptible Control | 86 | 79 | 44 | 93 | 65 | 49 | 54 |

1. ICMPE=ICRISAT Millet Pathology Ergot resistant line. ICMPES=ICMPE sib-bulk.
2. Of 20-40 inoculated heads in two replications.
3. Locations: SMR = Samaru (2 years' data), ABD = Aurangabad (3 years' data), JMN = Jamnagar (3-4 years' data), ICR = ICRISAT Center (3-4 years' data), LDH = Ludhiana (3-4 years' data), NDL = New Delhi (3-4 years' data), and MYS = Mysore (3 years' data)

Table 2. Performance of pearl millet inbred lines (ICMPE) and populations (ICMPES) with multiple disease resistance.

| Entry | Ergot severity (%)[1] | Smut severity (%)[2] | Downy mildew incidence (%)[3] |
|---|---|---|---|
| ICMPE 13-6-30 | 1 | 1 | 11 |
| ICMPE 34-1-10 | 6 | 1 | 1 |
| ICMPE 134-6-25 | 1 | 0 | 1 |
| ICMPE 134-6-34 | 1 | 0 | 1 |
| ICMPES 2 | 1 | 0 | 2 |
| ICMPES 9 | 7 | 1 | 8 |
| ICMPES 15 | 1 | 0 | 3 |
| ICMPES 16 | 2 | 0 | 3 |
| ICMPES 23 | 1 | 0 | 2 |
| ICMPES 28 | 4 | 0 | 2 |
| ICMPES 32 | 7 | 0 | 2 |
| ICMPES 34 | 1 | 1 | 1 |
| ICMPES 37 | 1 | I | 1 |
| Susceptible Control | 67 | 54 | 48 |

1. Based on 2 years (1983 and 1984) of testing at seven locations in the International Pearl Millet Ergot Nursery (IPMEN).
2. Based on the 1983 and 1984 IPMEN testing at two locations: Jamnagar and ICRISAT Center, India.
3. Based on the 1983 and 1984 IPMEN testing at six locations in India.

Ergot-resistant inbreds were sib-mated to produce sib-bulk populations (ICMPES) with improved agronomic traits and higher grain yield. Some of these populations possess high levels of resistance to diseases in addition to showing high grain-yield potential across locations in India (Table 3).

In most or all ergot-resistant lines, resistance seems to operate through short protogyny, rapid anthesis, and stigmatic constriction. Rapid development of constriction in the stylar tissue from pollination or aging leads to stigma withering and prevents ergot infection (Thakur and Williams 1980, Willingale and Mantle 1985, Willingale et al. 1986).

The genetics of ergot resistance is relatively complex. Resistance is recessive and polygenically controlled (Thakur et al. 1983c) but there is a need for more genetic investigations to clearly understand the resistance. An ultimate goal is to breed hybrids and varieties with ergot resistance at ICRISAT Center (Andrews et al. 1985), PAU, and other centers in India. At ICRISAT Center, some of the ergot-resistant lines have been identified as maintainers on established male-sterile lines and their conversion into male-sterile lines is in progress. This is encouraging for breeding ergot-resistant hybrids in the future.

A recurrent selection program has been continuing at PAU and several ergot-resistant composite

Table 3. Mean grain yield and disease reactions of five selected ergot-resistant populations (ICMPES).

| Entry | Yield (kg ha$^{-1}$)[1] | Ergot severity (%)[2] | Smut severity (%)[3] | Downy mildew incidence (%) |
|---|---|---|---|---|
| ICMPES 8 | 2210 | 1 | 0 | 0 |
| ICMPES 28 | 2170 | 0 | 0 | 0 |
| ICMPES 29 | 2050 | 0 | 0 | 0 |
| ICMPES 32 | 1970 | 1 | 1 | 0 |
| ICMPES 9 | 1940 | 1 | 0 | 1 |
| WC-C75 (control) | 1942 | 45 | 29 | 0 |
| SE | ±229 | | | |
| Mean | 1730 | | | |
| CV (%) | 23 | | | |

1. Mean of seven locations: ICRISAT Center high fertility, ICRISAT Center low-fertility, ICRISAT Center ergot nursery, Aurangabad, Pune, Bhavanisagar (all rainy season 1984), and ICRISAT Center, postrainy season 1984. Plot size 6 m$^2$.
2. Based on open-head inoculation in ICRISAT Center ergot nursery, rainy season, 1984.
3. Based on screening in the ICRISAT Center multiple disease nursery, rainy season 1984.

varieties have been bred. At ICRISAT an ergot-resistant composite has been formed by intermating 52 ergot resistant sib-bulks. Recurrent selection on this composite is in progress to select inbreds to be used as pollinators of hybrids and to produce open-pollinated varieties.

## Smut

An effective smut screening technique (Thakur et al. 1983b) has been developed: inoculating the plants at the boot-leaf stage with an aqueous suspension of *T. penicillariae sporidia.* grown on potato agar at 30°C for 3-5 d, covering the boot with parchment-paper selfing bags immediately after inoculation, and irrigating with overhead sprinklers to maintain the high relative humidity necessary for smut infection and development. Plants are scored for percentage smut severity 25-30 d after inoculation using the same scoring scale as for ergot (Thakur and Williams 1980) and resistant plants with good selfed seed are selected. This technique is precise, effective and easily transferable and has been used every year in 2 ha at ICRISAT Center during the rainy season and on a smaller scale at other locations.

There had been very few efforts prior to 1970 to screen and identify resistance. Murty et al. (1967) reported several accessions from Africa and India to be resistant and subsequently many other smut-resistant lines were reported (Yadav 1974, Pathak and Sharma 1976). But resistance stability of these lines was not confirmed, and there are no reports on utilization of these lines in resistance breeding programs. Since 1976, a systematic screening program at ICRISAT Center has identified many smut-resistant lines. Resistance stability of these lines has been determined through an International Pearl Millet Smut Nursery (IPMSN) at several locations in India and West Africa (Thakur et al. 1986). Lines with stable resistance are now available for use in breeding programs. In addition, some of these lines have shown high levels of resistance to downy mildew and improved agronomic traits (Table 4).

Information on genetics and the mechanism of smut resistance is limited. Yadav (1974) reported resistance to be controlled by either single or double genes. Observations at ICRISAT Center indicate resistance to be dominant and easily transferable (R.P. Thakur, ICRISAT, personal communication). Studies on inheritance and genetics of resistance are needed to clearly devise an effective resistance breeding strategy.

At ICRISAT Center, smut resistance is being incorporated in hybrids and varieties (Andrews et al. 1985). In hybrids, resistance is being.transferred to both parents. Smut-resistant lines which have been identified as maintainers are being converted into male-sterile lines by backcrossing.

Considerable progress has been made at ICRISAT Center in breeding smut-resistant varieties through recurrent selection and synthetic-breeding. Several population varieties have been derived from a smut-resistant composite, constituted in 1978, and a few synthetic varieties have been produced by directly using smut-resistant inbreds. In multilocational trials two population varieties, ICMV 82131 and ICMV 82132, and two synthetics, ICMS 8282 and ICMS 8283, have shown high levels of resistance to smut and downy mildew, and ICMV 82132 and ICMS 8283 have yielded more than the standard control WC-C75 (Table 5). Both these varieties have been entered in the AICMIP testing system.

## Future Control Strategies

The most effective and economical control of ergot and smut is through host-plant resistance. Pearl millet, a highly cross-pollinated species, is geneti-

Table 4. Performance of some selected smut-resistant lines in the International Pearl Millet Smut Nursery (IPMSN) during 1978-84.

| | Mean smut severity (%)[2] at | | | | Mean[3] Downy mildew incidence (%) |
|---|---|---|---|---|---|
| Entry[1] | Hisar | ICRISAT Center | Jamnagar | Bambey | |
| SSC FS 252-S-4 | 0 | 0 | 1 | 1 | 1 |
| ICI 7517-S-l | 1 | 1 | 1 | 1 | 1 |
| EBS 46-1-2-S-2 | 1 | 1 | 1 | 1 | 1 |
| EB 112-1-S-1-1 | 1 | 0 | 0 | 1 | 2 |
| NEP 588-5690-S-84 | 1 | 1 | 1 | 1 | 1 |
| P 489-S-3 | 1 | 0 | 1 | 4 | 1 |
| ICMPS 100-5-1 | 0 | 0 | 0 | 1 | 1 |
| ICMPS 200-5-5-5 | 1 | 0 | 0 | .4 | 1 |
| ICMPS 700-1-5-4 | 1 | 0 | 0 | - | 1 |
| ICMPS 900-3-1 | 1 | 0 | 0 | 1 | 1 |
| ICMPS 1300-2-1-2 | 1 | 0 | 0 | - | 2 |
| ICMPS 1400-1-6-2 | 1 | 0 | 0 | - | 1 |
| ICMPS 1500-7-3-2 | 0 | 0 | 0 | - | 1 |
| Susceptible control | 38 | 76 | 30 | 37 | 49 |

1. SSC = Super Serere, Uganda; ICI = ICRISAT inbred; EB = Ex Bornu, Nigeria; NEP = Lebanon; P = Mali; ICMPS = ICRISAT Millet Pathology Smut resistant lines.
2. Based on 20-40 inoculated heads in two replications.
3. Mean of four locations: Gwalior, Hisar, Jamnagar, and ICRISAT Center.
4. Entries not tested.

cally diverse for various traits. Presently the ICRISAT Genetic Resources Unit holds about 17 000 accessions of pearl millet from different geographic regions. So far only a small proportion of this collection has been evaluated for disease resistance. Screening genetic resource accessions will continue to identify newer sources of resistance that could be utilized in breeding programs to further diversify the genetic resistance base in the cultivars.

Table 5. Disease reactions and grain yield of smut-resistant varieties.

| Entry | Smut severity (%)[1] | Downy mildew incidence (%)[2] | Grain yield $(\mathrm{kg\ ha^{-1}})$[3] |
|---|---|---|---|
| ICMV 82131 | 4 | 1 | -[4] |
| ICMV 82132 | 4 | 2 | 1870 |
| ICMS 8282 | 1 | 1 | - |
| ICMS 8283 | 1 | 1 | 1760 |
| WC-C75 (Control) | 13 | 2 | 1640 |
| BJ 104 (Control) | 52 | 49 | - |
| SE | | | ±53 |
| Mean | | | 1810 |

1. Mean of 3 locations: Gwalior, Jamnagar, and ICRISAT in 1984.
2. Mean of 4 locations: Gwalior, Jamnagar, Hisar, and ICRISAT in 1984.
3. Mean of 11 locations in India in International Pearl Millet Adaptation Trial 1984 (IPMAT).
4. Data not received.

There is a need to understand more about the biology of the ergot and smut pathogens: their cultural, morphologic, and pathogenic variations, and existence of pathotypes or races.

The epidemiology of the diseases needs to be better understood: the relative role of ascospores and conidia in ergot disease, the role of collateral hosts, and survival of ergot sclerotia, conidia, and smut teliospores under natural conditions. These factors are important to devise proper resistance-breeding procedures.

Tissue-culture techniques for detection of resistance and preservation of disease-resistant stocks should be explored. Studies on genetics and resistance mechanisms should receive more attention to better understand the genetic diversity in the available resistance sources. The greater the genetic diversity and more stable the sources of resistance, the better the chances are of breeding more durable resistant cultivars.

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# Les insectes ravageurs du mil en Afrique de l'Ouest et les moyens de lutte

**Mbaye Ndoye[1] et Ruparao Gahukar[2]**

**Résumé**

*Dans la zone sahélienne de l'Afrique de l'Ouest, le mil (*Pennisetum americanum *(L.) Leeke) est attaqué par plusieurs espèces d'insectes appartenant à divers ordres. En général, ils sont répartis dans l'ensemble de la zone, mais leur incidence varie chaque année d'un site à l'autre. Dans les conditions actuelles de culture du mil, les foreurs des tiges (*Acigona ignefusalis, Sesamia *spp.) et la mineuse de l'épi (*Raghuva albipunctella*) tiennent une importance relativement élevée.*

*Des études concernant l'écologie des ravageurs ont été entreprises dans certains pays. Les techniques culturales ainsi que l'emploi des insecticides, de la résistance variétale et des ennemis naturels ont été expérimentés en vue de réduire les dégâts. Cependant, l'application de la lutte intégrée dans le cadre de l'agriculture paysanne nécessite encore des données complémentaires sur les seuils économiques et les problèmes socio-économiques.*

## Introduction

Le mil (*Pennisetum americanum*), parfois appelé mil à chandelle, millet ou petit mil, est la principale culture vivrière dans la zone sahélienne de l'Afrique de l'Ouest, qui s'étend sur huit pays : Iles du Cap-Vert, Sénégal, Gambie, Mauritanie, Mali, Burkina Faso, Niger et Tchad (Fig.1).

Dans cette région les cultures de mil sont fortement attaquées par des ravageurs de divers ordres : oiseaux granivores, insectes, champignons pathogènes et mauvaises herbes. Parmi ceux-ci, les plus remarquables sont les insectes signalés déjà par Risbec (1950) et Appert (1957) et confirmés par NDoye (1979a).

Les ravageurs du mil se trouvent dans tous les pays de la région, mais leur incidence varie selon la pluviométrie et le cycle des cultures; *sesamia*, par exemple, attaque le mil tardif dans la zone à pluviométrie élevée, alors que *Acigona* abonde dans les zones relativement sèches.

La détérioration des conditions pluviométriques de la zone sahélienne au cours des quinze dernières années, est accompagnée d'une aggravation de la contrainte entomologique à la production du mil. Ce fait fut noté par les délégués des pays sahéliens lors de la consultation gouvernementale sur les besoins du Sahel en matière de protection des cultures et des récoltes (FAO 1976) : plusieurs ravageurs dont l'importance économique était négligeable dans le passé, étaient devenus ces dernières années d'importance économique grave, plus particulièrement après la période de sécheresse et le retour de précipitations plus normales, mais en partie aussi, à cause de l'intensification et de la diversification de l'agriculture et de la pratique des cultures de contre-saison.

## Insectes ravageurs du mil

### Ravageurs de la plantule

Le mil est généralement semé en sec de sorte que la levée a lieu après les premières pluies. Les jeunes plantules sont alors exposées à de nombreux prédateurs. Une attaque précoce des iules (*Peridontopyge*

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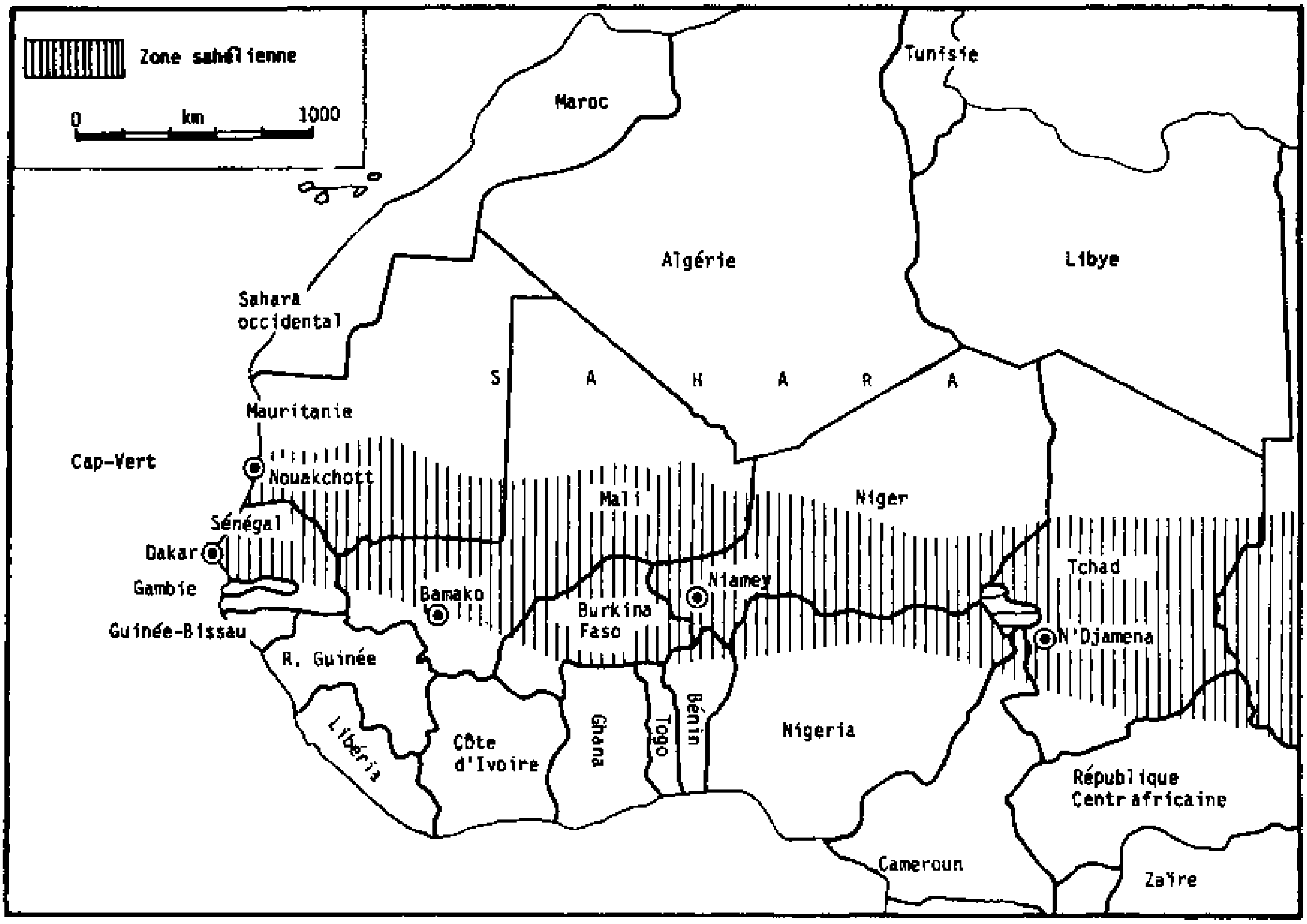


**Figure 1. Zone Sahélienne de l'Afrique de l'Ouest.**

spp.) nécessite souvent des resemis. Dans le groupe des sauteriaux, *Scapsipedus marginatus*, coupe les jeunes pousses à la base.

Jusqu'à cinq à six semaines après la levée, le mil est susceptible d'être attaqué par les mouches la plus abondante étant *Atherigona soccata*, surtout chez les semis tardifs (Deeming 1971). Les larves coupent les plantules à travers le "coeur", entraînant le jaunissement des feuilles médianes qui se dessèchent par la suite. En cas d'attaque tardive, la plante émet des talles non productives.

Les chrysomèles (*Lema planifrons, Chaetocnema tibialis*, etc.) se multiplient sur les feuilles où ils se nourissent de l'épiderme et du parenchyme provoquant ainsi des taches claires sur le feuillage. Les dégâts sont aggravés par la sécheresse car les feuilles se dessèchent entraînant la mort de la plante.

## Ravageurs du feuillage

Certaines espèces de chenilles lépidoptères s'attaquent de manière sporadique au feuillage du mil pendant la croissance végétative et reproductive. Les larves de première génération de *Spodoptera exigua, S. exempta* et *S. littoralis* ainsi que *Amsacta moloneyi* se présentent juste après la levée en causant des dégâts appréciables, souvent localisés (NDoye 1978). Les larves sont grégaires et se déplacent en bandes. Les larves de *Mythima lorevi* sont voraces et se trouvent souvent dans le verticille mais leur population est toujours limitée. Tous ces lépidoptères sont abondants en août.

Les sauteriaux infestent les graminées y compris le mil (Launois 1978). D'importants dégâts d'*Oedaleus senegalensis, O. nigeriensis, Higeroglyphus daganensis, Chrotogonus* spp. sont souvent notés en Mauritanie et au Niger.

Le puceron *Rhopalosiphum maidis* devient important quand la sécheresse se prolonge. Du fait de sa reproduction parthénogénétique, cette espèce peut développer une quarantaine de générations dans l'année. Les larves et adultes se trouvent au fond du verticille, sur les feuilles et les grains laiteux où ils succent la sève de la plante. Le développement de la plante est donc retardé. Ce puceron est également un vecteur de maladies virales. Quelques punaises (*Aspavia armigera, Calidea* spp., *Nezara viridula* et *Diploxis* sp.) succent la sève des jeunes feuilles mais leur incidence est toujours faible. Au Burkina Faso, le jaunissement des feuilles chez les plantes âgées est souvent occasionné par les larves du cercopide *Poophilus costalis* (Bonzi 1981).

## Foreurs des tiges

Plusieurs espèces de foreurs infestent le mil, à partir d'un mois et demi jusqu'à la récolte (Gahukar 1984). Les foreurs les plus remarquables sont : *Acigona ignefusalis* et *Sesamia calamistis*; le premier chez les variétés précoces et le deuxième chez les variétés tardives. La biologie et l'écologie de ces foreurs africains polyphages ont été étudiées par Ingram (1958), Harris (1962) et Usua (1968). Les larves d'*Acigona* rongent les feuilles du verticille et pénètrent dans les nervures principales; elles creusent ensuite la tige (Fig. 2) au-dessus d'un noeud et se nourrissent de la moelle des tiges. Les dégâts provoquent le dessèchement des feuilles médianes (coeur mort). La plante réagit en émettant des talles axillaires mais elles demeurent stériles. Les larves de *Sesamia* pénètrent directement dans la tige; elles endommagent le pédoncule et provoquent la verse de la plante.

*Acigona* peut compléter deux à trois générations durant la campagne agricole. Les adultes sortent à peu près un mois après les premières pluies. Les larves passent la saison sèche en diapause dans des tiges et les chaumes laissés au champ après la récolte et dans des tiges utilisées pour faire des tapades, qui servent alors de source d'infestation (Gahukar 1983a). L'incidence saisonnière des larves et de la population des papillons dépend de plusieurs facteurs tels que le stade de développement du mil, les conditions climatiques, etc. D'importants dégâts ont été observés sur les variétés traditionnelles au Mali (Doumbia et al. 1984), au Burkina Faso (Bonzi 1977), au Sénégal (NDoye 1977) et au Niger (Maiga 1984, ICRISAT 1984). En général, les foreurs sont actifs en août et septembre, cependant on a observé des larves de *Sesamia* même en novembre (Doumbia et al. 1984), car celles-ci n'entrent pas en diapause et peuvent se multiplier sur les plante-hôtes secondaires pendant toute l'année.

**Figure 2. Dégats d' *Acigona ignefusalis* sur la tige de mil.**

## Ravageurs de l'épi

Plusieurs insectes appartenant à divers orders s'attaquent au mil du début de la floraison jusqu'à la récolte. Leurs dégâts ont une incidence directe sur le rendement.

Cinq espèces de cécidomyies du mil (*Geromyia penniseti, Contarinia sorghicola, Lasioptera* sp., *Lestodiplosis* sp., *Stenodiplosis* sp.) sont présentes en Afrique de l'Ouest (Coutin et Harris 1968). *G. penniseti*, l'espèce la plus abondante est répandue dans le Sahel. Au Mali, Doumbia et al. (1984) ont identifié quelques plantes-hôtes secondaires de *Geromyia penniseti* telles que *Echinochloa stagnina, E. colonum, Pennisetum pedicellatum, P. asperifolium* et *Setaria pallidefusca*. Les dégâts sont infligés par la larve qui se nourrit sur l'ovaire et fait avorter le grain. Les glumes des fleurs attaquées conservent la forme plate. L'incidence varie considérablement; les variétés tardives étant plus attaquées lorsque des plantes à cycles différents sont cultivées ensemble ou à proximité dans la même région. La pullulation de la cécidomyie se situe normalement en septembre. A la fin de la saison de culture, les larves entrent en diapause puis en quiescence, à l'intérieur des épillets au contact des grains attaqués. Le cycle biologique est bouclé en deux semaines à la période de culture, le ravageur peut alors compléter quatre à cinq générations au cours d'une campagne agricole.

Deeming (1979) a identifié la mouche, *Dicraeus pennisetivora*, qui se trouve sur les grains en formation au Burkina Faso, au Sénégal et au Nigéria. L'attaque précoce de l'insecte se manifeste par le dessèchement complet de l'ovaire, alors que l'attaque tardive cause des lésions sur les graines.

Les mineuses de l'épi sont devenues les ravageurs les plus importants depuis la sécheresse des années

1972-74. Ce complexe comprend plusieurs espèces des genres *Raghuva, Masalia* et *Adisura* (Vercambre 1978, Laporte 1977, NDoye 1979b). L'espèce dominante et la plus nuisible au Sénégal est *R. albipunctella* (NDoye 1979b, Bhatnagar 1984) qui se rencontre dans tous les pays sahéliens. Les jeunes larves perforent les glumes et dévorent l'intérieur des fleurs, trahissant leur présence par des excréments en forme de petits granulés blanchâtres. Les larves âgées coupent les pédoncules floraux selon un tracé en spirale caractéristique, empêchant ainsi la formation du grain ou provoquant sa chute (Fig. 3). Sa biologie a été étudiée par Vercambre (1978) et Guèvremont (1982, 1983). En général, l'ampleur des dégâts dépend de plusieurs éléments dont : la coïncidence entre le vol des adultes et la période de début épiaison du mil (NDoye 1979c), la densité de la population larvaire, la réaction de la plante aux ravageurs et aux dégâts. La période d'activité du ravageur se situe normalement en août et septembre (NDoye 1979a; Guèvremont 1982, 1983). A la fin de la saison de culture, les larves âgées descendent au pied de la plante pour se nymphoser dans le sol où les chrysalides entrent en diapause et restent inactives. Les papillons émergent environ un mois après les premières pluies. Il n'y a qu'une seule génération par an (Fig. 4).

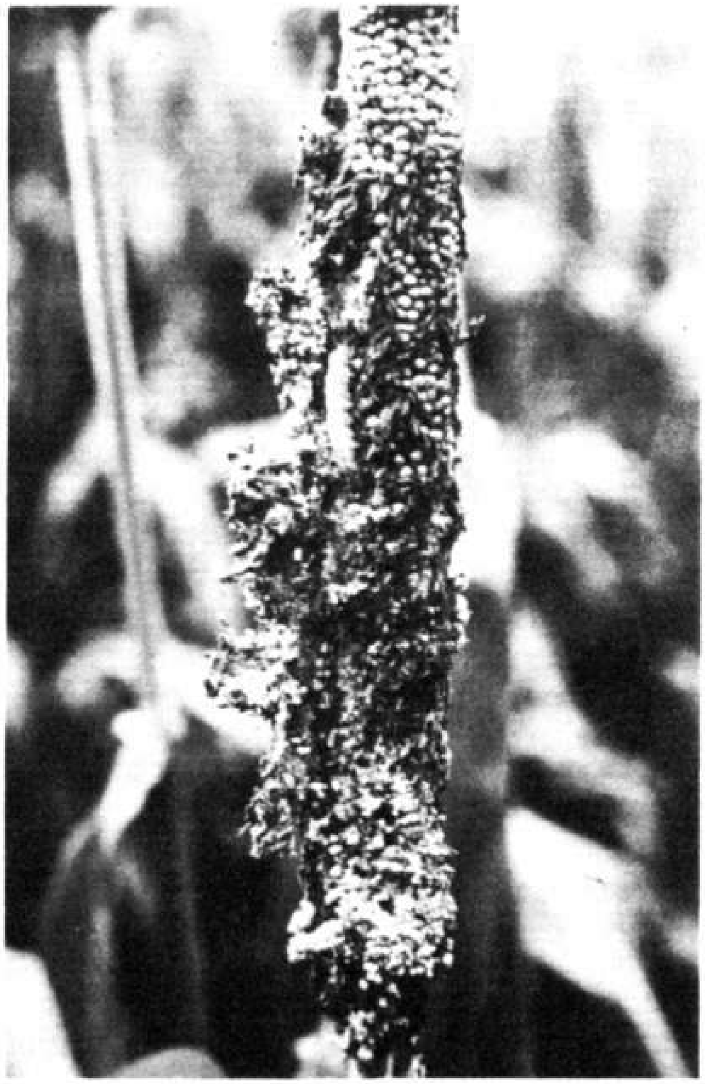

**Figure 3. Dégâts de *Raghuva albipunctella* sur l'épi de mil.**

Les chrysalides se trouvent dans l'horizon superficiel du sol (5-15 cm de profondeur) en terrain argileux alors qu'elles s'enfoncent plus profondément (15-30 cm) en terrain sableux.

D'autres lépidoptères tels que *Heliothis armigera, Eublemma gayneri, Pyroderces* spp. et *Celama* spp., se nourrissent des grains en développement, les coupant parfois en petits morceaux. Actuellement, ces insectes sont occasionnels ou d'une moindre importance mais leur incidence risque d'accroître chez les variétés à épis compactes qui facilitent l'hébergement des larves tout en les protégeant de leurs parasites.

Certaines espèces de Méloidés considérées nuisibles au mil sont également présentes dans le Sahel. Récemment, on a noté en Gambie, en Mauritanie et au Mali, une grande pullulation des espèces suivantes aux champs (Magema 1984, Doumbia et al. 1984, Zethner et Oliver 1984) : *Psalydolytta fusca, P. vestita, P. flavicornis, Cyaneolytta* spp., *Mylabris holosericea* et *M. pallipes.*

Leur distribution n'est pas encore bien connue, ni leur importance relative. Mais si le ravageur se manifeste en grand nombre au moment de la floraison des variétés locales, la récolte peut subir des pertes considérables. Les adultes dévorent le pollen et les fleurs femelles, ils sont responsables de l'avortement des grains ce qui rend stériles les épis. Les périodes de pullulation varient d'un endroit et d'une année à l'autre, mais elles se produisent le plus souvent en septembre (Doumbia et al. 1984).

On a parfois constaté des dégâts des scarabaeides, en particulier, *Pachnoda* spp., *Anomala senegalensis* et *Rhinyptia reflexa* sur les grains en maturation.

L'incidence des punaises au stade laiteux se manifeste par des taches crayeuses, noirâtres sur les grains ou des grains atrophiés. Les espèces d'*Agonoscelis versicolor, A. pubenscens, Diploxys* spp. et *Spilostethus* spp. sont actuellement les plus importantes.

La forficule (*Forficula senegalensis*) qui occupe la gaine sous-paniculaire, occasionne des stries rousses sur les feuilles entraînant leur jaunissement et ronge les fleurs et les grains laiteux.

Il faut enfin signaler *Melyris abdominalis* (Coléoptère, Melyridae) qui produit des dégâts assez variables chez les mils tardifs dans le sud du Sénégal.

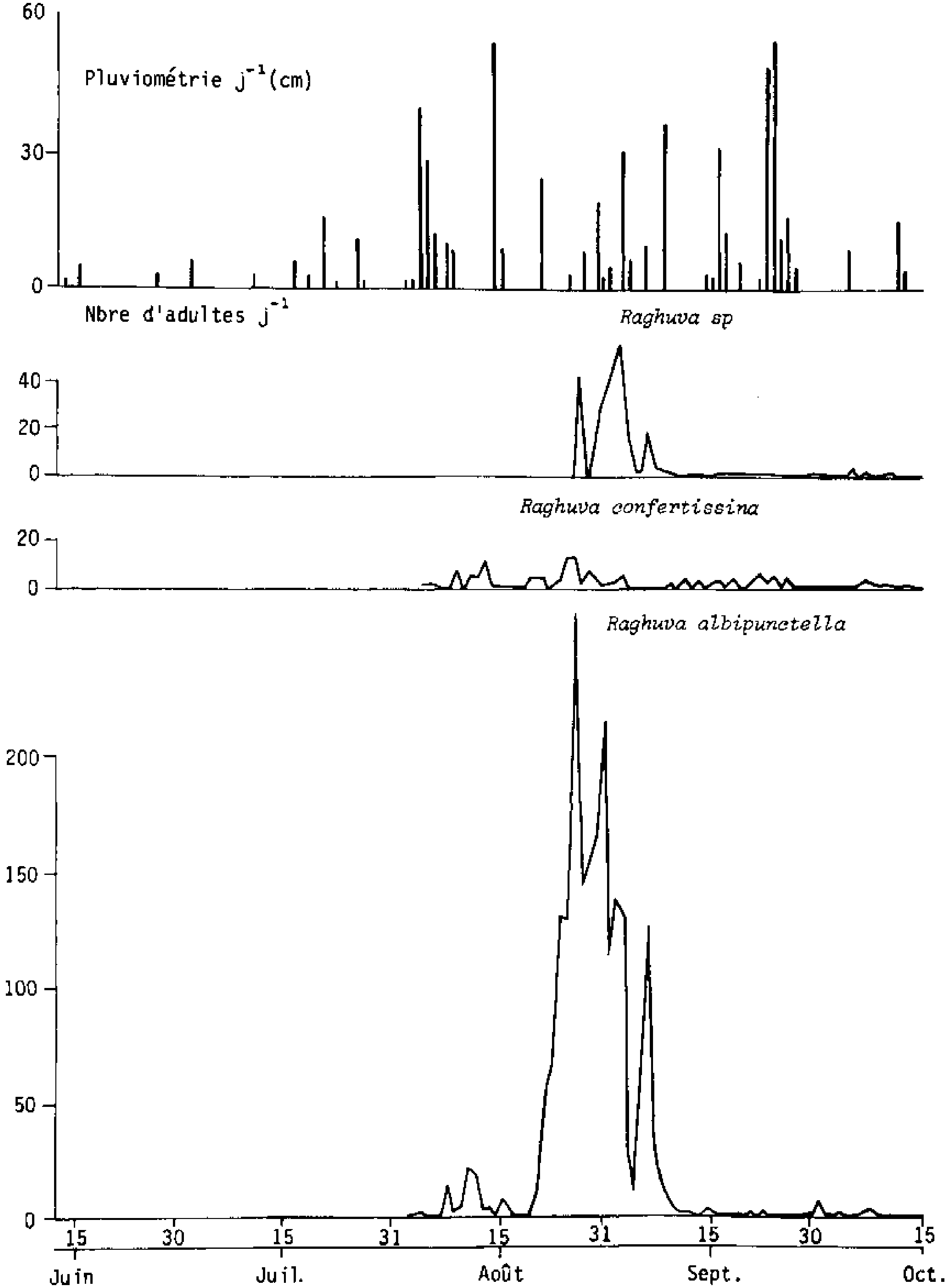


**Figure 4. Courbe de vol de la chenille des chandelles de mil au Sénégal, 1978.**

## Importance économique des insectes du mil

L'importance économique des insectes ravageurs dans la production du mil est reconnue au niveau global sans que des études adéquates soient consacrées à l'importance relative des différents groupes ou espèces.

Quelques travaux effectués au Nigéria et au Sénégal montrent que les foreurs des tiges, (Harris 1962, Bonzi 1977, NDoye 1977), la cécidomyie (Coutin et Harris 1968) et les mineuses de l'épi (Bos 1983) sont des ravageurs redoutables d'après les pertes fréquentes enregistrées. Malgré les dégâts élevés dus aux Méloidés en Mauritanie, en Gambie et au Mali, il manque une évaluation précise de la situation. La mineuse de l'épi, devenue un problème inquiétant depuis la sécheresse des années 1970, est aujourd'hui considérée comme le principal ravageur du mil dans le Sahel.

## Moyens de lutte

### Pratiques culturales

**Utilisation des feux de bois.** Allumés pendant la nuit autour des champs de mil, les feux réduisent l'attaque des Méloidés sur les épis (Magema 1984). Cette pratique est bien connue en milieu rural dans le Sahel.

**Labour du sol.** Un labour profond soit à la fin d'hivernage soit avant le semis de la prochaine campagne peut réduire l'importante population de chrysalides de *Raghuva* en diapause dans le sol. Celles-ci sont alors exposées à la dessication et aux prédateurs, notamment, les oiseaux (Vercambre 1978).

**Brûlage partiel, ensachage et destruction des tiges.** Le brûlage partiel des tiges de mil juste après la récolte permet de détruire 61-84% des larves et 98-100% des chrysalides d'*A. ignefusalis*. De même, l'ensachage des tiges dans des sacs en plastique a donné un taux de réduction de 66-78% et 99% respectivement (Gahukar et al. sous presse). Ces deux méthodes, lorsqu'elles sont exécutées judicieusement, n'affectent pas la qualité des tiges utilisées pour fabriquer des tapades, des clôtures ou des toits de maisons. Les tiges laissées parfois aux champs pour nourrir les animaux et, en même temps, réduire l'érosion éolienne abritent souvent des larves diapausantes d'*A. ignefusalis* qui y passent la saison sèche. Afin de réduire la population résiduelle du ravageur, les tiges sont brûlées ou coupées en morceaux pour le fourrage.

**Date de semis.** Le semis tardif des variétés à court cycle permet de baisser le taux d'infestation de la mineuse de l'épi (CNRA 1977, Vercambre 1978, Zethner et Oliver 1984) sauf dans le cas des variétés photosensibles qui fleurissent en même temps que la pullulation des papillons. La coincidence de l'épiaison et du pic d'activité de la population volante dans la région détermine l'ampleur des dégâts de ce ravageur (NDoye 1979c). Le décalage de la date de semis s'est montré comme un facteur efficace pour esquiver l'attaque.

**Conduite de la culture.** Les larves de certains défoliateurs tels que *Spodoptera* spp. et les sauteriaux peuvent se développer sur les graminées sauvages qui poussent dans le champ. Le sarclage permet d'extirper ces végétaux tout en favorisant le développement de la plante qui ainsi résiste mieux aux dégâts de ces ravageurs.

**Fertilisation.** L'apport d'engrais azoté améliore significativement la hauteur et le développement des plantes. On a constaté que les épis plus résistants sont relativement moins attaqués par la mineuse (Gahukar et al. sous presse). Pourtant, la dose de 50 kg N $ha^{-1}$ et 30 kg P $ha^{-1}$ n'a pas donné des résultats significatifs (Zethner et Oliver 1984). En fait, ces plantes sont plus susceptibles aux foreurs et risquent de se casser avant la récolte (Gahukar 1983b).

### Utilisation des insecticides

Une ou deux applications des insecticides suivants, effectuées à la floraison se sont révélées très efficaces contre les mineuses de l'épi : endosulfan à la dose de 525-700 mg m.a. $ha^{-1}$ (Vercambre 1978), chlordimeform à 750 g m.a. $ha^{-1}$ (CNRA 1977), Décis ULV (diméthoate + deltaméthrine) à 4 litres $ha^{-1}$ (Gahukar 1984) et trichlorfon (dipterex + triflurmuron) à 1 kg m.a. $ha^{-1}$ (Guèvremont 1982). Une seule application de Décis ULV, de thuricide (*Bacillus thuringiensis*) ou de dimilin (diflubenzuron) a permis de réduire le taux d'infestation et la population larvaire de *Raghuva* (Gahukar et al. sous presse). Le traitement effectué en début d'épiaison était plus efficace que celui de début de floraison ou début de maturation des grains.

Mais il faut signaler certains problèmes liés aux traitements d'insecticides : faible rentabilité, risque de verse de la plante en cas de traitements sur épis, phytotoxicité, techniques d'application, résidu dans les grains et les tiges.

L'application de HCH autour des feux de bois a permis de réduire le taux d'infestation de *Psalydolytta vestita* de 17 à 8% (CILSS 1985). Le Décis (50 g m.a. $ha^{-1}$) était plus efficace que le carbofuran (125-500 g m.a. $ha^{-1}$) contre les Méloidés (Doumbia et al. 1984).

Le fenitrothion quoique efficace dans la lutte contre la cécidomyie s'est révélé dangereux pour les parasites et les plantes; on a alors recommandé la phosalone (Coutin 1970).

## Résistance variétale

Du fait de l'absence de méthodes appropriées d'élevage de masse des insectes du mil en conditions contrôlées, les études sur la résistance variétale dans la zone sahélienne ont été menées sans infestation artificielle avec des oeufs ou de jeunes larves.

Les résultats disponibles concernent surtout la mineuse de l'épi (*Raghuva albipunctella*), le foreur des tiges (*Acigona ignefusalis*) et le complexe des Méloidés.

En ce qui concerne la mineuse de l'épi, le criblage en conditions d'infestation naturelle du matériel génétique local et introduit permet de déterminer le niveau et les mécanismes de résistance des différents génotypes.

Les variétés suivantes sont retenues comme résistantes à *R. albipunctella*: Souna, 3/4 HK-78, ICMS 7819, ICMS 7838, IBV 8001, H24-38, Nigerian Composite, HKB-Tif, CIVT, HKP, Zongo, Nieluva, Boudouma, IBMV 8302, INMG 1, INMG 52, INMV 5001, SRM-Dori, $P_3$ Kolo, ITV 8001, Kassblaga, Youmée-Nini, Tass-Yombo (Gahukar 1981, 1983b, 1984; ICRISAT 1984; Guèvremont 1982, 1983; Maiga 1984; CILSS 1985).

Cette résistance est due soit à la non préférence de la femelle pour la ponte (IBV 8001, ICMS 7838, Souna, ICMS 7819, H24-38), soit à l'antibiose vis-à-vis le ravageur (IBV 8001, 3/4 HK-78). Certains génotypes (H9-127, ICMS 7819) parviennent à minimiser les pertes occasionnées par la mineuse (tolérance), grâce à leur aptitude à produire, de nombreuses talles fructifères.

La coïncidence de l'émergence des épis avec le vol des papillons est un facteur essentiel qui est conditionné par la pluviosité, le cycle de la variété, la date de semis et les pratiques culturales. Par exemple, les variétés tardives telles que Sanio au Sénégal; NKK et CNM 127 au Mali; Sadoré, Torini, Haini Kirei et leurs hybrides au Niger (Gahukar 1983b, Doumbia et al. 1984, ICRISAT 1984); ou les variétés très précoces telles que Souna de Ségou (SRCVO 1980) ne sont pas attaquées par la mineuse (pseudo-résistance). Il y a donc une correlation significative entre le taux d'infestation et le cycle de maturation du mil ($r = -0{,}83$) et la période d'émergence de l'épi ($r = -0{,}70$ à $-0{,}88$) (ICRISAT 1981, Guèvremont 1982, 1983).

Quelques caractéristiques de l'épi seraient liées aux dégâts de *R. albipunctella*, notamment, la longueur et la position des soies ainsi que la longueur, la compacité et le diamètre de l'épi. De tous ces caractères, seule la compacité (mesurée par le nombre des fleurs ou grains) est étroitement liée aux dégâts ($r = 0{,}81$) (Guèvremont 1983, Gahukar 1984). Les épis compactes ainsi que les courtes soies involucrales et des pédoncules floraux chez la variété Souna du Mali seraient des éléments essentiels dans l'inhibition de l'oviposition et du développement des larves (Guèvremont 1982).

En ce qui concerne les foreurs, les variétés INMB 106, INMB 218, INMB 155 se sont montrées tolérantes au Niger (ICRISAT 1984). La variété Zongo produit une sécrétion qui inonde les galeries où les larves sont logées (NDoye 1977) : il s'agirait d'une résistance par antibiose.

En ce qui concerne les Méloidés, au Mali, Doumbia et al. (1984) n'ont trouvé aucune relation entre l'attaque et les caractères de l'épi (position des fleurs à l'intérieur des glumes; forme, longueur, orientation et rigidité d'aristation).

## Lutte biologique

Risbec (1950, 1960) a recensé les ennemis naturels (prédateurs, parasites et pathogènes) de la plupart des insectes ravageurs du mil. Récemment, on a identifié une vingtaine d'insectes auxiliaires (Tab. 1) qui s'attaquent aux divers stades de développement de *Raghuva* (Vercambre 1978; Gahukar 1981; Guèvremont 1982, 1983; Bhatnagar 1983, 1984). Parmi ceux-ci, *Bracon hebetor* (Braconidae), *Litomastix* sp. (Encyrtidae) et *Cardiochiles* spp. (Chalcididae) semblent les plus importants, le parasitisme pouvant atteindre un taux de 48% pour les oeufs, 95% pour les larves et 2% pour les chrysalides (Guèvremont 1983, Bhatnagar 1984). Malheureusement leur activité n'est significative qu'à la fin de la campagne, surtout, pendant les années sèches.

**Tableau 1. Prédateurs, parasites et pathogènes inventoriés sur les oeufs, les larves et les chrysalides de *Raghuva albipunctella* dans le Sahel.**

| Ordre | Famille | Espèce d'insecte/pathogène | Stade attaqué |
|---|---|---|---|
| Prédateurs | | | |
| Hémiptère | *Anthocorcidae* | *Orius* sp. | oeuf, larve |
| | *Pentatomidae* | *Glypsus conspicuus* Westw. | larve |
| | *Reduviidae* | *Ectomocoris fenestratus* Flug. | larve |
| | | *Katanga etiennei* Schoutedon | larve |
| Coléoptère | *Carabidae* | *Chlaenius boisduvalii* Dejean | larve |
| | | *C. dusaultii* Dufour | larve |
| | | *Pheropsophus* sp.nr.lafertei Arrow | larve |
| Hyménoptère | *Eumenidae* | non identifié | larve |
| | *Formicidae* | non identifié | larve, chrysalide |
| | *Vespidae* | *Polistes* sp. | larve |
| | *Chrysopidae* | *Chrysopa* sp. | larve |
| Parasites | | | |
| Hyménoptère | *Bethylidae* | *Goniozus* sp. | larve |
| | *Braconidae* | *Apanteles* sp. (Ultor group) | larve |
| | | *Bracon hebetor* Say | larve |
| | | *Bracon* spp. | larve |
| | | *Cardiochiles* sp. | larve |
| | *Chalcididae* | non identifié | larve |
| | *Encyrtidae* | *Litomastix* sp. | oeuf |
| | *Ichneumonidae* | *Hardromanus* sp. | chrysalide |
| | *Trichogrammatidae* | *Trichogrammatoidea* sp. | oeuf |
| Diptère | *Bombyliidae* | *Thyridanthrax* sp.nr. *kappa* Bowden | chrysalide |
| | *Tachinidae* | *Goniophthalmus halli* Mes. | larve |
| Nématode | *Mermithidae* | *Hexamermis* sp. | larve |
| Pathogènes | | | |
| Champignons | *Fungi-Imperfecti* | *Aspergillus flavus* Link ex Fr. | larve |
| | | *Aspergillus* sp. (Ochraceus group) | larve |
| Bactérie | | non identifiée | larve |

Les éléments essentiels de la biologie de ces trois parasites ont été établis ces dernières années, en vue d'explorer les moyens de leur utilisation comme agents de lutte biologique.

*B. hebetor* est un ectoparasite larvaire très actif dont le cycle biologique s'achève en 7-10 jours. Mais son efficacité est parfois limitée par des hyperparasites *Eurytoma* sp. (Pteromalidae) et *Pediobus* sp. (Eulophidae). Ce dernier pouvant attaquer jusqu'à 56% des parasites au Niger (Guèvremont 1983). *B. hebetor* vit aux dépens d'*Ephestia* sp. pendant la saison sèche dans les greniers. Son utilisation en tant que facteur de contrôle par transfert naturel du parasite aux champs de mil en août-septembre, est actuellement sous étude.

*Litomastix* sp. est un parasite polyembryonnaire oophage qui reste en diapause jusqu'en février quand il émerge des larves en prénymphose dans le sol. Jusqu'à 800 parasites ont été récupérés d'une seule larve et le parasitisme peut atteindre 80-90% dans des conditions favorables, pourtant le taux en plein champ n'a jamais dépassé 31% (Vercambre 1978, Bhatnagar 1984).

*Cardiochiles* sp. a parasité seulement 8% des larves durant la floraison du mil (Bhatnagar 1984); cependant, la diversification des cultures semble favoriser le parasitisme par une augmentation de la population des parasites. *Cardiochiles* sp. se développe en juillet-août sur *H. armigera* associé à *Acarthospium hispidium* et ensuite sur le même insecte hôte attaquant le maïs en août-septembre.

Les larves et les chrysalides d'*Acigona* sont attaqués par de nombreux parasites (Tab. 2) (Risbec 1950, NDoye 1977, Gahukar 1981). L'ichneumonide, *Syzeuctus* sp., est répandu au Sénégal et au Nigéria où il peut réduire la population larvaire jusqu'à 30% (Harris 1962, Bhatnagar 1984). Un autre parasite, *Goniozus procerae*, n'attaque qu'environ 2% des larves diapausantes (NDoye 1980).

Six parasites des larves et des pupes de la cécidomyie *Geromyia penniseti* ont été identifiés : *Tetyrastichus diplosidis, Platygaster* sp., *Aphanogmus* sp., *Eupelmus popa, Eupelmus* sp., *Tetrastichus* sp. Le plus important est *Tetrastichus* sp. (Eulophidae) qui représente 85% de la population parasitaire totale en fin de saison (Coutin et Harris 1968).

Des diptères parasites (*Heliocobia* sp.) ont été obtenus des adultes de *Mylabris holocericea* (CILSS 1985).

Les parasites sont peu actifs en saison sèche en raison des conditions climatiques et de la diapause de l'insecte hôte. Cette situation entraîne un décalage entre la dynamique du parasite et celle de l'insecte hôte. Bien que les ennemis naturels indigènes entraînent une forte diminution des populations de certains ravageurs, cette entomofaune auxiliaire n'arrive pas à maîtriser les infestations. L'introduction de parasites appropriés offrira une solution intéressante. Ceux-ci devraient présenter les caractéristiques suivantes : bonne capacité de rechercher l'in-

**Tableau 2. Prédateurs, parasites et pathogènes inventoriés sur les oeufs, les larves et les chrysalides d'*Acigona ignefusalis* dans le Sahel.**

| Ordre | Famille | Espèce d'insecte/pathogène | Stade attaqué |
|---|---|---|---|
| Prédateurs | | | |
| *Arachnida* | - | *Pyemotes ventricesus Newfs.* | larve |
| Parasites | | | |
| Diptères | *Chloropidae* | *Ceratopogon risbeci* Séguy | larve |
| | | *Epimadiza* sp. | chrysalide |
| | Phoridae | *Aphiochaeta* sp. | larve |
| | *Tachinidae* | *Sturmiopsis parasitica* Curr. | larve, chrysalide |
| Hyménoptères | | | |
| | *Bethylidae* | *Goniozus procerae* Risb. | larve |
| | *Braconidae* | *Apanteles sesamiae* Cam. | larve |
| | | *Euvipio rufa* Szepl. | larve |
| | | *E. fascialis* Szepl. | larve |
| | | *Glyptomorpha* sp. | chrysalide |
| | | *Rhaconotus soudanensis* Wilkn. | larve |
| | *Chalcididae* | *Hyporchalcidia sondanensis* Stef. | chrysalide |
| | *Encyrtidae* | *Euzkadia* sp. (? *integralis* Merc.) | larve |
| | *Eulophidae* | *Pediobius furvus* Gah. | chrysalide |
| | | *Tetrastichus atriclavus* Wtrst. | chrysalide |
| | *Ichneumonidae* | *Chasmias* sp. | chrysalide |
| | | *Dentichasmias busseolae* Hein | chrysalide |
| | | *Syzeuctus* spp. | larve |
| | *Scelionidae* | *Platytelenomus hylas* Nixon | oeuf |
| Pathogènes | | | |
| Champignon | - | *Metarrhizium anisopliae* (Met.) Sorok | larve |

secte hôte, spécificité à cet hôte, potentiel biotique élevé et bonne adaptabilité à l'environnement nouveau. A cet effet, l'échange de matériel entre l'Afrique de l'Est et de l'Ouest serait prometteur d'après les indications de Mohyuddin et Greathead (1970).

### Lutte intégrée

La lutte intégrée est une combinaison de diverses méthodes pratiques, efficaces et économiques, en vue de maintenir la population des ravageurs au dessous du seuil économique.

Plusieurs méthodes ont été expérimentées contre la mineuse de l'épi *R. albipunctella*, dont : choix d'une variété améliorée, IBV 8001, apparemment résistante aux insectes et aux maladies, lâchers de parasites en particulier, *Bracon hebetor*, et une seule application, en début d'épiaison, d'endosulfan, peu dangereux pour la faune auxiliaire.

Des études détaillées sur la biologie, l'écologie et les différents moyens de lutte sont nécessaires pour aboutir à une stratégie globale contre le complexe des insectes ravageurs du mil (NDoye et al. 1984).

Cette méthode est pratique et semble offrir la seule solution globale applicable dans les conditions actuelles de la production du mil dans le Sahel et en Afrique de l'Ouest.

## Conclusions et perspectives

L'analyse de la situation actuelle a amené les pays du Sahel à opter pour un programme global de lutte intégrée contre les ravageurs de toutes les cultures vivrières afin de les maintenir à un niveau inférieur au seuil économique.

La lutte intégrée qui vise à réunir toutes les méthodes appropriées, en tenant compte du milieu et de la dynamique des populations des ravageurs doit s'inscrire dans le cadre de l'agriculture paysanne dans le Sahel. Afin d'aboutir à une méthode praticable, il faut définir les points suivants : l'objectif de la lutte dans le cadre du système de production donné, et les contraintes éventuelles (biologique, technique, socio-économique, etc.) dans la conduite des opérations (Geiger 1982).

Les résultats obtenus par le Projet lutte intégrée du CILSS dans les pays du Sahel serviront à formuler une première stratégie de lutte; cependant cette approche se heurte à certaines difficultés. Des études approfondies sur le seuil économique, la biologie et l'écologie des principaux ravageurs sont indispensables; la recherche étant encore prioritaire, en attendant l'application des résultats acquis au niveau paysan.

La participation de tous les acteurs du développement est souhaitable pour assurer le succès.

La défense des cultures de mil devrait reposer sur une combinaison de la résistance variétale et de la lutte biologique; ce qui demande peu d'efforts de la part du paysan.

Le choix des techniques complémentaires, soit l'enfouissement ou le brûlage des tiges, soit le labour en fin de cycle dépendra de la nature du ravageur visé. La lutte chimique ne sera pas écartée à condition de faire un choix judicieux quant aux cibles et aux produits utilisés.

Le mil, culture vivrière de base dans le Sahel, sera cultivé dans la région malgré ces contraintes. Cependant une approche pluridisciplinaire aux problèmes phytosanitaires qui s'intègre parfaitement dans le système de culture apportera une solution durable tout en assurant un gain réel. Celui-ci ne saura être mesuré en termes économiques, mais plutôt en termes de stabilité de production. Une telle approche bénéficiera considérablement le paysan sahélien.

A fin d'y parvenir, il faudra poursuivre les inventaires et préciser la dynamique des principaux ravageurs, en particulier la mineuse de l'épi et les foreurs des tiges. Par ailleurs, l'exploitation des données sur la dynamique des populations permettra d'établir un système d'avertissement qui est à la base même de toute lutte intégrée. Enfin, il convient de renforcer le transfert des acquis de ces dernières années en milieu réel.

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# Insect Pests of Pearl Millet in West Africa and their Control

**Mbaye NDoye[1], and Ruparao Gahukar[2]**

***Abstract***

*In the Sahelian zone of West Africa, several orders of insects infest pearl millet. They occur throughout the region, however, pest incidence varies yearly from one location to another. Stem borers (*Acigona ignefusalis, Sesamia *spp.) and the spike worm (*Raghuva albipunctella*) are apparently major pests under present cropping conditions.*

*The ecology of the pests has been studied in some countries. Cultural techniques, insecticides, resistant varieties, and natural enemies have been tested to reduce pest damage. The application of integrated pest management strategies in subsistence agriculture requires further data on economic thresholds and socioeconomic problems.*

## Introduction

Pearl millet *(Pennisetum americanum)* is a major food crop of the West African Sahelian zone that extends through eight countries: Cape Verde, Senegal, Gambia, Mauritania, Mali, Burkina Faso, Niger, and Chad (Fig. 1).

In this area, a wide range of pests, including birds, insects, pathogenic fungi, and weeds are known to attack pearl millet. Of these, insect pests are the most injurious as reported by Risbec (1950) and Appert (1957), and recently confirmed by NDoye (1979a).

Although millet parasites occur throughout the Sahel, their specific incidence varies according to rainfall and cropping patterns. For example, *Sesamia* is present on late millets in high-rainfall regions, but *Acigona ignefusalis* is found in relatively dry areas.

The deficit rainfall conditions in the Sahel during the last 15 years have led to increased pest incidence. During the government consultation on the requirements of the Sahel for crop and postharvest protection (FAO 1976), it was unanimously agreed by the delegates from the Sahelian countries that "several economically unimportant pests have, during the past few years, become a serious economic constraint following the drought and subsequent return to normal conditions. This is also partially due to crop intensification and diversification and growing of off-season crops."

## Insect Pests of Pearl Millet

### Seedling Pests

Pearl millet is planted during the dry season. The crop emerges after the first rains, and seedlings are exposed to a number of pests. Myriapod *(Peridontopyge* spp.) attacks, especially in the early growth stages, often require the crop to be replaced. The grasshopper, *Scapsipedus marginatus,* cuts seedlings at the base.

Fly infestation, particularly the shootfly *Atherigona soccata* in late crops, occurs up to 5-6 weeks after emergence. The larvae are responsible for deadheart formation, which yellows and dries leaves. In case of a late attack, the plant generates nonproductive tillers.

Leaf beetles (*Lema planifrons, Chaetocnema tibialis,* etc.) multiply on the leaves, feed on the epidermis and parenchyma, and cause light colored spots

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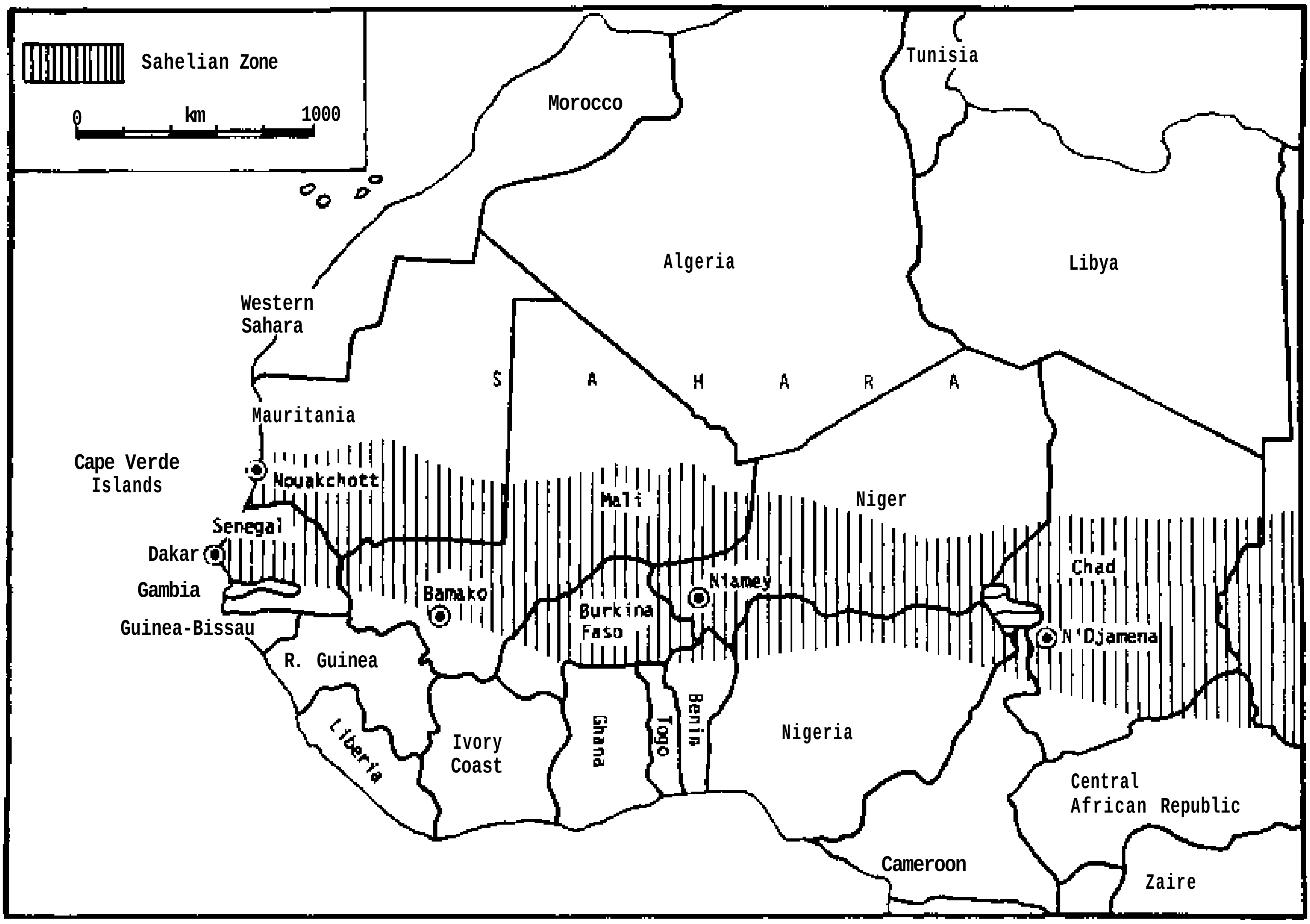


**Figure 1. West African Sahelian zone.**

to appear on the leaves. Drought conditions only aggravate the damage as the leaves wilt and the plant finally dies.

## Leaf Pests

Lepidopterous armyworms are important pests of millet foliage during the vegetative and reproductive stages, but their attack is sporadic. First-generation larvae of *Spodoptera exigua, S. exempta, S. littoralis,* and *Amsacta moloneyi* appear just after emergence, causing substantial, often localized damage (Ndoye 1978). The larvae migrate in gregarious bands. *Mythima loreyi* are found lodged in the leaf whorl; they are voracious leafeaters but their number is limited. All these armyworms are usually abundant in August.

Pearl millet is susceptible to grasshopper attack, as are other graminaea (Launois 1978). Severe damage by *OedaJeus senegalensis, O. nigeriensis, Hige-roglyphus daganensis,* and *Chrotogonos* spp. has often been recorded in Mauritania and Niger.

Aphids *(Rhopalosiphum maidis)* become active during periods of prolonged drought. Due to their parthenogenetic reproduction, aphids can produce up to 40 generations annually. The larvae and adults suck the sap from the leaf whorl, leaves, and milk-stage grain, thus retarding plant development. Moreover, the aphid is a vector for viral diseases. Certain bugs *(Aspavia armigera, Calidea* spp., *Nezara viridula, Diploxis* sp.) suck the sap of young leaves, but their incidence is low. In Burkina Faso, leaf yellowing in mature plants is often caused by larvae of the spittle bug *(Poophilus costalis)* (Bonzi 1981).

## Stem Borers

From 1.5 months after emergence until harvest, pearl millet is exposed to several species of borers (Gahukar 1984); the most important are *Acigona ignefusalis* on early varieties, and *Sesamia calamistis* on late varieties. The biology and ecology of these polyphagous African stem borers have been studied by Ingram (1958), Harris (1962), and Usua (1968).

*Acigona* larvae devour the leaf whorl by penetrating the main veins, then tunnel through the stems above the node level (Fig. 2) and feed on the stem pith. Subsequent dessication of the central leaves results in deadheart formation. The plant may develop axillary tillers but they are nonproductive. *Sesamia* larvae enter the stem directly, and are responsible for peduncle damage and plant lodging.

*Acigona* can complete 2-3 generations during the cropping season. The adults emerge about 1 month after the first rains. A source of infestation is larvae that pass the dry season in diapause in stalks and stubble left in the field after harvest, and panels made from plant stems (Gahukar 1983a). Seasonal incidence of both larval and adult stem borers depends on several factors, such as the stage of crop development, and climatic conditions. Severe damage has been observed on landraces in Mali (Doumbia et al. 1984), Burkina Faso (Bonzi 1977), Senegal (NDoye 1977), and Niger (Maiga 1984, ICRISAT 1984). Stem borers are generally active in Aug-Sep; however, *Sesamia* larvae have also been observed in November (Doumbia et al. 1984) because they have no diapause and can multiply on secondary plant hosts throughout the year.

## Head Pests

Pest damage caused between flowering and harvest has a direct effect on yield. Several types of insect pests have been reported at this stage.

Five species of the millet midge: *Geromyia penniseti, Contarinia sorghicola, Lasioptera* sp., *Lestodiplosis* sp., and *Stenodiplosis* sp., are present in West Africa (Coutin and Harris 1968). *G. penniseti*

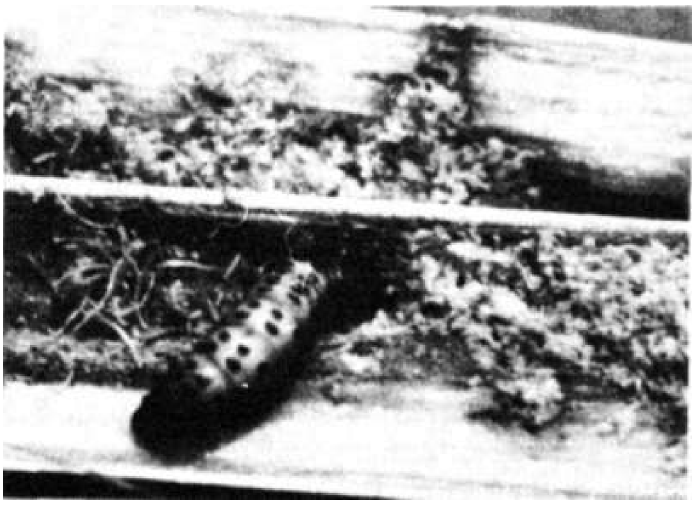

**Figure 2. *Acigona ignefusalis* damage on millet stems.**

is the most abundant and is common throughout the Sahel. In Mli, secondary plant hosts of *G. Penniseti* identified by Doumbia et al. (1984) include *Echinochloa stagnina, E. colonum, Pennisetum pedicellatum P. asperifolium,* and *Setaria pallidefusca.* Damage is caused by larvae feeding on the ovary, leading to grain abortion. Glumes of the infested florets retain their flat shape. Incidence varies greatly; it is high on late varieties when grown together with varieties of different duration in the same field of within the same region. Under normal conditions the brood emerges in September. At the end of the cropping season, the larvae enter dispause and then quiescence in the spikelets, attached to the infested grain. During the cropping season the life cycle is completed in 2 weeks, allowing 4-5 generations per season.

Deeming (1979) has reported the presence of a fly, *Dicraeus pennisetivora,* that attacks maturing grain in Burkina Faso, Senegal, and Nigeria. An early attack leads to total ovary dessication and a late attack causes lesions on the grain.

Spike worms have become major pests since the 1972-74 drought. This complex includes species of the *Raghuva, Masalia,* and *Adisura* genera (Vercambre 1978, Laporte 1977, NDoye 1979b). *R. albipunctella* is the most destructive species in Senegal (NDoye 1979b, Bhatnagar 1984); it is also widespread in all the Sahelian countries. The young larvae perforate the glumes and devour the floret core. They can be detected by the small whitish granular excreta. Mature larvae cut through the peduncles in a characteristic spiral, inhibiting grain formation or causing grain shattering (Fig. 3). The biology of the pest has been studied by Vercambre (1978) and Guevremont (1982, 1983). The extent of damage depends on synchrony of adult buildup with early heading (NDoye 1979c), density of larval population, and plant response to pests and damage. Peak activity normally occurs in August and September (NDoye 1979a; Guevremont 1982, 1983). At the end of the cropping season, the mature larvae descend to pupate in the soil where the pupae enter diapause and remain inactive. Adults emerge 1 month after the first rains. There is only one generation per year (Fig. 4).

In clayey soils the pupae lie close to the soil surface (5-15 cm deep), in sandy soils they are buried deeper (15-30 cm).

Other lepidopterous pests, e.g., *Heliothis armigera, Eublemma gayneri, Pyroderces* spp., and *Celama* spp. also feed on developing grain, often cutting them into small pieces. These pests are sporadic and

**Figure** 3. ***Raghuva*** *albipunctella* **damage** on millet **heads.**

of minor importance at present. But incidence increases in varieties with compact heads that support these insects and protect them from parasites.

Several species of blister beetles known to be millet pests are found in the Sahel. Significant field infestation of *Psalydolytta fusca, P. vestita P. flavicornis, Cyaneolytta* spp., *Mylabris holosericea,* and *M. palhpes* has been reported in Gambia, Mauritania, and Mali (Magema 1984, Doumbia et al. 1984, Zethner and Oliver 1984). The distribution and relative importance of these insects is not yet well known. Heavy infestation at flowering on local cultivars can cause considerable damage. Adults devour the pollen and female flowers and are responsible for grain abortion and head sterility. Time of population build up varies for each location and year, but occurs most frequently in September (Doumbia et al. 1984).

*Pachnoda* spp., *Anomala senegalensis, Rhinyptia reflexa,* and other scarab beetle species have sometimes been observed on developing grain.

Bugs damage grain at the milk stage. The symptoms are chalky black spots on the grain or atrophied grain. *Agonoscelis versicolor, A. pubenscens, Diploxys* spp., and *Spilostethus* spp. are the most frequent species.

*Forficula senegalensis* is found in the panicle sheath, and produces reddish-brown streaks on the leaves which subsequently turn yellow. They also devour the florets and milk-stage grain.

*Melyris abdominalis* (Coleoptera: Melyridae) is a pest of late millets in southern Senegal, causing variable damage.

## Economic Importance of Pearl Millet Pests

There is consensus that insect pests on the whole are injurious to pearl millet; however, specific studies have rarely been conducted on the relative economic importance of the different species or complexes.

Studies in Nigeria and Senegal confirm the importance of stem borers (Harris 1962, Bonzi 1977, NDoye 1977), millet midge (Coutin and Harris 1968), and spike worms (Bos 1983), as evidenced by frequent losses recorded in these countries. Recently, blister beetle damage has been observed in Gambia, Mali, and Mauritania, but no accurate evaluation has been made of the situation. Spike worms have assumed major pest status since the recent drought, and are a serious problem of pearl millet crops.

## Control Methods

### Cultural Techniques

#### Fire

It is a common practice in the rural Sahel to light fires around millet fields at night. This has been known to reduce blister beetle populations on the heads (Magema 1984).

### Tillage

Deep plowing either at the end of the rainy season or before planting the next crop can reduce large populations of diapausing *Raghuva* pupae in the soil. They are exposed to predators, mainly birds, or are dessicated (Vercambre 1978).

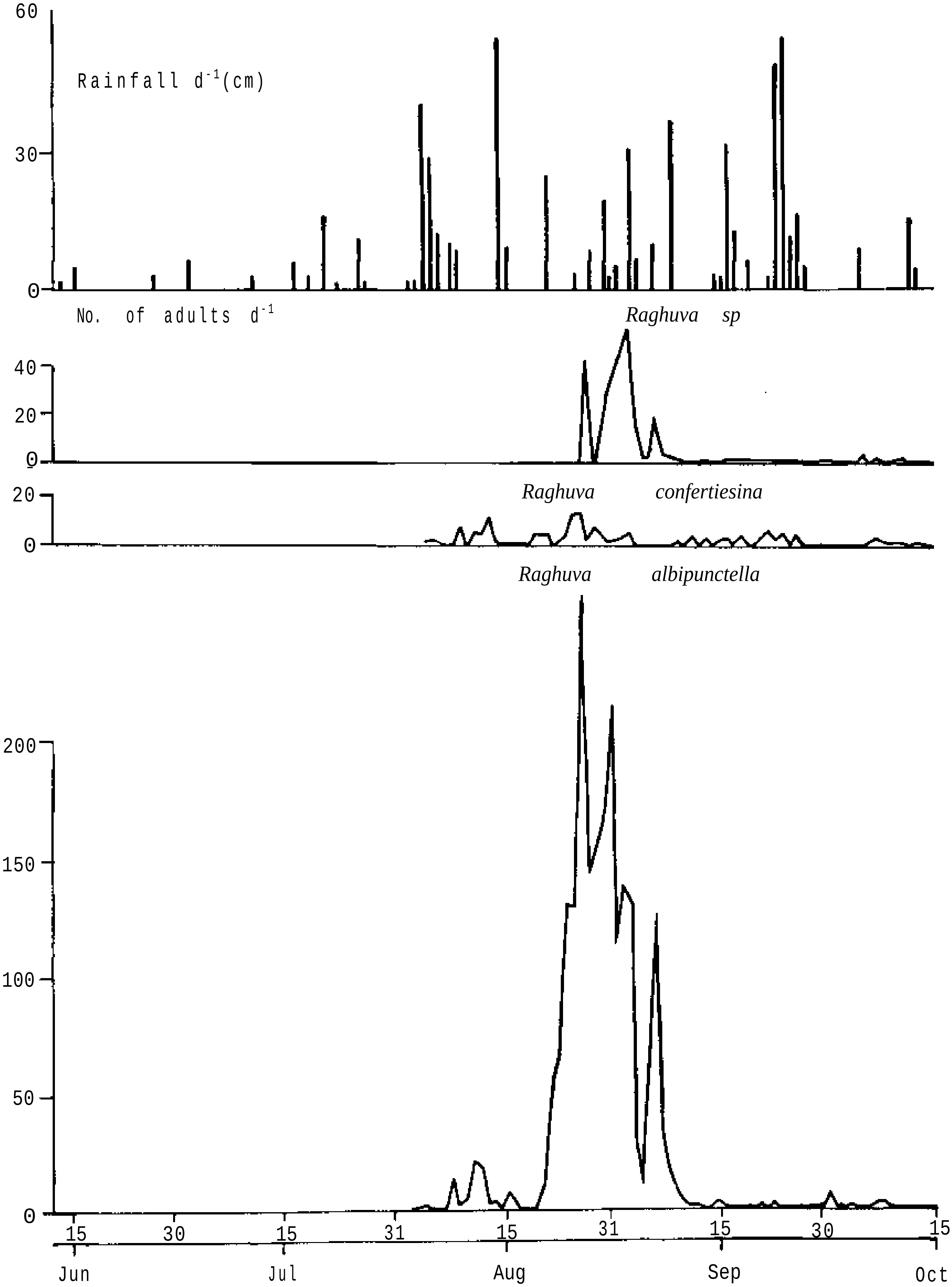


**Figure 4. Pest building for pearl millet spikeworm in Senegal, 1978.**

### Partially Burning, Bagging, and Destroying Stalks

Partially burning pearl millet stalks immediately after harvest destroys 61-84% of the larvae and 98-100% of the pupae of *A. ignefusalis*. The rate is 66-78% for larvae and 99%, for pupae when stalks are put in plastic bags (Gahukar et al. In press). These two methods, carried out carefully, do not affect the quality of stalks used for making walls, fences, or roofs. Stalks are sometimes left in fields to provide fodder for animals or to check wind erosion, but tend to support *Acigona* larvae during the dry season. Burning or cutting these stalks for animal feed, decreases residual populations of the pest.

### Planting Time

Late planting of short-duration varieties reduces spike-worm infestation (CNRA 1977, Vercambre 1978, Zethner and Oliver 1984). But photoperiod-sensitive, short-duration varieties flower when adult infestation is at its highest. The extent of damage is determined by the synchrony of adult peak activity with heading (NDoye 1979c). Delayed planting is an effective way to avoid pest attacks.

### Crop maintenance

Larvae of certain defoliators such as *Spodoptera* spp. and grasshoppers are likely to develop on wild grasses in the field. Removal of these weeds by hoeing also improves plant development and the ability to resist pests.

### Fertilizer

Nitrogen fertilization significantly increases plant height and improves plant growth. Heads are more vigorous and less prone to spike-worm attack (Gahukar 1985). However, 50 kg ha-» N and 30 kg ha"1 P did not significantly influence infestation (Zethner and Oliver 1984), infact, stem-borer incidence was higher, and caused stems to break before harvest (Gahukar 1983b).

## Insecticides

One or two applications at flowering of the following insecticides can effectively control spike worms: endosulfan 525-700 mg ha"1 a.i. (Vercambre 1978), chlordimeform 750 g ha"1 a.i. (CNRA 1977), Decis ULV (dimethoate + deltamethrine) 4 liters $ha^{-1}$ (Gahukar 1984), and trichlorfon (dipterex + triflurmuron) 1 kg $ha^{-1}$ a.i. 1 (Guevremont 1982). Similarly, a single application of Decis ULV, thuricide *Bacillus thuringiensis)* or dimilin (diflubenzuron) successfully checked infestation and larval populations of *Raghuva* (Gahukar et al. In press). Treatments applied at early heading were more effective than those at an early stage of flowering or grain filling.

Certain problems are related to insecticide treatments: low economic returns, risk of lodging in the case of head treatments, phytotoxicity, application techniques, and residue in grain and stalks.

Surrounding the field fires mentioned earlier with a band of HCH has decreased *PsaJydoJytta vestita* infestation from 17 to 8% (CLISS 1985). Decis (50 g $ha^{-1}$ a.i.) was more effective than carbofuran (125-500 g $ha^{-1}$ a.i.) against blister beetles (Doumbia et al. 1984).

Fenitrothion treatment effectively controlled midge infestation, but because it was hazardous to plants and beneficial parasites, phosalone was recommended instead (Coutin 1970).

## Varietal Resistance

Several studies on varietal resistance have been conducted in the Sahelian Zone, but without artificial infestation by eggs or young larvae, because appropriate methods for mass rearing millet pests have not yet been developed.

Available data chiefly concern the spike worm, *Raghuva albipunctella* the stem borer, *Acigona ignefusalis;* and the blister beetle complex. Screening of local and introduced germplasm provided valuable information on the mechanisms and level of spike-worm resistance of the different genotypes.

The following cultivars were classified as resistant to *R. albipunctella:* Souna, 3/4 HK-78, ICMS 7819, ICMS 7838, IBV 8001, H24-38, Nigerian Composite, HKB-Tif, CIVT, HKP, Zongo, Nieluva, Boudouma, IBMV 8302, INMG 1, INMG 52, INMV 5001, SRM-Dori, $P_3$ Kolo, ITV 8001, Kassblaga, Youmee-Nini, Tass-Yombo (Gahukar 1981, 1983b, 1984; ICRISAT 1984; Guevremont 1982, 1983; Maiga 1984; CILSS 1985).

This resistance is based either on ovipositional nonpreference (IBV 8001, ICMS 7838, Souna, ICMS 7819, H24-38) or on antibiosis (IBV 8001, 3/4 HK-78). Certain genotypes (H9-127, ICMS 7819) are capable of minimizing pest damage (i.e., have tolerance to the pest) because of their ability to produce a large number of tillers.

The synchrony of head emergence with peak activity of adults is determined by rainfall, cultivar duration, planting date, and cultural practices. For example, late varieties such as Sanio in Senegal; NKK and CNM 127 in Mali; Sadore, Torini, Haini Kirei, and their hybrids in Niger (Gahukar 1983b, Doumbia et al. 1984, ICRISAT 1984); or the very early varieties such as Souna from Segou (SRCVO 1980), are not attacked by the spike worm (pseudo-resistance). There is significant correlation between infestation rate and crop duration (r=-0.83) and time of head emergence (r=-0.70 to -0.88) (ICRISAT 1981; Guevremont 1982, 1983).

Certain head characteristics could be related to *R. aJbipunctella* damage, e.g., length and position of bristles; and head length, compactness, and diameter. Of all these characteristics, only compactness — measured by the number of florets or grains—is correlated to pest damage (r=0.81) (Guevremont 1983, Gahukar 1984). In the Malian Souna variety, the combination of compactness and short involucre and peduncle bristles probably make it unsuitable for oviposition and larval development (Guevremont 1982).

Stem-borer tolerance is found in the varieties INMB 106, INMB 218, and INMB 155 from Niger (ICRISAT 1984). In Zongo, a secretion in the galleries where the larvae are lodged (NDoye 1977) may be a resistance mechanism (antibiosis).

Blister beetle incidence was not related to head chracteristics (position of florets within the glumes, shape, length, direction, and rigidity of bristles) in Mali (Doumbia et al. 1984).

## Biological Control

Risbec (1950, 1960) has listed the natural enemies (predators, parasites, pathogens) of most millet pests. Recently about 20 auxiliary parasites of *Raghuva* have been identified for different development stages (Table 1) (Vercambre 1978; Gahukar 1981; Guevremont 1982, 1983; Bhatnagar 1983, 1984). Among these, *Bracon hebetor* (Braconidae), *Litomastix* sp. (Encyrtidae), and *Cardiochiles* spp. (Chalcidiae) appear to be of major importance with parasitism of up to 48% for eggs, 95% for larvae, and 2% for pupae (Guevremont 1983, Bhatnagar 1984). Their activity has a significant effect only at the end of the cropping season, especially in dry years.

The biology of these three parasites, and their subsequent use as biological control agents has been studied.

*B. hebetor* is a very active larval ectoparasite with a life cycle of 7-10 days. But its performance can be inhibited by hyperparasites: *Eurytoma* sp. (Pteromalidae) and particularly *Pediobus sp.* (Eulophidae) which attacks up to 56% of the parasites in Niger (Guevremont 1983). *B. hebetor* survives on *Ephestia* sp., a pest of stored grain, during the dry season. Studies are underway to determine the most effective use of *B. hebetor* in pest control by transferring it naturally to pearl millet fields in Aug-Sep.

*Litomastix* sp. is a polyembryonic egg parasite that remains in dispause until February when it emerges from prepupal host larvae in the soil. Up to 800 parasites have been collected from a single larva. Although parasitism can potentially reach 80-90% under favorable conditions, it has not yet exceeded 31% in the field (Vercambre 1978, Bhatnagar 1984).

*Cardiochiles* sp. parasitized only 8% of the larvae during flowering (Bhatnagar 1984), but the number of parasites is expected to increase with crop diversification. This pest develops in Jul-Aug on *Heliothis armigera* in association with *Acarthospium hispidium*, and later appears on the same insect host as it infests maize crops in Aug-Sep.

Larvae and pupae of *Acigona* are attacked by several parasites (Table 2) (Risbec 1950, NDoye 1977, Gahukar 1981), including *Syzeuctus* sp. (Ichneumonidae). This parasite is common in Senegal and Nigeria where it is reported to have reduced the larval population by up to 30% (Harris 1962, Bhatnagar 1984). Another parasite *Gonozius procerae* attacks only 1-2% of the diapausing larvae (NDoye 1980).

Six parasites infest the larvae and pupae of the midge *Geromyia penniseti: Tetyrastichus diplosidis, Platygaster* sp., *Aphanogmus* sp., *Eupelmus popa, Eupelmus* sp., *Tetrastichus* sp. The most important is *Tetrastichus* sp. (Eulophidae), which represents 80% of the total pest population at the end of the season (Coutin and Harris 1968).

Diptera parasites *(Heliocobia* sp.) were collected from *Mylabris holocericea* adults (CILSS 1985).

The parasites are less active during the dry season when their insect hosts are in diapause and climatic conditions break the parasite-pest synchrony. Although local natural enemies of certain pests contribute greatly to reducing the insect host population, they are not capable of controlling the pests. The introduction of well-selected exotic species would be more useful. These should have a good host-location ability, specificity to the host, high

Table 1. Predators, parasites, and pathogens observed on the eggs, larvae, and pupae of *Raghuva albipunctella* in the Sahel.

| Order | Family | Species of insect/ pathogen | Stage attacked |
|---|---|---|---|
| Predators | | | |
| Hemiptera | *Anthocoridae* | *Orius* sp. | egg, larva |
| | *Pentatomidae* | *Glypsus conspicuus* Westw. | larva |
| | *Reduviidae* | *Ectomocoris fenestratus* Flug. | larva |
| | | *Katanga etiennei* Schouted on | larva |
| Coleoptera | *Carabidae* | *Chlaenius boisduvalii* Dejean | larva |
| | | *C.dusaultii* Dufour | larva |
| | | *Pheropsophus* sp.nr.lafertei Arrow | larva |
| Hymenoptera | *Eumenidae* | unidentified | larva |
| | *Formicidae* | unidentified | larva, pupa |
| | *Vespidae* | *Polistes* sp. | larva |
| | *Chrysopidae* | *Chrysopa* sp. | larva |
| Parasites | | | |
| Hymenoptera | *Bethylidae* | *Goniozus* sp. | larva |
| | *Braconidae* | *Apanteies* sp. (*Ultor* group) | larva |
| | | *Bracon hebetor* Say | larva |
| | | *Bracon* spp. | larva |
| | | *Cardiochiles* sp. | larva |
| | *Chalcididae* | unidentified | larva |
| | *Encyrtidae* | *Litomastix* sp. | egg |
| | *Ichneumonidae* | *Hardromanus* sp. | pupa |
| | *Trichogram- matidae* | *Trichogrammatoidea* sp. | egg |
| Diptera | *Bombyliidae* | *Thyridanthrax* sp.nr. *kappa* Bowden | pupa |
| Nematode | *Tachinidae* | *Goniophthalmus halli* Mes. | larva |
| | *Meramithidae* | *Hexamermis* sp. | larva |
| Pathogens | | | |
| Fungi | *Fungi* | *Aspergillus flavus* Link | larva |
| | *Imperfecti* | *Aspergillus* sp. *(Ochraceus group)* | larva |
| Bacterium | - | unidentified | larva |

biotic potential, and environmental adaptability. Exchange of East and West African material is planned following the indications of Mohyuddin and Greathead (1970).

## Integrated Pest Management

Integrated pest management combines various practical, efficient, and economical methods to maintain pest levels below the economic threshold. In the case of the spike worm *R. albipunctella*, the methods tested include use of an improved cultivar (IBV 8001, apparently pest and disease resistant), release of parasites (particularly *B. hebetor)*, and only one application at early heading of an insecticide known to be safe for auxiliary fauna (endosulfan).

Detailed studies on the biology and ecology of the pests and their parasites, and on the different control methods, are required to determine a global strategy against the pearl millet pest complex (NDoye et al. 1984). Integrated pest management is a practical method, and appears to offer the only global.solution that can be applied throughout West Africa and the Sahel under the present cropping conditions.

## Conclusion and Perspectives

The analysis of the prevailing pest situation has led the Sahelian countries to choose a global, integrated pest management program against pests of all food

Table 2. Predators, parasites, and pathogen observed on the eggs, larvae, and pupae of *Acigona ignefusalis* in the Sahel.

| Order | Family | Species of insect/ pathogen | Stage attacked |
|---|---|---|---|
| Predators | | | |
| *Arachnida* | - | *Pyemotes ventricesus* Newfs. | larva |
| Parasites | | | |
| Diptera | *Chloropidae* | *Ceratopogon risbeci* Seguy | larva |
| | | *Epimadiza* sp. | pupa |
| | *Phoridae* | *Aphiochaeta* sp. | larva |
| | *Tachinidae* | *Sturmiopsis parasitica* Curr. | larva, pupa |
| Hymenoptera | *Bethylidae* | *Goniozus precerae* Risb. | larva |
| | *Braconidae* | *Apanteles sesamiae* Cam. | larva |
| | | *Euvipio rufa* Szepl. | larva |
| | | *E. fascialis* Szepl. | larva |
| | | *Glyptomorpha* sp. | pupa |
| | | *Rhaconotus soudanensis* Wilkn. | larva |
| | *Chalcididae* | *Hyporchalcidia soudanensis* Stef. | pupa |
| | *Encyrtidae* | *Euzkadia* sp. (? *integralis* Merc.) | larva |
| | *Eulophidae* | *Pediobius furvus* Gah. | pupa |
| | | *Tetrastichus atriclavus* Wtrst. | pupa |
| | *Ichneumonidae* | *Chasmias* sp. | pupa |
| | | *Dentichasmias busseolae* Hein | pupa |
| | | *Syzeuctus* spp. | larva |
| | *Seelionidae* | *Platytelenomus hylas* Nixon | egg |
| Pathogen | | | |
| Fungus | - | *Metarrhizium anisopliae* (Met.) Sorok | larva |

crops in order to maintain pest levels below economic thresholds.

The integration of all appropriate methods based on the ecology and dynamics of pest populations should be relevant for small farmers. In order to develop a feasible complex of methods, the objective of pest management in the given cropping system, and possible constraints (biological, technical, socioeconomic, etc.) expected during the operations, should be clearly established (Geiger 1982).

The results from the CILSS Projet Lutte Integree in the Sahelian countries would be useful in formulating a preliminary strategy, but this approach raises certain problems. In-depth studies on the economic thresholds, and the bioecology of the major pests are essential, because research will remain a predominant factor until results can be applied in farmers' fields.

Pearl millet pest control programs should be based on varietal resistance and biological control. This ideal combination requires minimum effort from farmers.

Other techniques such as burning or burying stalks and postharvest cultivation should be used depending on the nature of the pest. Chemical control should not be rejected completely, but used judiciously according to the target pest and chemical products used.

Millet is a staple food crop in the Sahel and will be grown despite the present constraints. However, a relevant multidisciplinary approach to crop protection problems will provide long-term solutions and real advantages that cannot be measured in economic terms, but in terms of stable and regular yields. Such an approach would benefit the Sahelian farmer considerably.

In order to achieve this, pest surveys and studies on the dynamics of the major pests—particularly stem borers and spike worms—should be advanced further. Population dynamics data is useful to establish a warning system that is essential to all integrated pest management programs. Finally, the transfer of research results of the last few years to the farmer should be intensified.

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# Role and Utilization of Microbial Associations to Facilitate Pearl Millet Growth.

**D. H. Hubbell**[2]


### Abstract

*Plants growing in a natural soil environment respond to prevailing chemical, physical, and biological factors unique to that soil. The importance of root-microbe associations that enhance plant growth is becoming increasingly apparent. This enhancement occurs with a wide variety of microbes in diverse agronomic situations. Some of these beneficial associations, such as Rhizobium-legume, nitrogen-fixing symbioses and mycorrhizal associations, have been recognized and agronomically exploited for many years. The unique requirements which must be met to insure the successful establishment and function of these associations are briefly reviewed. Other root-microbe associations are beneficial but the nature and extent of the relationships are often much less obvious in terms of their structure and/or function. These latter associations vary in direct proportion to the variability of their soil environments, which is enormous. Soil factors can be controlled only within meager limits. The existing root-microbe associations, therefore, are generally recalcitrant to agronomic exploitation through manipulation of soil or microbial factors. Technology cannot at present supply requirements which have not been met naturally through evolution. However, modern plant genetics research may, in the future, provide or enhance specific plant rhizosphere environments which will select for ubiquitous, indigenous soil microbes with the inherent ability to form growth-enhancing root associations.*



### Résumé

**Rôle et exploitation de l'association des microbes en vue de faciliter la croissance du mil :** *En milieu naturel, les plantes réagissent aux éléments chimiques, physiques et biologiques particuliers au sol donné, ce qui fait ressortir de plus en plus l'importance des associations racine-microbe pour une meilleure croissance de la plante. Il existe une grande variété de microbes dans différentes situations agronomiques. Certaines associations bénéfiques telles que celles de mycorhizes, de Rhizobium-légumineuse ainsi que les symbioses pour la fixation de l'azote, étaient mises en évidence et exploitées en agriculture depuis plusieurs années. Les conditions particulières assurant l'établissement et le fonctionnement de ces associations sont expliquées brièvement. D'autres associations racine-microbes sont également bénéfiques mais la nature et l'envergure de leur rapport sont moins évidentes en termes de structure et de fonctionnement. Ces associations varient en fonction de la variabilité du sol qui, en fait, est énorme. Les éléments du sol ne sont maîtrisables que d'une manière très limitée. Les associations racine-microbes existantes ne se prêtent pas facilement à l'exploitation agronomique par la manipulation des éléments du sol et des microbes. La technologie ne peut pas remplacer le travail de l'évolution naturelle dans ce domaine. Cependant, grâce à la recherche moderne sur la phytogénétique il serait possible de créer un rhizosphère spécifique favorable aux microbes indigènes du sol capables de s'associer aux racines afin d'améliorer la croissance de la plante.*


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## Introduction

Root-microbe associations which enhanced plant growth were observed in ancient times. The biological nature of such phenomena was not understood until the advent of the microscope and the discovery of microorganisms. The more easily observed cause-and-effect relationship of microbial pathogens on plants, and their obvious devastating effects, prompted early and intensive study of root-microbe (R-M) interactions of a pathological nature. Recognition and study of beneficial R-M interactions or associations has lagged far behind. Nonetheless, the concept, or the vague realization of the presence of these associations, has been with us for many years. Inoculation of legumes with nitrogen-fixing *Rhizobium* to enhance soil fertility was practiced in a crude form as early as 300 BC. The practice was not put on a firm scientific foundation until the classic studies of the phenomenon by Hellriegel and Willfarth, and Lawes and Gilbert, followed by isolation of the microorganism by Beijerinck (reviewed by Fred et al. 1932).

The suspicion that plants, or more specifically plant roots, had to contend with more than just chemical and physical factors of the soil environment has been confirmed. The concept that microorganisms are a constant and critical biological factor in the soil environment of plant roots was given clear definition by Hiltner's statement of the "rhizosphere effect" (Katznelson et al. 1948). Since that time, soil microbiologists have achieved a better understanding of the topic. The nature and implications of many kinds of nonpathological R-M associations has been comprehensively discussed (Dommergues and Krupa 1977).

In this paper, the term R-M association is used arbitrarily in a restricted sense, to imply R-M associations which are to some degree mutually beneficial or symbiotic in their interaction. Two cases in which the major benefit seems to favor the plant component are discussed: *Rhizobium-legume* and mycorrhizal associations. This is followed by a general discussion of "cryptic" or "associative" R-M systems of a decidedly less obvious beneficial nature. With that background, the relative potential of these associations as plant growth enhancing systems is discussed. Certain ideas, concepts, and generalities are described which can be confidently extrapolated to pearl millet and are relevant to R-M associations.

Literature citations are limited to monographs, reviews, and in some cases, individual papers which have been pivotal in developing our current conception of R-M associations. This is done reluctantly; a great debt is owed to the many scientists whose excellent work, although uncited here, has been invaluable to the formulation of this paper.

## Symbiotic R - M Associations

Numerous characteristics of the *Rhizobium-legume* system contribute to its successful role of facilitating legume growth:

- There is a unique, almost absolute, specificity of rhizobia for infection, nodulation, and nitrogen fixation in plant roots of the Leguminosae.
- The rhizobia provide the plant with an essential nutrient, nitrogen, which is the element that most often limits plant growth. This is done by utilizing atmospheric nitrogen, "fixing" or reducing it from that unavailable form to a form which is available to support growth of both the plant and the rhizobia.
- Specialized structures, nodules, are induced to form on the roots of successfully infected legumes. These nodules are a rare example of an instance where, in most cases, a pure culture of an organism occurs in nature. The unique mechanism of root infection by rhizobia generally precludes the entry of other microbes, thereby evading competitive effects.
- Simple microbiological methods can be used to isolate the homologous rhizobia from these nodules. These isolates can be grown, purified, and maintained in a virulent state on common laboratory media. This permits large-scale culture of the rhizobia to produce the large amounts of inoculum required. Nitrogen fixation, whether by chemical or biological means, is an energy-intensive process. Indeed, spiraling energy costs to produce nitrogen fertilizer by chemical means are the strongest justification for our efforts to enhance biological fixation of nitrogen in legumes and other plant families.
- The root nodule is a specialized structure; it has morphologically and functionally differentiated tissues. A critical feature is the vascular strands which ramify from the root stele into the so-called bacteroid zone, located more or less centrally in the nodule, where nitrogen fixation occurs. This feature is vital to the success of the interaction since it provides a means for direct exchange of required nutrients between plant and microbe. Rhizobia receive the energy substrate required for fixation, from photosynthate trans-

located through the root phloem. In exchange, nitrogen fixed in the bacteroid tissue is released to the root xylem which then translocates it throughout the plant. Required substrates and products of the process are thus exchanged with high efficiency, in the absence of factors which would diminish or eliminate the beneficial effect, such as the presence of other organisms competing for the final product.

These, then, are the main characteristics of the *Rhizobium-legume* association which make it an R-M system beneficial to the host plant. The same characteristics make it successful as an agronomically exploitable system. A comprehensive treatise on the associated technology of its utilization is available (Somasegaran and Hoben 1985). Briefly, this is accomplished by inoculation of seed or soil at planting time with selected rhizobia strains of established quality. This greatly enhances the chances for early onset of infection, nodulation, and nitrogen fixation. Successful attempts to manipulate this system are directly proportional to the knowledge that has accumulated through prolonged basic and applied study of the nature of the system (Vincent 1982, Broughton 1982, Alexander 1984). Successful inoculation of legumes with rhizobia is by no means inevitable, but its high success rate is more than sufficient to justify its use in standard agronomic practice.

This system remains the best understood example of a biologically intimate and beneficial R-M association. Its closest competitor for this honor is the ubiquitous root-fungus associations referred to generically as "mycorrhizae". These R-M associations are critically important in enhancing root uptake of phosphorus when available soil phosphorus is limited.

This second example of a biologically intimate and beneficial R-M association has also been long recognized. A subgroup, ectomycorrhizae, alter the morphology of infected roots in a visually distinctive way. This subgroup is found predominantly on the roots of woody perennial plants and is therefore of lesser interest agronomically.

The other major subgroup, the endomycorrhizae or vesicular-arbuscular mycorrhizae (VAM), occur on the roots of most herbaceous plants and virtually all of the agronomically important crop plants. For this reason alone they are worthy of exhaustive long-term investigation. They are no longer studied merely as a biological oddity, but rather as a symbiotic R-M association which plays a significant and often critical role in the survival, growth, and productivity of agronomic crops. We currently have enough information to appreciate their overwhelming potential value in this respect.

Progress in the study of VAM has been rapid and substantial. However, since the VAM fungi are obligate symbionts on plant roots, our current inability to grow the fungi alone in massive amounts severely restricts the quality and quantity of both basic and applied experimentation. Virtually all "pure culture" studies must be conducted with spores, laboriously sieved from the soil, or with a mixed inoculum of spores, hyphae, and root fragments derived from the roots of axenically maintained potted plants. Until this limitation is removed, progress in basic understanding and agronomic exploitation of the VAM will be held largely in abeyance. This current limitation will eventually be removed by such systematic studies as those of Siqueira et al. (1985). The current dilemma is probably because researchers do not know enough about the nutritional requirements of the fungal symbiont. The numerous and complex roles of these fungi have been discussed recently and comprehensively by Bagyaraj (1984), Tinker (1984), Subba Rao and Krishna (In Press), Krishna (1985) and many others. Applied aspects of VAM have been recently reported (Ferguson 1984). A current and thorough treatise on the methodology associated with mycorrhizal research is available (Schenck 1982).

Aside from the beneficial effect of enhancing plant growth, this R-M association bears scant resemblance to the previously described *Rhizobium*-legume system. The VAM fungi are ubiquitous and normally infect their respective host plants under most conditions permitting plant growth. However, they produce no macroscopically visible sign of infection (i.e., altered root morphology), and their presence is detected only by microscopic observation of root tissue.

Although the *Rhizobium-legume* and VAM associations are functionally similar (providing a critical mineral nutrient which often limits plant growth), there are important dissimilarities between them. The rhizobia have an inexhaustible supply of the nutrient (atmospheric nitrogen), a supply of energy (photosynthate generated by sunlight) required to reduce the nitrogen to a utilizable form, and a closed system which permits a direct and efficient transfer of the nitrogen to the plant host.

The VAM fungi, on the other hand, do not generate utilizable phosphorus as a plant nutrient. They merely increase plant uptake of available phosphorus via hyphal exploration of a much larger soil volume, followed by increased uptake of available phosphorus by the roots via direct hyphal transfer. In soils where total phosphorus is low and the element is largely removed rather than recycled, this inevitably leads to a "mining effect". Eventually, phosphorus must be added, whether the VAM are present or not. However, this may not be the case if phosphorus is present in large quantity in a "fixed" or insoluble form.

Having identified the role or importance of these two classic examples of symbiosis, it now becomes important to consider why these divergent R-M associations are biologically successful. By understanding why these systems work, study of other potentially beneficial R-M associations becomes more rational. There is great predictive value in understanding the basic concepts of the functioning of the mycorrhizae and *Rhizobium-legume* systems.

Briefly stated, these two symbiotic R-M associations are biologically successful because of the high degree of intimacy which has evolved between the organisms which has evolved. In both cases, morphological, physiological, and biochemical characteristics have evolved in such a specialized way that external factors mitigating against or limiting the beneficial effects on plant growth are minimized. Within limits, the biological mechanisms for nitrogen fixation in nodulated legumes, and phosphorus uptake in mycorrhizal plants are resistant (not immune) to adverse or process-limiting influences.

## Cryptic R-M Associations

It was pointed out above that plants growing in natural soil have their roots exposed to diverse, indigenous soil microorganisms. These R-M associations are either overtly detrimental to the plant (pathogenic), or beneficial, as in the two examples of symbiosis documented above. Considering the number of different plants and microbes involved, there must be an infinite number of R-M associations, the nature and significance or role of which must be considered. It has been suggested that there are many potentially beneficial R-M associations which lie in the gray area of possible, equivocal, or unverified existence. These have been referred to as "cryptic" associations since their presence and/or effects are not visually obvious (Hubbell and Gaskins 1980). Suggested possibilities were the effects on plant growth of rhizosphere microbes which produce plant growth promoting substances (PGPS) or fix nitrogen as free-living organisms, or both.

Such possibilities are not hypothetical but their recognition was not easy. Early work in Russia attempted to demonstrate enhanced plant growth (crop yield) by soil inoculation with free-living, nitrogen-fixing and/or phosphate-solubilizing microbes. Their results largely failed statistical tests and independent confirmation (Mishustin and Naumova 1962). However, certain growth-enhancing effects, although small, have been confirmed. These effects are now generally attributed to the production of PGPS in the seedling rhizosphere by the inoculated microbe(s) (Brown 1974). Subsequently, a number of papers dealt with plant growth effects produced by free-living, nitrogen-fixing microbes. These reports were suggestive but inconclusive. However, a landmark paper (Dobereiner and Day 1976) bestowed scientific credibility on the concept of 'associative' nitrogen fixation applied to the *Azospirillum-Digitaria* system. The potential agronomic significance of this research generated an immediate international response among investigators which exists, at abated levels, even to this day. Numerous publications have covered this topic in recent years (Vose and Ruschel 1981, Gaskins et al. 1983, Knowles 1983, Hubbell and Gaskins 1984, Elmerich 1984, Wani 1985, Wani and Lee 1986). Most of the research to date has not been done on pearl millet, but it does not diminish the value or validity of the generalizations which can be drawn from studies of "associative" nitrogen-fixation in grasses other than *Pennisetum* spp.

Early enthusiasm for the agronomic future of associative nitrogen fixation has dwindled. Initial estimates of nitrogen fixed and crop yield increases attributed to these associations were either unrepeatable or were found to have been badly overestimated when attempted in other laboratories (van Berkum and Bohlool 1980, Lethbridge et al. 1982). Belatedly, much of this can be attributed to the absence or inappropriate use of technology and a truly exasperating level of biological variability inherent in the system. Much of the difficulty may have been that initial field studies were designed on the assumption that the associative system was amenable to the same inoculation concepts and methodology applied so successfully with *Rhizobium*. It was not. The reasons are based on the biological nature of the association.

The associative microbes, such as *Azospirillum* (and numerous others) are ubiquitous in agricultural soils, but occur in low numbers, and are most frequently found in the rhizosphere of many tropical grasses and other plants exhibiting a $C_4$ metabolism.

They are not strong competitors in the soil since they die back to original population levels within a few weeks following inoculation. They do not enjoy a biologically unique or highly specific association with their plant hosts. Root invasion is superficial at best and appears to be limited to intercellular penetration of the outer cortex and colonization of dead cells. Hence, it must be characterized as primarily a rhizoplane/rhizosphere phenomenon. It is clearly established that nitrogen is fixed in this situation. However, the activity is low, and the final product is not released and transferred directly to the plant. Most or all is immobilized in microbial tissue and must be mineralized prior to plant utilization. The small but consistently observed beneficial effects on plant growth resulting from inoculation with *Azospirillum* can be attributed largely to production of PGPS by the microbes, analogous to the Russian work discussed earlier. The microbes can apparently compete successfully for carbohydrates or other energy substrate sufficient to maintain a low population level, but not enough to support a significant level of nitrogen fixation. Their inability to establish a unique, highly specific, and selective niche within the root tissue denies them access to a constant high supply of energy, optimum (microaerophilic) conditions for fixation, and a mechanism for release and direct transfer of the nutrient to the plant.

## Utilization of Beneficial R-M Associations

In considering the possibility of utilizing or agronomically exploiting beneficial R-M associations via inoculation, certain difficult questions must be asked. Is inoculation biologically feasible? In most cases it is not. Successful inoculation is dependent on the fortunate but rare coincidence of numerous required circumstances or conditions.

Implicit in the information given above are compelling reasons for the ability or inability to utilize these three representative R-M associations on a field scale. *Rhizobium* can be used because the unique features of the plant-microbe asssociation make it biologically possible. In the case of VAM fungi, wide utilization on a field scale in future is being established as a strong theoretical possibility, the full realization of which may await only the development of a medium for independent growth of pure cultures of the VAM fungi in large quantities.

There is a sharp distinction between theoretical (laboratory) and practical (field) success of inoculation. The former demonstrates the existence of a phenomenon and the potential for manipulation of genetically based characteristics of the organism(s), while the latter demonstrates the feasibility of adopting inoculation as a standard management practice. Utilization traditionally implies field inoculation. Because in the majority of cases inoculation fails, an early conclusion is that associative R-M systems cannot be utilized directly, via conventional methods of seed or soil inoculation, to enhance plant growth. The best available scientists and facilities make such inoculation systems work unpredictably, to a limited extent, or not at all in carefully controlled and managed laboratory, greenhouse and field conditions. This cannot be expected from farmers on any scale. These are strong negative statements but they have one important and perhaps all-redeeming qualification.

The redeeming qualification is this: studies to date indicate that various microbes, loosely associated with plant roots, have the ability to enhance plant growth by different means, including nitrogen-fixation (a long term effect); PGPS production, leading to enhanced root production and increased nutrient uptake (an early short-term effect); and possible inhibition of root pathogens. These are demonstrated effects and, moreover, there is increasing evidence that they are genotype-specific. This means that they are controlled by plant genetic factors (Neal et al. 1973). As suggested earlier, there is a very real potential to utilize these systems, not by technological manipulation of the microbes (inoculation) but by manipulation of the plant genetic information.

Establishing and successfully maintaining a beneficial R-M association by inoculation is the exception rather than the rule. Success depends on meeting certain unique requirements which rarely are met naturally and even more rarely provided by man. The organisms are there in the required diversity in a dynamic soil environment which maintains the diversity through the process of constant change. The rhizosphere of a particular plant genotype provides a relatively stable microbial niche or environment created by unique biochemical properties of the root. Such environments can be designed to select specifically or predictably for specific microbes or groups of microbes which will preferentially thrive in that environment and, as a consequence of their activities, enhance plant growth. This might include for example, microbes functioning as nitrogen-fixers, producers of PGPS, or microbes antagonistic to root pathogens indigenous to the soil.

In order to accomplish this expeditiously, botanists, microbiologists, and agronomists in specialized areas such as physiology, nutrition, and genetics, must first describe the form and define the function of the systems. They must determine the range of conditions under which these systems do or do not function. This information may then be used by plant breeders to produce plant genotypes which possess the characteristics needed to preferentially favor rhizosphere colonization by potentially beneficial indigenous soil microbes. The requisite microbes are already there. A highly favorable environment in the form of a "genetically engineered" rhizosphere must be provided in order to increase their numbers and activity.

Details of how this might be accomplished are the domain of plant geneticists. One possible approach may be for the breeder to avoid selecting plant genotypes that show maximum fertilizer response. Many root-microbe associations form more readily and yield maximum benefits under low-fertility conditions.

Perhaps through utilization of more primitive germplasm, plants could be bred or selected which grow reasonably well under a range of adverse conditions. Soil moisture, pH, temperature, etc., and the microbiological component of the soil environment, can be modified only to a limited extent on a field scale, if at all. The most promising alternative appears to be breeding plant genotypes which will inherently encourage or support beneficial R-M associations capable of enhancing plant growth.

## Summary

The symbiotic nitrogen-fixing association of *Rhizobium* with legumes is successfully exploited agronomically via inoculation. The rhizobia infect and fix nitrogen intracellularly in the roots via a mechanism which permits direct and efficient exchange of substrates and products in an environment largely insulated from process-limiting environmental factors. The rhizobia can be grown in the massive amounts required for large-scale field application.

The symbiotic association of VAM fungi with herbaceous plants, which enhances plant uptake of phosphorus (and other beneficial effects), is also biologically feasible for agronomic exploitation via inoculation. Again, this is because the fungi establish an intimate intracellular association in the roots

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of the host plants; this permits efficient plant-microbe nutrient exchange in a system that is largely insulated against potentially process-limiting factors. Future agronomic exploitation on a practical field scale may be largely dependent on development of means to grow the fungi independently in mass culture as an inoculant source.

Cryptic R-M associations, as exemplified by the *AzospiriJIum-grass* association, are known to possess characteristics which can enhance plant growth under special conditions. These include nitrogen-fixation and production of PGPS. The microorganisms can be grown in mass culture, so availability of inoculant poses no limitation to agronomic exploitation. However, the absence of a specialized morphological and physiological intimacy in this type of association makes successful, wide-scale exploitation via inoculation impossible or highly improbable.

A highly promising alternative to inoculation as a means of exploiting these cryptic associations is to breed plant genotypes with genetically-based characteristics which determine rhizosphere properties conducive to establishment and function of indigenous cryptic microbes. Whatever the mechanism, these microbes would have the requisite ability to enhance plant growth.

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# Discussion

The five papers in this session dealt with three subjects: diseases, insect pests, and beneficial microbial associations with roots.

Diseases are generally an important constraint to pearl millet production in Asia, and some years and some locations are very important in West Africa. It appears that downy mildew is the most important disease, and the aggressiveness of this pathogen appears to be greater in West Africa than in India. Smut can be important in certain localities in both India and West Africa. Under cooler conditions, rust can become pronounced in both East and southern Africa, and in India, especially after the flowering stage. Much less is known about diseases in East and southern Africa, although it is known that all three diseases can be severe.

Downy mildew and ergot became important yield reducers under farmers' conditions only after widespread cultivation of hybrids in India in the early 1970s, a caution that should be borne in mind as production of improved cultivars increases in Africa.

It would appear that insect pests are a greater problem for pearl millet production in the Sahelian region of West Africa than in the pearl millet-growing areas of India.

Two serious biological constraints to millet production which were not dealt with in this session are birds and *Striga.* Birds are an important problem in the major pearl millet-growing areas of both Africa and Asia, while *Striga* is an especially serious problem in parts of Sahelian Africa. Solutions will not be easy to find.

The use of rhizosphere-associated microbes to enhance pearl millet growth is a research area that could yield significant benefits. Certain soil bacteria are known to fix atmospheric nitrogen, and mycorrhizae enhance the availability of phosphorus. In India, use of inoculum of associative nitrogen-fixing bacteria is being recommended to pearl millet farmers. However, before microbial associations can be fully utilized by farmers to enhance pearl millet growth, techniques to manipulate these organisms must be developed so they can be used on a consistent basis.

# Climatic and Edaphic Limitations to Pearl Millet Yields

# Crop Growth in Semi-Arid Environments

G.R. Squire[1,4], C.K. Ong[2,5] and J.L. Monteith[3]

*Abstract*

*Methods are presented for analyzing growth and yield of crops when water is limiting and not limiting. Examples are given from collaborative research between ICRISAT and the University of Nottingham, UK, on pearl millet grown in a range of controlled and natural environments.*

**Résumé**

**Croissance des cultures en milieux semi-arides :** *La communication présente les méthodes d'analyser la croissance et le rendement des cultures sous conditions hydriques à la fois adéquates et déficitaires. Des exemples sont tirés des études effectuées en collaboration entre l'ICRISAT et l'Université de Nottingham en Angleterre, sur le mil cultivé dans une série d'environnements allant de naturel à contrôlé.*

## Introduction

The semi-arid tropics is a region distinguished by large seasonal differences in important environmental factors. Rainfall is the dominant factor and influences to varying degrees solar radiation, air and soil temperatures, and the saturation vapor pressure deficit of the atmosphere (D). Generally, crops are grown during two contrasting seasons: the rainy season, when at least part of the soil profile is periodically rewetted by rain; and the postrainy season, when there is very little rainfall and the crop usually grows on a store of water in the soil. Of the other variables, saturation deficit changes most and is most tightly coupled to rainfall. It is unusual to find large saturation deficits when rain falls frequently and vice versa. However, the coupling between rainfall and D is broken for isolated patches of irrigated land, which have little effect on the atmosphere around them.

At ICRISAT Center, where mean annual rainfall is 800 mm, mean monthly D ranges from 1-4 kPa, mean daily maximum temperature from 20-30°C, and insolation from 15-24 MJ $m^{-2}d^{-1}$. In certain other areas, daily mean temperature may rise above 30°C and saturation deficits above 4 kPa (Sivakumar et al. 1984), but these are probably extreme conditions during growing seasons.

In this review, growth and yield are examined in relation to two sets of conditions within the ranges experienced at Hyderabad, India (latitude 18 °N). In the first set, rainfall is frequent, and consequently soil moisture is often near field capacity and D is 1.0-1.5 kPa (10-15 millibar). In the second, the crop is sown on a soil profile near field capacity; thereafter rainfall is sparse or absent, and D is generally

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Submitted as CP 375 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

much larger, about 2-4 kPa. Different environmental factors are limiting in these different circumstances, and they are examined separately for convenience. (Where appropriate, growth and yield are also considered in relation to the independent effects of D itself).

Examples are given from work mainly on pearl millet *(Pennisetum americanum)* and groundnut *(Arachis hypogaea* L.) which forms part of a collaborative research program between ICRISAT and the Department of Physiology and Environmental Science at Nottingham University, UK. The central analysis compares five stands of the pearl millet hybrid BK 560 grown in conditions ranging from the controlled environment greenhouses at Nottingham to very dry, postrainy seasons at Hyderabad and Niamey, Niger (latitude 14°N) (Table 1).

Terms used in this paper, and units, where appropriate, are defined as follows:

e = amount of dry matter formed per unit radiation intercepted (conversion coefficient) (g $MJ^{-1}$)
f = fraction of mean daily insolation intercepted by the canopy
lv = root length per unit soil volume (cm $cm^{-3}$)
p = fraction of total dry matter allocated to an organ
q = amount of dry matter produced per unit of water transpired (g $K^{-1}$)
t = time (d)
D = saturation vapor pressure deficit (kPa)
E = amount of water that the crop extracts from the soil (kg $nr^{2}$)
K = extinction coefficient
L = leaf area index (area of foliage per unit ground area)
Lm = maximum leaf area index
S = total radiation (daily mean) (MJ $m^{-2}$)
T = mean daily temperature (°C)
Tb = base temperature (°C)
W = dry matter production (kg $nr^{2}$)
$\alpha$ = water extraction front velocity (cm $d^{-1}$)
$\theta_1$ = thermal duration from sowing to 0.5 f (°Cd)
$\theta_2$ = thermal duration from sowing to maturity (°Cd)

## Dry Matter Production When Water is Not Limiting

The dry matter (W) produced by a stand growing on moist soil can be represented by

$$W = Sfet \text{ —(1)}$$

This form of analysis is appropriate when radiation is limiting, either because the foliage is too sparse to intercept all the available radiation or because it exists for a small fraction of the year.

### Interception of Solar Radiation

The area of foliage, represented by leaf area index (L), most strongly determines f at any time. For many tropical cereals and legumes grown at typical narrow row spacings, f can be related to L by an extinction coefficient (K) that depends mainly on the orientation and distribution of foliage. The value of K may change slightly with time if the organs intercepting most of the radiation change their orientation, or if the foliage becomes more randomly

Table 1. Stands of pearl millet.

| Stand | Location | Year | Season | Daily maximum D (kPa) | Soil water | Planting density ($m^{-2}$) | Reference |
|---|---|---|---|---|---|---|---|
| I | Nottingham | 1979 | - | 1.4 | W[1] | 28.6 | Squire et al. 1984b |
| II | Hyderabad | 1978 | Rainy | 1.5-2.0 | W | 22.2 | Reddy & Willey 1981 |
| | | | | | | | Marshall & Willey 1983 |
| | | | | | | | Gregory A Reddy 1982 |
| HI | Hyderabad | 1977/78 | Postrainy | 2.4 | W | 26.6 | Gregory & Squire 1979 |
| IV | Hyderabad | 1977/78 | Postrainy | 2.4 | D[2] | 26.6 | Squire et al. 1984a |
| V | Niamey | 1980/81 | Postrainy | 4.0 | D | 11.5 | Azam-Ali et al. 1984a, b |

1. W = rainfed or frequently irrigated.
2. D = irrigated to field capacity at sowing, and then irrigated no further.

oriented as the canopy closes, but generally K may be treated as a constant for a given species and cultivar grown in wet conditions.

The total amount of radiation intercepted by a stand also depends on the period over which an intercepting surface is present. The extent and size of this surface was examined in terms of f, for four of the stands of pearl millet shown in Table 1, which began intercepting radiation at about 10 days after sowing (DAS), and were harvested at about 75 DAS (Fig. 1). Stand I intercepted most radiation and grew in a humid atmosphere and moist soil in a glasshouse with controlled environment at Nottingham. It achieved a maximum L of about 6, corresponding to a maximum f for total radiation (S) of 0.85 (0.93 for photosynthetically active radiation). Mean f was 0.34 between sowing and anthesis (45 DAS) and 0.83 S thereafter. From sowing to maturity, mean f was 0.54; averaged over a year it was 0.11.

These values of f were achieved by stands for which emergence was successful, for which the canopy expanded rapidly in the absence of drought and nutrient deficiency, and for which there was negligible senescence after anthesis. Such successful emergence and rapid expansion of the canopy have also been observed in wet conditions in the semi-arid tropics, but there leaf area usually decreases as a result of senescence to reduce f by about 10% after flowering (Reddy and Willey 1981, Alagarswamy and Bidinger 1985). Fractional interception may be reduced considerably more than this in the field by a shortage of nutrients, but there is a dearth of reliable quantitative information on such effects when water is also not limiting.

In a simple model of light interception by pearl millet canopies well supplied with water and nutrients, Squire et al. (1984b) showed mean f to depend on three main factors: (a) maximum f, (b) the time from sowing to the time when f achieved half its maximum value, and (c) the time from sowing to maturity. Work in controlled environments at Nottingham showed that variation in solar radiation,

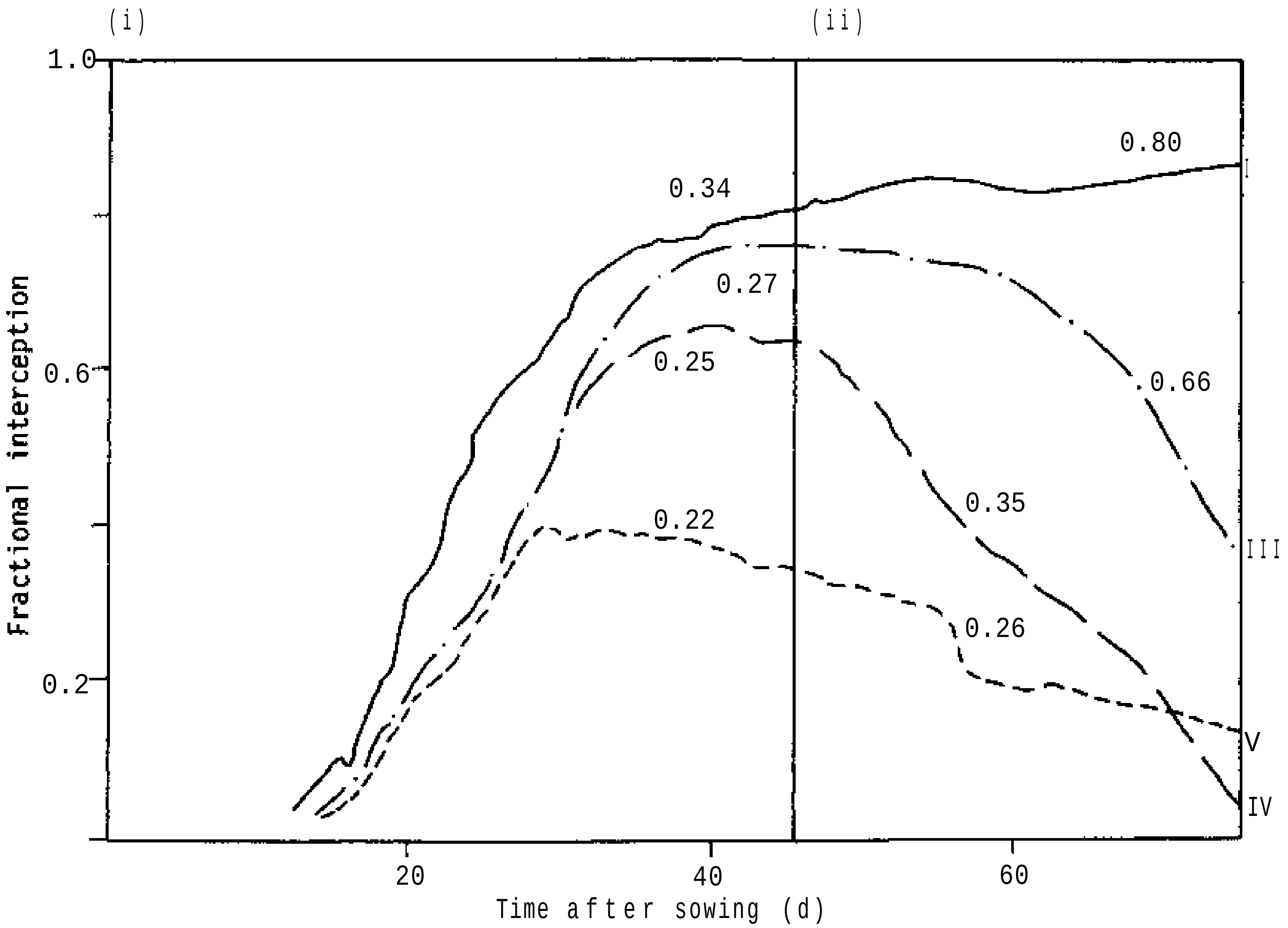


**Figure 1. Fractional interception of total solar radiation (f) for four stands of pearl millet (BK 560) (i) before and (ii) after anthesis. Numbers I-V refer to crops in Table 1. Numbers above each curve show mean f.**

over the range that occurs in the field, had little effect on any of these factors, but temperature strongly affected (b) and (c), although it had little influence on (a). Temperature governed (b) through its control of emergence (Mohamed et al. 1986), initiation of leaf primordia (Ong 1983a), and expansion of leaf laminae (Squire and Ong 1985), the rates of which increased linearly with temperature above a common base of 10°C. Consequently, the period between sowing and when f was half its maximum could be represented by a thermal duration $(\theta_1)$, which is an integral of time and temperature above an appropriate base (Squire et al. 1984a). Most of the period between sowing and final harvest was also strongly governed by temperature (Fussell et al. 1980, Ong 1983b), and was represented by a second thermal duration $(\theta_2)$. As temperature increases, the duration of the foliage $(\theta_2-\theta_1)$ decreases and the canopy intercepts less radiation whereas, if temperature decreases, the canopy grows more slowly over a longer period, and therefore intercepts more radiation.

## Conversion of Intercepted Radiation

The conversion coefficient (e) is the weight of dry matter produced per unit of solar radiation intercepted. In a range of moist environments including

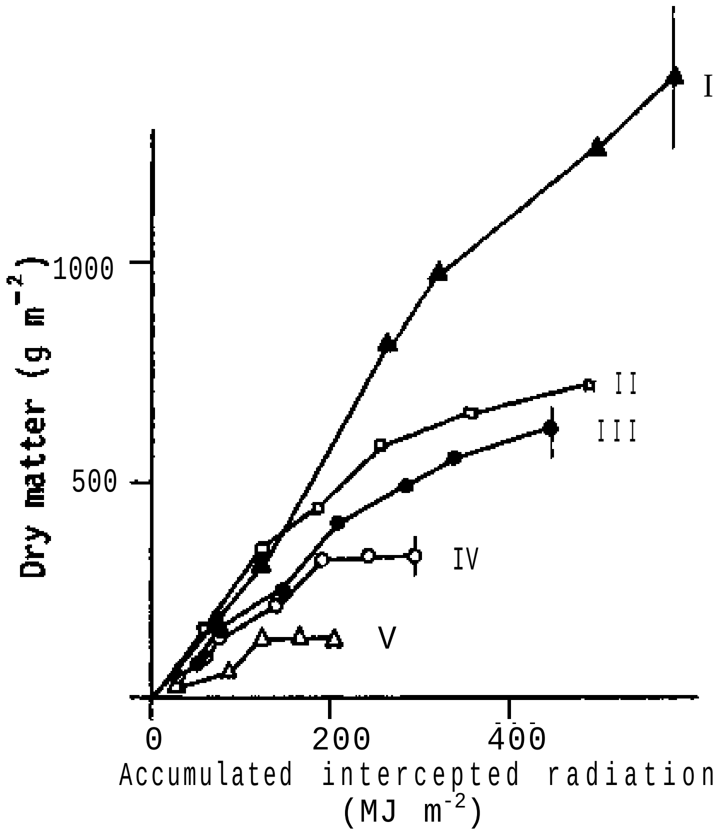


**Figure 2. Dry matter production (above ground) and intercepted total solar radiation for five stands of pearl millet (cv. BK 560). Table 1 gives details of crops.**

northern Australia (Begg 1965), Hyderabad in the rainy season (Reddy and Willey 1981, Marshall and Willey 1983, Alagarswamy and Bidinger 1985), and the controlled environments at Nottingham (Squire et al. 1984b), e measured over several weeks was around 2.5 g MJ$^{-1}$ of the total radiation (for further discussion see Ong and Monteith 1985). This maximum value of e was achieved from sowing to harvest only by stand I (Fig. 2). At Hyderabad, this maximum was measured only between sowing and anthesis, and was reduced thereafter by senescence as shown by stand II. Senescence clearly had a considerable effect on productivity, but it is not known why it was absent in stands grown at Nottingham (Squire et al. 1986).

Unlike f, e was only weakly affected by temperature over the range at Hyderabad, although it decreased at temperatures below 20° C (Fussell et al. 1980, Squire et al. 1984b).

### Synthesis

In moist environments, where temperature and solar radiation are the main variables affecting productivity, equation 1 can be rewritten as

$$W = Se\,(1-\exp\{-KLm\})[(\theta_2-\theta_1)/T)] \quad - (2)$$

(Squire et al. 1984b). As e and Lm are only weakly affected by temperature, W decreases as the duration of the canopy decreases with increasing temperature. Figure 3 shows the modeled response of maximum W to mean temperatures between 20-30° C for stands of pearl millet using maximum values of e, Lm, $\theta_1$, and $\theta_2$ as given by Squire et al. (1984b). Such heavy crops have been grown in the controlled environments at Nottingham and occasionally in very moist conditions in the tropics (Begg 1965, Enyi 1977); but crops of these or comparable cultivars in rainy seasons in the semi-arid tropics are at most half of the mass shown in Figure 3. One of the causes of this is the effect of senescence on e referred to earlier, but other causes may be limiting effects of other environmental factors such as saturation deficit or nutrient deficiency.

## Limiting Factors

### Saturation Deficit

There is now much evidence from work in controlled environments that the potential transpiration rate,

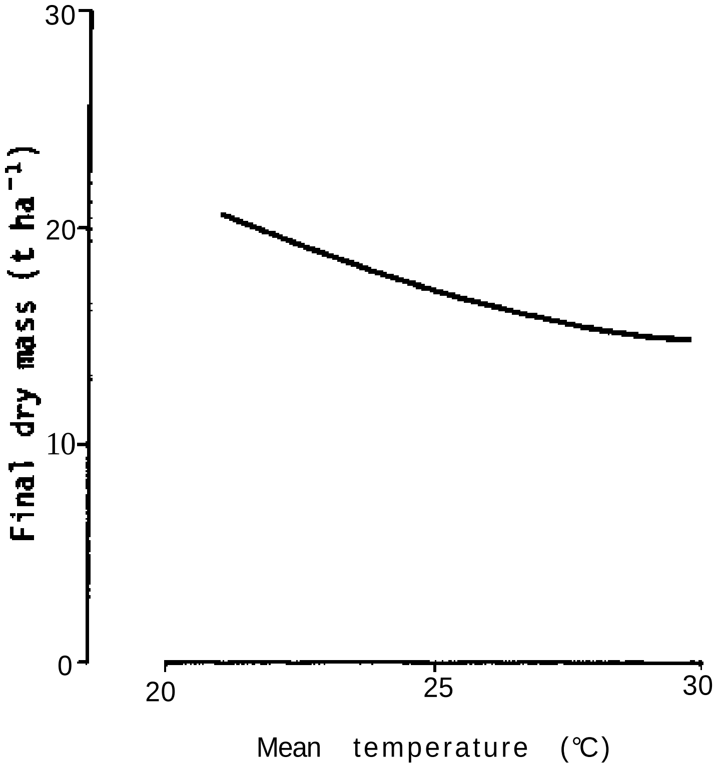


**Figure 3. Modeled relation between mean temperature and final dry mass of pearl millet BK 560.**

as represented by the saturation vapor pressure deficit (D), has important effects on dry matter production, even on plants growing in moist soil. Saturation deficit affects growth by reducing the rate of leaf expansion and by reducing leaf conductance and thereby the rate of photosynthesis (Schulze and Hall 1982).

There is little direct evidence on which to assess the effect of D by these mechanisms on productivity of stands in the field. Work in controlled environments suggests that both f and e may decrease in response to increasing D by about 10% per kPa (Nagarajah and Schulze 1983, Squire et al. In press). At a given site in the semi-arid tropics, D is closely coupled to rainfall, but D also varies between sites over a range of about 2 kPa, and may therefore affect productivity between different sites during the rainy season to an extent similar to that of temperature shown in Figure 3. Effects of D may be even larger on irrigated crops exposed to drier air.

### Nutrient Deficiency

The extent to which dry matter production is limited by nutrient deficiency is shown by the very large yield increases in response to fertilizer, both in rainy and dry postrainy seasons (Kanwar et al. 1984, Huda et al. 1985). However, there is little systematic information on how fertilizer affects interception and conversion of solar energy. Work on temperate cereals shows that the main effect of applying nitrogenous fertilizer is to increase the rate of leaf expansion, and therefore to increase the seasonal mean value of f. In contrast, the conversion coefficient is independent of nutrient status over a wide range. These responses are generally consistent with those for pearl millet found by Coaldrake and Pearson (1985a and b), but the direct response of e to nutrients has still to be investigated.

## Dry Matter Production When Water is Limiting

Shortage of water in the soil may reduce the rate of leaf expansion and therefore delay formation of the canopy and reduce its size. The shortage may also reduce (1) the effective duration of the crop in that the store of water may be used before the crop has reached maturity; and (2) the rate of photosynthesis, and thereby e, through effects on leaf physiology. These effects of water shortage (usually in combination with dry air) reduced f, e, and dry matter production in postrainy seasons at Hyderabad and Niamey compared with moist environments considered earlier (Figs. 1 and 2). Productivity over 75 d fell from 1.2 kg $m^{-2}$ to 0.15 kg $m^{-2}$, a factor of eight, as the climate became drier.

It is possible to examine such a range of productivity in terms of the factors in Equation 1, but for that analysis it is necessary to know how the balance between demand for water by the atmosphere and the supply of water from the soil controls water and turgor potentials in the plant, and how these, in turn, limit physiological processes such as photosynthesis and leaf extension. At present, this analysis is impossible, simply because much of the information is fragmentary. It is more feasible (and instructive) to analyze productivity in terms of the limiting factor itself—the supply of water. In this analysis, dry matter production (W) depends on two factors: the amount of water that the crop extracts from the soil (E), and the amount of dry matter produced per unit of water extracted (q):

$$W = Eq \quad - (3)$$

### Extractable Water

The total water supply in the soil depends on physical factors. In many soils of the semi-arid tropics, the top 2 m holds from 100-250 mm of water at field capacity (Russell 1978, Williams 1979). A part of this (10-20%) can be lost to the atmosphere directly from the soil surface. The rest is available for transpiration. The fraction of this available water that can be removed by roots depends on factors such as the size and density of the root system.

## Size of the Root System

The root system of crops sown at narrow row spacings can be considered to descend in the form of a two-dimensional front. The rate and duration of movement of the root front determines the volume of soil accessible to the root system. In soil columns within a controlled environment greenhouse, Gregory (In press) showed that roots extend at a rate strongly determined by temperature at the shoot meristem. Comparing root profiles below stands II, IV, and V of Table 1, suggests that the rate at which roots penetrate the soil may be influenced by the wetness and density of the soil (Fig. 4). In a uniform sandy soil of low bulk density (stand V), this rate averaged 4.5 cm $d^{-1}$ over the first 30 d, during which it reached a maximum of 7 cm $d^{-1}$. By comparison, in Alfisols at Hyderabad it was less than half these rates, although it was faster below a drying soil (stand IV) than one rewetted by rainfall (stand II).

Measurements of changes in the water content and water potential in a soil suggest that the deepest layer from which water is extracted by a stand growing on stored water (the water extraction front) lags slightly behind or keeps pace with the root front. The extraction front velocity ($\alpha$) is about twice as fast for pearl millet and sorghum as for groundnut, consistent with the difference in rates of root extension for these species (Fig. 5). The relation shown for the cereals is the mean of measurements on four stands, for which $\alpha$ was similar in both Vertisols and Alfisols. In contrast, $\alpha$ was different from 50 d after sowing for the two groundnut stands of the same

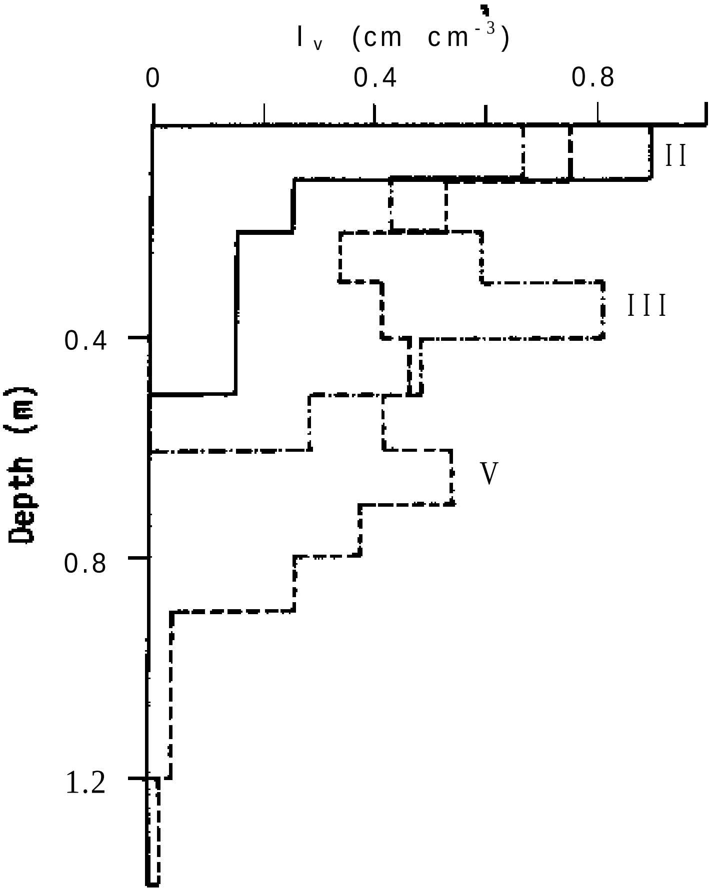


**Figure 4. Rooting profiles at about 32 d after sowing for pearl millet stands grown at Hyderabad in the rainy season (———) Hyderabad in the postrainy season (.....), and Niamey in the postrainy season (—). L-v is the length of root per unit soil volume. Table 1 gives references.**

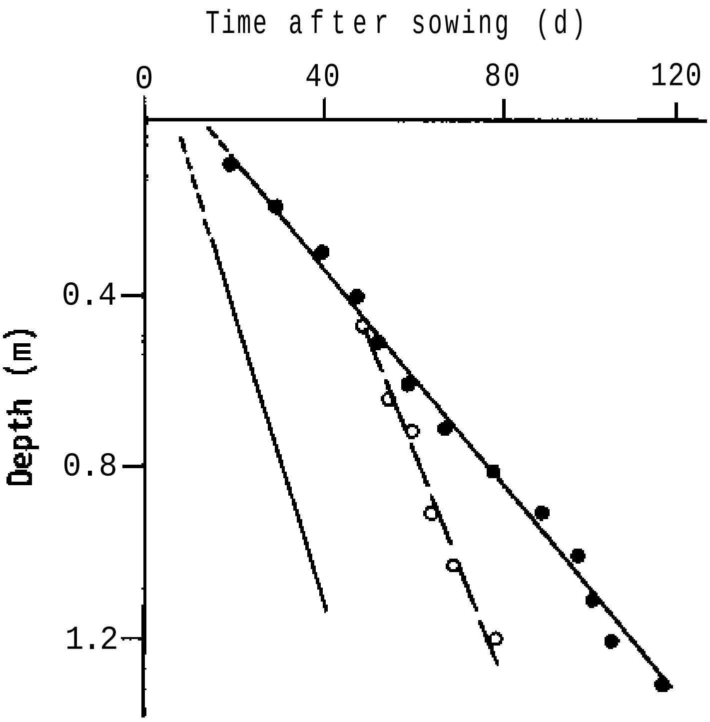


**Figure 5. Increases in the maximum depth of water extraction with time from sowing for stands grown at Hyderabad: (•) groundnut (cv. TMV 2) in the postrainy season of 1981-82 (data of L.P. Simonds and S.N. Azam Ali); (o) groundnut, same cultivar, same season, 1982-83 (data of R.B. Matthews, J.H. Williams, D. Harris, Nottingham, UK and ICRISAT), and (—) the mean for three stands of sorghum and one of pearl millet (data of Piara Singh, ICRISAT).**

cultivar grown in successive seasons. (The reason for this difference is not known).

The duration of a moving front appears to be similar to the duration of vegetative production above ground. For the pearl millet hybrid BK 560 examined in Hyderabad, this duration closely matched the duration over which the canopy formed, about 550°Cd, equivalent to 37 d at a mean meristem temperature of 25°C, by which time the front had descended about 1.0-1.5 m.

## Root Length per Unit Soil Volume

The quantity of roots in any layer of soil is most conveniently described in terms of a length of root per unit soil volume (lv). This quantity usually decreases with depth, implying that tertiary and higher order branches continue to be initiated and to extend while the front moves below them. The extent of root proliferation in a soil layer above the front appears to depend on the frequency of rewetting surface soil layers, and on soil structure. In the rainy season at Hyderabad (stand II), most roots were in the surface layers, where lv was 1.0-1.5 cm $cm^3$ at anthesis, even though the front descended to 1 m (Gregory and Reddy 1982). In the postrainy season at Niamey (stand V), lv ranged between 0.4 and 0.6 cm $cm^3$ down to 0.8 m, below which roots were present in small quantity to 1.4 m. In the postrainy season at Hyderabad, similar values of lv to those at Niamey were observed down to 0.5 m, but below this, lv decreased abruptly as a result of a soil layer of high bulk density.

It is not yet clear how lv influences the minimum volumetric content to which water is reduced. Some authorities (Ritchie 1972, Russell 1978) assume that if roots are present in a soil layer, they extract water to a volumetric content equivalent to an arbitrary but realistic soil water potential of -1.5 MPa. They are then able to define a volume of extractable water for a given soil. For Vertisols and Alfisols at Hyderabad, the extractable water in the top 1.5 m of the profile ranges from 95-200 mm (Russell 1978).

The idea of a volume of extractable water forms the basis for a model of water extraction by roots being developed at ICRISAT (Monteith 1986). However, this concept cannot be applied indiscriminately to all crops and soils, as there is evidence that the volume of water extracted from a soil also depends on atmospheric conditions. If lv in that part of the soil profile supplying most of the water is so small that the maximum extraction rate is only a small proportion of the potential evaporation rate, the aerial organs may have to compensate by reducing leaf area and leaf conductance. This may effectively preclude further extraction (and dry matter production) even though water potential remains above -1.5 MPa. (Squire et al. 1984a, give an example of this for pearl millet, stand IV).

## Dry Matter/Water Ratio (q)

It is well established that the amount of dry matter produced by a stand in a given atmospheric environment is directly proportional to the amount of water it transpires (Kanemasu et al. 1984). However, q is strongly affected by atmospheric conditions. It ranged from 6.4 to 2.1 g $kg^{-1}$ for four stands of pearl millet, and was smaller in drier atmospheres such that the product of q and D varied only over a range of 27% of the mean of the four stands (Table 2). At least part of the relatively small differences in qD between stands may have been the result of sampling errors in estimating W and soil water content, or of using atmospheric saturation deficit rather than leaf-to-air saturation deficit, or of failing to distinguish properly between transpiration and evaporation from the soil surface.

An inverse relation between D and the ratio of photosynthesis rate to transpiration rate has been observed for many species and has a physiological basis. At any given value of leaf conductance, increasing D increases transpiration rate without affecting photosynthesis rate. The inverse relation between D and q implies that the proportion of photosynthate respired is conservative in a wide range of environments. (For further discussion see Bierhuizen and Slatyer 1965, Tanner and Sinclair 1983, Monteith 1986).

Table 2. Comparison of dry weight (W), transpired water (E), dry matter-water ratio (q), saturation deficit (D) and the product of q and D for four of the millet stands shown in Figures 1 and 2.

| Stand | W ($g\ m^{-2}$) | E ($kg\ m^{-2}$) | q ($g\ kg^{-1}$) | D (kPa) | qD ($kPa\ g\ kg^{-1}$) |
|---|---|---|---|---|---|
| I | 1440 | 220 | 6.4 | 1.4 | 9.0 |
| III | 600 | 150 | 3.9 | 2.4 | 9.5 |
| IV | 310 | 70 | 4.5 | 2.4 | 11.0 |
| V | 170 | 80 | 2.1 | 4.0 | 8.4 |

The conservative nature of qD is extremely valuable for modeling productivity in dry areas.

### Synthesis

Whereas temperature and solar radiation set the upper limit for productivity of a given cultivar in wet climates, extractable water and saturation deficit set this limit in dry environments. Relations have been calculated between W and D for pearl millet at two extreme values of extractable water corresponding to the range defined by Russell (1978) for soils at Hyderabad (Fig. 6). The total mass of pearl millet in postrainy seasons is unlikely to rise above 10 t $ha^{-1}$ and will generally be much smaller.

Table 3. Main factors determining final standing dry weight.

| | | | | |
|---|---|---|---|---|
| (a) Soil water not limiting | | | | |
| | Stand | | P | $e^3$ |
| | II | 0.50 | 0.83 | 0.61 |
| | III | 0.42 | 0.80 | 0.56 |
| (b) Soil water limiting | | | | |
| | Stand | W | $E^4$ | |
| | IV | 0.22 | 0.31 | 0.60 |
| | V | 0.12 | 0.36 | 0.35 |

1. W = dry matter production.
2. f = fraction of mean daily insolation intercepted by the canopy.
3. e = amount of dry matter formed per unit radiation intercepted (conversion coefficient).
4. E = amount of water that the crop extracts from the soil.
5. D = saturation vapor pressure deficit.

## Limitations to Productivity—Summary

Productivity and its causative factors, for the stands in Table 1, are expressed as a fraction of stand I, the most productive (Table 3). For the two stands for which water was not limiting, W was reduced mainly through effects on the conversion coefficient (e); mean fractional interception was reduced by only 20%, a consequence of unknown factors mainly affecting maximum leaf area. The reduction in e (0.61) for stand II, which grew in a similar atmospheric environment to stand I, was entirely related to senescence after anthesis. This effect was by far the largest limiting productivity in moist conditions. The additional reduction in e (0.56) for stand III may have been caused by the effect of D on photosynthesis referred to earlier.

For the two stands, IV and V, for which water was limiting, W was reduced through effects both of extracted water (E) and of D operating via qD. In the extreme case of stand V for which productivity was reduced by a factor of about 8, both E and q in Equation 3 were reduced by factors of about 2.8. The difference in W (a factor of almost 2) between stands IV and V growing in very different environments but extracting a similar amount of water was predominantly caused by a difference in D.

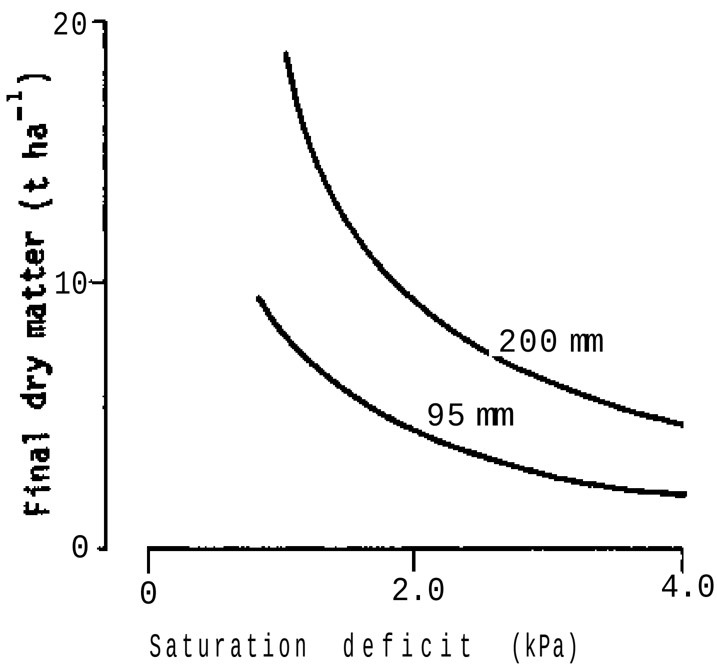


**Figure 6. Modeled relation between final dry mass of pearl millet and saturation deficit for representative soils. Numbers by curves show volumes of extractable water in the top 1.5 m of soil.**

## Partition of Assimilate

In wet climates, the amount of dry matter allocated to the organs that constitute yield can be considered in terms of the factors in Equation 1, with the addition of a fraction (p) defined as the fraction of total dry matter (TDM) allocated to the relevant organ. As the process of allocation usually coincides with an associated developmental phase, its duration is strongly governed by temperature above a base and can be defined as a thermal duration (Ong 1983b, 1984; G.R. Squire, personal communication). In controlled environments at Nottingham, the partition fraction changed little (about 0.4) over the temperature range at Hyderabad, and the final mass of stems and panicles was determined mainly by corresponding thermal durations. Mass decreased as temperature increased (as for total plant mass shown in Fig. 3).

This conservatism of the partition fraction appears to depend upon the size of the sink within the reproductive organ, in the form of units such as grains or pods, being matched with the final mass of the organ. This matching of number and plant mass appears to operate through a physiological mechanism that senses the thermal growth rate of the plant at some specific stage in its life. Thermal growth rate is defined as the rate of dry matter production per unit of thermal time. Very tight relations between thermal growth rate before anthesis and grain number have been found for maize (Hawkins and Cooper 1981) and pearl millet (Ong and Squire 1984).

The coordination between grain number and mass breaks down if one of the physiological processes determining number is affected by other factors. For example, when low temperature affected pollination and grain set in pearl millet (Fussell et al. 1980), the panicle filled more slowly and the partition fraction was much less than at higher temperatures (Squire 1984a).

### Partitioning when Water is Limiting

For a crop growing on stored water, yield may be reduced not only because T D M production is reduced, but also because the dry conditions may affect two other important factors:

- the distribution of assimilate between roots and shoots, and
- the timing of developmental events in relation to the availability of water in the soil.

### Root/Shoot Ratios

The rate at which water is extracted from the soil by a root system must equal the rate at which it is transpired through the leaves. Plants have several mechanisms to achieve this equilibrium: the root system may be increased relative to leaf area, leaf area may be reduced, leaf conductance may be reduced, and leaves of some species may change their orientation to effectively reduce leaf area.

As conditions became drier, the root system of pearl millet both descended and proliferated more rapidly (Fig. 4) and the root length per unit leaf area increased by a factor of three (Table 4). This difference in root-length/shoot-area ratio may have been caused to some extent by the different soil conditions, but it is notable that the ratio increased more or less in proportion to the saturation deficit at the three sites (Table 2), and that the ratio divided by D is 10 times less variable between sites than the ratio itself. As D is a factor that strongly determines transpiration rate, this conservatism implies that the root/shoot ratio responded to match the water extraction rate with the transpiration rate.

The modification of the root length/ leaf area ratio had a relatively small effect on root mass at anthesis (not shown), but root/shoot mass ratio increased considerably with increasing dryness from 0.045 for stand 1 to 0.29 for stand V. In relation to the very large differences in total plant mass, the mass of roots was virtually constant in these different environments.

### Timing of Development

The timing of the sequence of developmental events from emergence to final harvest is determined mainly by temperature, and in some species also by photoperiod (Mahalakshmi and Bidinger 1985a, Ong 1983a and b). The time available for growth is determined by the volume of water accessible to the roots divided by the mean rate at which it is extracted (here termed water-time, as by Monteith, 1984). If developmental-time and water-time are equal, development is able to proceed to maturity. If the water-time is less than the developmental-time, then the yield will depend on there being:

- sufficient water-time to support growth until the reproductive sink has been determined, and
- a capacity to retranslocate assimilate from other organs to the reproductive sink.

### Water-Time

Since water-time is calculated by the volume of accessible water divided by the mean transpiration rate, it is affected by attributes of the root system (e.g., root front velocity), and of the canopy (mean conductance, area), the relations between which are not well understood. Nevertheless, there are grounds for considering that the water-time provided by a

Table 4. Root and shoot characteristics for three of the stands shown in Figures 1 and 2 and Table 1, 31-33 DAS.

| Stand | Root length per plant (m) | Root length per leaf area (m $m^{-2}$) | Root weight per plant (g) | Root length per weight (m $g^{-1}$) |
|---|---|---|---|---|
| II | 63 | 980 | 0.98 | 64 |
| IV | 120 | 1540 | 0.75 | 160 |
| V | 370 | 3370 | 2.6 | 140 |

store of given volume may be somewhat insensitive to the atmospheric environment. As potential transpiration rate rises (for example, in response to an increase of D), leaf area and conductance tend to fall, thereby conserving the actual transpiration rate. Such a response was shown by the two stands of pearl millet (IV and V) that extracted a similar amount of water from the soil. Despite the large difference in D between these sites, mean actual transpiration rate from both stands was between 1.5 and 2 mm $d^{-1}$, a result of compensation mainly in leaf area. Consequently, the supply of water lasted about 45 d in both cases. The duration between sowing and anthesis for this hybrid grown without drought stress is also about 45 d at the prevailing temperature. The dry conditions had no effect on this duration so the water-time was just sufficient to support development to anthesis and grain set.

However, developmental- and water-time may not be so well matched for other varieties or in other environments. In several studies at Hyderabad, the ability of a variety to yield when grown on stored water depended on earliness (defined by the period between sowing and flowering) and susceptibility for development to be delayed by drought. Generally, earlier and less-susceptible cultivars avoided drought stress and thereby yielded more than later and more susceptible ones (Mahalakshmi and Bidinger 1985a; F.R. Bidinger, V. Mahalakshmi and Durga Prasad a Rao, ICRISAT, personal communication).

This work also showed that the degree of synchrony in flowering of different tillers was an important factor to be accounted for when matching developmental-time to water-time (Mahalakshmi and Bidinger 1985b). When stands grew on a store of water which was not replenished later in the season, early synchronous flowering gave rise to more yield than late asynchronous flowering. But for stands whose store was replenished around anthesis, asynchronous flowering among tillers usually gave rise to more yield: the late-flowering tillers which grew in less stressed conditions compensated for the poor yield of the early-flowering tillers.

**Retranslocation of Assimilate**

In the case of stands IV and V, most of the foliage died shortly after anthesis, but the stem and panicle remained alive until the end of the thermal duration for the whole crop. Between anthesis and maturity, the panicles filled, apparently with assimilate translocated from the stem. Factors controlling the rate of retranslocation in these circumstances are not known. Azam Ali et al. (1984a) point out that the partition fraction for panicles at final harvest was remarkably constant (about 0.5) among the various experimental treatments of which stands IV and V were part. However, smaller fractions have been found in other experiments (Mahalakshmi and Bidinger 1985a).

The volume of extractable water at these two sites was at the lower end of the range defined by Russell (1978) for soils at Hyderabad. Therefore, cultivars with developmental-time requirements similar to BK 560 would generally be able to grow at least until anthesis, thus insuring some yield. The maximum yield of this cultivar growing on stored water can now be estimated from Figure 6, assuming that the maximum partition fraction for panicles is about 0.5. Within the range of mean maximum D from 2.5-4.0 kPa, panicle yield on a deep Vertisol would range from 3.8-2.4 t $ha^{-1}$, and on a medium Alfisol from 1.8-1.1 t $ha^{-1}$.

## Opportunities for Plant Breeding

From work in controlled environments and in the field, one or two current genotypes of pearl millet can now be defined in terms of a set of important physiological characters. From a simple model currently being developed at Nottingham, it may be possible to estimate the effect of genotypic change in many of the characters on TDM production and yield.

For example, when water is not limiting, an increase in the base temperature (Tb) for development by 1°C would prolong the duration of the foliage ($\theta_2$-$\theta_1$) and thereby increase total productivity and panicle yield of pearl millet by 7%. Mohamed (1984) found evidence of considerable variation in Tb between cultivars germinated on a thermal gradient plate in the laboratory. As Tb appears to be similar for all processes, this technique may be useful to identify cultivars with a thermal duration suitable for a particular environment.

With respect to yield when water is limiting, the analysis indicated six attributes deserve the attention of plant breeders (and physiologists):

- the dry matter-water ratio,
- the root front (or water extraction front) velocity,
- the duration of movement of the front,
- root length per unit soil volume,
- developmental time in relation to water-time, and
- compensating mechanisms that affect harvest index (e.g., retranslocation of stored assimilate, degree of synchrony of tillering).

The model could be used to indicate the relative importance of physiological characters to stands growing on stored water (as in the example in Table 5). The first part of the table lists a set of environmental factors typical of a postrainy season. The second part lists the initial set of relevant physiological variables, based on pearl millet hybrid BK 560. Values for most of these variables are realistic, but those for three of them have been simplified for this example: the specific root length (m $g^{-1}$), root length per unit soil volume, and the volumetric water content of the soil when extraction has ceased, are assumed constant throughout the profile. The third part of the table shows calculations based on information in the first and second parts and gives panicle yield based on the initial set of characters as 88 g $m^{-2}$. The third part also shows the effect on this of a 10% increase in the value of one variable—the water extraction front velocity. Maximum rooting depth and the volume of extractable water increased, the latter by more than 10% since none of the extra water made available was lost from the soil surface. The extra dry matter produced (30 g $m^{-2}$) was much greater than the amount of extra root mass required (3 g $m^{-2}$), and yield increased by about 13 g $m^{-2}$ or 15%. There is probably enough information on which to base comparable calculations for most other variables, except for lv, the effect of which on final volumetric water content is unclear.

Table 5. Demonstration of a procedure for predicting the effect of change in a physiological character (in this case extraction front velocity, a) on yield of pearl millet in a hypothetical dry environment.

| | | |
|---|---|---|
| 1. Environmental factors | | |
| Solar radiation | 18 MJ $m^{-2}$ $d^{-1}$ | |
| Temperature | 25°C | |
| Saturation deficit | 3.5 kPa | |
| Total soil evaporation | 25 mm | |
| Soil depth | >1.5 m | |
| Initial volumetric water content (uniform with depth) | 0.2 | |
| 2. Initial physiological characters | | |
| Sowing to anthesis | 17 d + 460°Cd | |
| Specific root length | 130 m $g^{-1}$ | |
| qD | 10.0 kPa g $kg^{-1}$ | |
| lv (constant throughout profile; reduces volumetric water content to 0.1) | 0.4 cm $cm^{-3}$ | |
| Mean extraction front velocity ($\alpha$) | 2 cm $d^{-1}$ | |
| Partition fraction for panicles (shoots only) | 0.5 | |
| 3. Calculations | Control | With 10% increase in $\alpha$ |
| Maximum rooting depth (m) | 0.96 | 1.06 |
| Extractable water (kg $nr^2$) | 71 | 81 |
| q (g $kg^{-1}$) | 3.0 | 3.0 |
| Total dry weight (g $m^{-2}$) | 213 | 243 |
| Weight of roots (g $nr^2$) | 37 | 41 |
| Weight of panicles (g $m^{-2}$) | 88 | 101 |

## Future Work

The effects of solar radiation and temperature on growth and crop yields in the semi-arid tropics are now relatively well understood compared to many of the effects of water. Future research in water relations should concentrate on at least these specific topics:

- the effect of saturation deficit (independently of soil water) on interception and conversion of solar radiation;
- the relation between some attribute of the root system, such as lv, on both the rate of water extraction and the water content when extraction has ceased; and
- the effects of high temperature (35-50°C) independent of saturation deficit, on leaf expansion, development, and dry matter production.

Research on all these responses should be continued in realistic controlled environments, but work on the second can be effectively performed only in the field.

The systematic effects of nutrient concentration in the soil are even less well-documented than those of water and need to be tackled within the structure of a model of growth and yield that takes into account the effects of solar radiation, temperature, saturation deficit, and water supply.

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# Making Millet Improvement Objectives Fit Client Needs: Improved Genotypes and Traditional Management Systems in Burkina Faso

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### Abstract

*Farm-level surveys and farmers' test data from three agroclimatic zones of Burkina Faso are analyzed to demonstrate how results of on-farm research can help define more appropriate objectives for pearl millet improvement programs in the West African semi-arid tropics. Indigenous varietal change and farmers' planting practices are examined to set guidelines for an efficient allocation of program resources among cultivars with various maturity lengths and degrees of photoperiod sensitivity. The gap in performance between on-station trials and on-farm tests is reviewed and contributing factors are considered. An analysis of land-use patterns shows that millet is generally cultivated in highly diversified farming systems except in the extreme arid regions. As a result management decisions affecting millet are not independent but are a function of comparative returns to inputs applied to other crops competing for farm-level resources. Due to millet's greater suitability to poor soils and its lower response to inputs, farmers maximize profits and reduce risk by cultivating millet on their least productive land with little use of variable inputs. The paper concludes that in farming systems where millet competes with crops which are significantly more management responsive, breeders should consider low-input management on marginal land as the most probable condition in which new millet cultivars will be adopted on an important scale in the foreseeable future. Crop improvement programs aiming at such systems should emphasize improving yield stability by incorporating greater resistance to yield-loss factors at the farm level.*

### Résumé

**Adaptation des objectifs de l'amélioration du mil aux besoins des clients—génotypes améliorés et systèmes de gestion traditionnels au Burkina Faso :** *L'analyse des données tirées des enquêtes et des essais en champs paysans conduits en trois zones agroclimatiques du Burkina Faso a montré l'importance des recherches en milieu réel dans l'élaboration des objectifs plus appropriés pour les programmes d'amélioration du mil dans les zones tropicales semi-arides en Afrique de l'Ouest. L'amélioration variétale locale et les pratiques culturales traditionnelles soft examinées afin de permettre une allocation efficace des ressources des programmes parmi les cultivars à cycle et photosensibilité variés. L'article passe en revue la différence dans les résultats entre les essais en stations et en champs paysans et les facteurs en cause. Une analyse des modes d'utilisation des terrains montre que le mil est en général cultivé dans des systèmes de production très divers sauf dans les régions extrêmement arides. Par conséquent, les décisions de gestion concernant la culture du mil prennent en considération les rendements comparatifs aux intrants donnés à d'autres cultures qui sont en concurrence avec le mil pour les ressources en champs paysans. Vu l'adaptabilité plus grande du mil aux sols pauvres et sa réponse faible aux intrants, les paysans maximisent les gains et réduisent les risques en cultivant le mil sur les terrains les moins productifs*

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Submitted as CP 374 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

*avec l'apport faible des intrants variables. L'auteur préconise en conclusion que dans les systèmes de production où le mil est en concurrence avec les cultures répondant mieux à la gestion, les sélectionneurs doivent considérer la gestion à intrants faibles sur les sols marginaux comme la condition la plus vraisemblable dans laquelle de nouveaux cultivars de mil seront bientôt adoptés à une grande échelle. Les programmes d'amélioration variétale ayant pour but tels systèmes doivent mettre l'accent sur la stabilité du rendement en rendant les variétés plus résistantes aux facteurs limitants à niveau paysan.*

## Introduction

A successful crop improvement program must have appropriate objectives, however, "appropriate" is not always easily defined. Knowledge of the physical and management characteristics of target cropping systems into which the new cultivars are to fit is essential so that crop traits attractive to farmers can be incorporated. However, such targets are multiple, moving, and complex. Throughout the West African semi-arid tropics (WASAT), cropping systems differ widely across farm types and across and within agroclimatic zones. This means that distinct target farmers (or "recommendation domains") need to be identified and evaluated in order to assign priorities among alternative crop improvement objectives. Cropping systems—and the broader farming systems of which they form a part—are also constantly evolving from demographic changes, infrastructure development, and changes in the types and availability of complementary production technologies. Because breeding programs require years to breed stable, improved cultivars, the pace and direction of such changes need to be gauged at the outset in order to define objectives which will fit the most probable future adoption conditions.

WASAT farmers have also diversified cropping systems with the result that management decisions on varietal selection, timing of cultural operations, and input intensity directed at one crop, are rarely independent—they affect the resources available to other crops and activities. Crop improvement objectives based on an assessment of probable returns to resources, e.g., fertilizer allocated to one crop may be frustrated by competing demands or returns for these same resources from the farmers' other cropping activities.

This paper uses farm-level data from Burkina Faso to demonstrate how these considerations can be applied to define millet improvement objectives for several zones in the WASAT. Millet's importance in the major cropping systems and land-use patterns of Burkina Faso is reviewed. Varietal diversity in local millets, how farmers perceive and exploit this diversity, and how breeders can use such information to set program priorities among maturity groups is examined. Millet's special role as a crop grown with low inputs in the WASAT cropping systems is considered by comparing management responsiveness and input-use patterns among the major cereals. Results from farmers' tests of promising millet cultivars are reviewed to assess the major constraints blocking their adoption, followed by conclusions concerning appropriate millet improvement objectives and methods.

Data used in the analyses are drawn primarily from baseline surveys and farmers' tests conducted by the ICRISAT/Burkina Faso Economics Program in 1981-1985. Some 150 randomly selected farmers participated in the on-farm research in six villages chosen as representative of the three major agroclimatic zones in the WASAT: the Sahel (380 mm average annual rainfall during the survey period), the Sudan savanna (560 mm), and the northern Guinea savanna (780 mm). Drought conditions prevailed throughout the survey period as annual rainfall fell below the long-term average for all villages and all years. Percentages of the zonal long-term rainfall averages for the survey period were 67% in the Sahel, 75% in the Sudan, and 80% in the northern Guinea zones.

## Role of Millet in Regional Cropping Systems

### Cropping Patterns

Higher rainfall and longer cropping seasons increase farmers' options as one moves from the Sahel in the north to the Sudan savanna and northern Guinea savanna zones in the south (Table 1). Among the cereals, millet is more tolerant to arid conditions, and therefore is the dominant cereal in the Sahel zone where it occupies more than 90% of the cultivated area. In higher rainfall environments the proportion declines to approximately 25% in the Sudan

Table 1. Percentage of cultivated area sown to major crops, as sole crop or in a crop mixture, in three agroclimatic zones of Burkina Faso, ICRISAT survey results, 1981.

| | Zone | | | | | |
|---|---|---|---|---|---|---|
| | Sahel | | Sudan savanna | | Northern Guinea savanna | |
| Crop | Sole | Mixture | Sole | Mixture | Sole | Mixture |
| Millet | 92 | 0 | 27 | -1 | 13 | 0 |
| White sorghum | 4 | - | 53 | - | 31 | 2 |
| Red sorghum | - | - | 4 | 1 | 15 | 2 |
| Maize | 1 | 1 | 2 | - | 4 | 12 |
| Groundnut | 1 | 1 | 9 | - | 4 | 5 |
| Earthpea | - | - | 2 | - | - | 2 |
| Cowpea | 0 | 42 | 0 | 60 | 0 | 20 |
| Cotton | - | - | 1 | 0 | 30 | 1 |
| Other | 1 | 1 | 2 | 0 | 2 | 0 |

1. - = Less than 0.5%.

and 15% in the northern Guinea savanna zones. Millet is replaced principally by sorghum, which rises from about 5% in the Sahel to 60% in the Sudan savanna (the transition zone between millet and sorghum), and to 45% in the northern Guinean savanna, where sorghum is a competitive crop with cotton on similar soil types.

Approximately 60% of the millet area is sown as an intercrop, most frequently with cowpea as the secondary component. Cowpea density generally varies from 1000-5000 plants $ha^{-1}$, and millet from 10 000-30 000 plants $ha^{-1}$. The intercropping frequency increases in more arid zones, but with a decline in the densities of both components. Intercropping is more important among limited-resource farmers who are not equipped with animal traction equipment (as in approximately 85% of the farm units in Burkina Faso).

Research conducted by the ICRISAT Agronomy Program in Burkina Faso, has found that although a cowpea intercrop generally has little effect on millet grain yields, increased millet density can severely reduce cowpea grain yields (Stoop 1984a). Whether there are important differences among millet cultivars competing with cowpea has not been examined, but such research on sorghum cultivars has found highly significant differences among cultivars (Stoop 1984a). If similar differences exist for millet, then compatibility with a cowpea intercrop would be an important selection criteria in millet improvement programs, especially those targeted at limited-resource farmers in the Sahel and Sudan savanna.

## Land Use Patterns

The highly diverse cropping patterns of WASAT farmers reflect not only their objective of producing a varied diet, but also their strategy to exploit soil microvariability and to reduce risk. Farmers lack the means to modify land quality by intensive use of purchased inputs, deep plowing, or irrigation. However, they match land types to crop requirements to maximize aggregate productivity and to lower the risk of year-to-year production variability. Millet is important in satisfying both these objectives.

Soil microvariability is principally related to distance from habitation points and toposequence position. Studies in Burkina Faso (Prudencio 1983) and elsewhere in West Africa (Norman et al. 1981) have found that, because of high transport costs, manure and other organic wastes are concentrated around habitation points, and their use declines rapidly with distance from dwellings. Farmers exploit this fertility gradient by planting crops which they consider to be the most responsive to enhanced soil fertility within an intensively cultivated inner management ring, while planting less responsive crops on fields at greater distances. Maize and red sorghum are the crops most frequently concentrated within the inner management ring, while millet is most commonly sown on those distant fields which are least frequently manured (Prudencio 1983).

Exceptions to these general land-use patterns are imposed by soil quality differences linked to toposequence position. Fields located on upper slopes tend to have poor, sandy, gravelly top soils, with a low kaolinitic clay fraction and relatively poor organic matter content. Together these lead to low cation exchange capacities (5 meq 100 $g^{-1}$ soil), and thus low buffering capacities (Stoop 1984b). Such soils are often shallow (25-50 cm) and droughty since they are frequently located over lateritic caps remaining from the old, highly weathered landscape. Lower slope fields are generally deeper, have higher organic matter content, and higher fractions of swelling clays, which together improve water-holding, cation exchange, and buffering capacities. Experiments of the ICRISAT Agronomy Program in Burkina Faso have shown that there are highly significant interactions between land type and crop on grain yields (Stoop 1984b). Results indicate that the optimal allocation of cereals along the toposequence is millet on upper-slope fields, white sorghum on mid-slopes, maize and red sorghum along lowland margins, and rice in temporarily inundated swamp land.

Farmers' actual land-use patterns generally follow this model, particularly in the Sudan savanna and northern Guinea savanna zone where rainfall is sufficient to support the widest cropping options. In these zones, farmers use millet as a means of exploiting their least productive land, in part to insure additional food security in low rainfall years. Farmers recognize that sorghum may produce more food on such soils under good rainfall conditions, but that in poor years millet yields tend to be more assured. An analysis of time series data on farm-level yields for a range of crops has confirmed that the interannual coefficient of variation is lowest for millet (Lang et al. 1984). The generally low input, extensive management of millet is consistent with its role in the farmers' strategy to reduce aggregate production risk.

## Evolution of WASAT Farming Systems and Implications for Varietal Change

The below-average rainfall, which has prevailed nearly unbroken in much of the WASAT since the late 1960s, has combined with a longer-term increase in population pressure to destabilize traditional farming systems and to create new and increasingly urgent pressures for change. Lower mean rainfall has been accompanied by shorter cropping seasons and greater intraseason variability. As a result, traditional crops, cultivars, and crop mixtures are becoming less well adapted than in earlier periods. Simultaneously, the rapid increase in rural populations, currently estimated to be nearly 3% $a^{-1}$ (which will double the population in less than one generation) has forced farmers in many regions to reduce fallow periods and to expand cultivation to more distant fields, and to marginal soils located on the upper portions of the toposequence. One result is that farmers demand cereal cultivars with shorter maturity and greater stability under low-fertility and drought conditions for these environments.

## Diversity and Indigenous Change in Local Millet Cultivars

ICRISAT surveys have confirmed that farmers in each zone test and adopt new millet cultivars better suited to the new climate and soil conditions (ICRISAT 1984, pp. 328-330). Farmers in the ICRISAT study villages distinguished an average of between four and seven local cultivars of pearl millet pervillage in the three zones. Adoption histories often showed rapid and widespread adoption of new varieties and indicated that the pace of varietal change has probably accelerated during the last 20 years. In one of the Sahel study villages, for example, all but one of the seven millet cultivars currently sown by farmers had been introduced during the last 15 years, and of the six new cultivars, five were locals which had been introduced informally by farmers acting independently of the agricultural extension system. It is significant that the characteristic common to all of the most recently adopted local cultivars was their shorter maturity.

A statistical analysis of farmers' planting dates by cultivar confirmed that farmers in the Sudan and northern Guinea savanna zones exploit this genetic diversity by changing to relatively shorter-duration millet cultivars as the planting season progresses. Employing an analysis of variance, highly significant ($P<.001$) differences were found in first planting dates among the local cultivars within individual villages in the Sudan savanna and northern Guinea savanna.

These results carry at least four implications for crop improvement programs.

- Somewhat shorter maturity is a valid objective to incorporate in the breeding of improved cultivars. How much shorter and what weight should be given to various maturity groups are considered in the next section.

- Well adapted, early-maturity, local materials are already available in local land races for use as breeding material. Primary reliance on exotic materials for early maturity may not be necessary.
- In tests of new materials, breeders must employ local control cultivars which correspond to the maturity of the new cultivars being tested if valid comparisons are to be made.
- Farmers are not irrationally attached to their traditional cereal cultivars. Rather they are willing, indeed anxious, to experiment with and adopt new cultivars which they evaluate as being better suited to their needs.

### Assigning Weights to Research on Millets of Various Maturity Groups

Most cereal improvement programs in the WASAT have responded to the growing demand for earlier-maturing cultivars by accenting this characteristic in their selection and breeding. Methods to establish priorities among maturity groups, however, are poorly defined. The ICRISAT Millet Improvement Program in Burkina Faso, for example, focuses on breeding two cultivar groups for the Sudan savanna transition zone: photoperiod-sensitive, full-season cultivars which mature in about 120-140 d; and photoperiod-low-sensitive or photoperiod-insensitive, short-duration cultivars (80-110 d) for late sowing conditions. While it is difficult to define with precision, the current allocation of program resources is approximately three-quarters to long- and one-quarter to short-cycle materials.

One way to test whether this is an appropriate balance is to compare the allocation of research resources with the maximum potential area on which cultivars of various maturities could be adopted as direct replacements for locals while holding planting patterns (timing, area, etc.) unchanged. In Burkina Faso, outside of the Sahel there is very limited first planting adoption potential for new millet cultivars with cycle lengths of less than 110 d (less than 15% of millet area is available in the Sudan and less than 5% in the northern Guinea savanna) (Fig. 1). To reach adoption potential of 50% of first planting area, cultivars with maturity lengths of 115-135 d are appropriate in the Sahel, 130-140 d in the Sudan savanna, and cultivars > 165 d are required in the northern Guinean zone. As material for replanting, the potential for early-maturing millets is only slightly more important, and is generally less than 15% of the area in the Sahel and Sudan savanna. Thus the total adoption potential of 80-110 d cultivars in the Sudan savanna villages varied between about 17% in 1981 to about 22% in 1982. According to these studies the data suggest a nearly correct allocation of resources in the Burkina Faso millet program to the short-maturity group.

Short-maturity cultivars would be grown more if cropping systems were adopted which use relay cropping or delayed first plantings to allow greater soil preparation. But to justify allocating more resources to breeding such cultivars, researchers should first clearly define the alternative cropping systems for these cultivars, and evaluate the likelihood of these systems being adopted in the foreseeable future.

The timing of farmers' plantings has another important implication in setting millet improvement objectives. Labor-intensive, hand-planting methods and the irregular distribution of early-season rainfall combine to extend major first plantings of millet over a period of about 45 d in the Sahel zone to more than 60 d in the northern Guinean Zone. Under these circumstances photoperiod-insensitive cultivars with short planting windows are poorly suited for broad adoption. An important degree of photoperiod sensitivity, which lends increased planting date flexibility, is necessary to expand the adoption potential of new cultivars.

## Comparative Management Responsiveness among Crops and Cultivars

The different responses of major cereals to enhanced soil fertility and improved soil tillage is well documented. The implications of such differences to crop improvement strategies in diversified cropping systems and input scarcity is less well recognized.

### Technical Response and Returns to Fertilizer

The experimental results found by the Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres (IRAT) in Burkina Faso is typical of the broad differences in response to fertilizer among cereals (Bonnal 1983). During 1978-1982 in two locations, 100 kg cotton complex fertilizer (14:23:15) plus 50 kg $ha^{-1}$ urea (47% N) gave a grain-yield increment that was highest for sorghum (760 kg $ha^{-1}$), and substantially lower for millet (230 kg $ha^{-1}$). Similar crop differentials have been observed

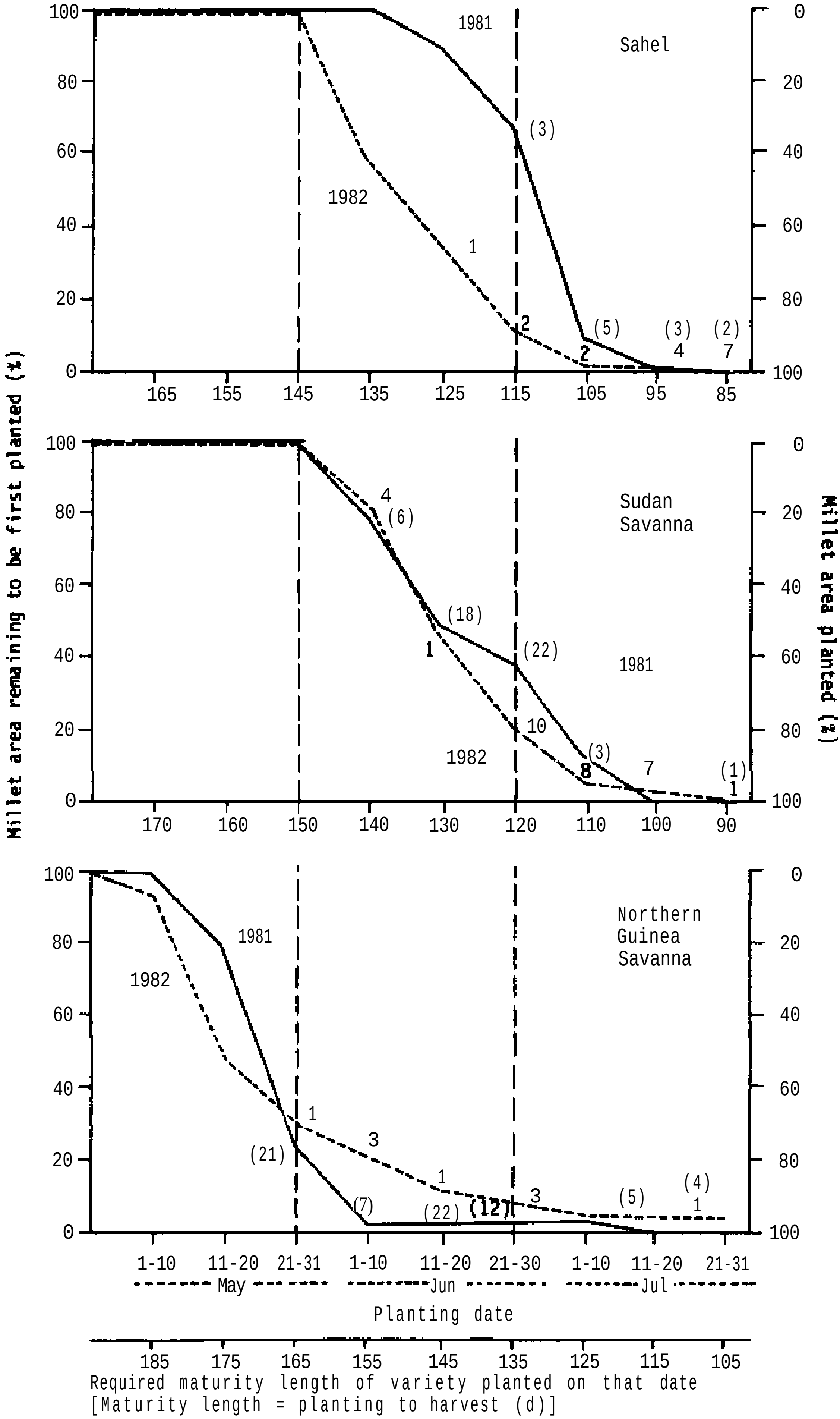


**Figure 1. Evolution of millet area planted May-July in three zones of Burkina Faso, 1981, 1982. The percentage of total millet area replanted during the 10-day period is written in parenthesis for 1981 and without parenthesis for 1982.**

in tests conducted by ICRISAT on farmers' fields. Grain yield responses were particularly low in the Sahel region where agroclimatic conditions essentially limit farmers to millet production (Table 2). Moreover, in the Sudan savanna, where farmers have wider options to allocate their scarce fertilizer to either sorghum or millet, the yield response for millet was approximately two-thirds of the sorghum response.

The low absolute response in the principal millet producing zone, and the low relative response of millet compared to sorghum (and other cereals) in the transition zone create powerful economic disincentives against the use of fertilizer on millet. In the ICRISAT farmers' tests just cited, average returns to the recommended fertilizer dose when applied to local millet cultivars in the Sahel Zone were consistently negative, and average returns in the Sudan savanna were only 10% (Table 2).

Table 2. Average yield increment to the recommended fertilizer dose, 100 kg $ha^{-1}$ cotton complex fertilizer (14:23:15) plus 50 kg $ha^{-1}$ urea (47% N) in three zones of Burkina Faso, ICRISAT farmers' tests, 1983, 1984.

| | | Grain yield increment (kg $ha^{-1}$) | |
|---|---|---|---|
| Zone | Cultivar | Millet | Sorghum |
| Sahel | Test | 120 | 90 |
| | Local | 140 | 30 |
| Sudan savanna | Test | 280 | 500 |
| | Local | 330 | 400 |
| Northern Guinea savanna | Test | NA | 510 |
| | Local | NA | 450 |

It is important to note that ICRISAT farmer tests evaluating the economics of phosphorus fertilizers applied to millet in the Sahel Zone of Niger have produced higher returns than tests in Burkina Faso. Differences are due to higher millet grain prices in Niger, and because the most available and currently recommended fertilizer in Burkina Faso is imported primarily for use on cotton and is therefore not an efficient formula for millet.

A further analysis of returns over a range of fertilizer doses has shown that at all doses, average financial returns were highest in the more humid Guinean Zone and declined systematically in more arid areas, becoming marginal or negative in the Sahelian sites (ICRISAT 1984, pp. 313-314). The risk of financial losses followed a similar south-north pattern. Moreover, when sorghum was compared to millet in the Sudan transition zone, risks were consistently lower and financial returns to fertilizer higher. Finally, at real economic prices (subsidy removed), complex fertilizer would be an attractive investment only in the southern zones when applied to sorghum at one-half the recommended rate, and urea would be economic when applied to sorghum but not to millet in the Sahel and Sudanian Zones.

In short, following production efficiency criteria alone, policymakers at the national level would concentrate fertilizer use in the northern Guinea savanna zone, where millet area is relatively unimportant, and limit use in the Sahel Zone where millet dominates. At the farm level, where farmers have the option, priority for fertilizer use would be given to sorghum (or to other relatively more responsive crops) well before millet. These conclusions become particularly crucial when national fertilizer supplies are limited (for example from subsidy rationing effects—see Mclntire 1985), and when farm-level capital is a constraint. Both conditions are typical of most WASAT countries. When either fertilizer availability or farm capital is limiting, farmers can nevertheless maximize their profits by allocating fertilizer between crops according to this marginalist principle: apply crop-specific doses at which the last unit of fertilizer applied to each crop produces identical increases in the value of production.

The farm-level decision to allocate fertilizer according to marginalist rules of profit maximization can be demonstrated by modeling an average farm of 2.5 ha sorghum and 1.2 ha millet in the Sudan savanna transition zone using response coefficients estimated from farmers' test data. Only when farmers are able to spend more than 25 000 CFA to purchase fertilizer (five times the current average household expenditure on all variable inputs in that region), would they begin to allocate fertilizer to millet. With less available capital, farmers would maximize their profits by allocating all their fertilizer to sorghum, or to other more fertilizer- responsive crops. If farmers were to cultivate a sorghum cultivar with greater fertilizer responsiveness (such as ICSV 1002 in the present example), fertilizer would be rationally allocated to millet only when the fertilizer dose on sorghum had surpassed 250 kg $ha^{1}$, representing a total household investment of nearly 90 000 CFA.

For breeders, these results mean that outside of the Sahel, unless the fertilizer responsiveness of new millet cultivars can be substantially increased to levels competitive with the other major cereals, very low fertility conditions should be considered as an integral part of the most probable cropping systems in which millet will be grown. For the Sahel Zone, where arid conditions exclude major cultivation of other crops which respond more to fertilizer, relative profitability among crops is a less important criterion for farm-level decision making, and low absolute response and high risk of loss become the major obstacles to fertilizer use. At the level of national policy, efficiency criteria alone would concentrate fertilizer supplies in the more humid zones, not in the Sahel. Thus again breeders face the probability of low fertilizer management systems in which new millet cultivars will be adopted.

### Response to Improved Soil-Water Management

The preceeding points about fertilizer responsiveness are also true for millet's relative response, compared to other crops, to tillage and other improved soil-water management practices. Experiments conducted by the ICRISAT Soil-Water Management Program in 1981 showed that sorghum's grain-yield response to tied ridges and mulch was approximately four times greater than that for millet, with an absolute response difference of more than 1 t $ha^{-1}$. Similarly, four years of ICRISAT farmers' tests across zones showed that the average grain-yield increment for local sorghum cultivars was 140 kg $ha^{-1}$ and for selected cultivars it was 200 kg $ha^{-1}$, compared to 40 kg $ha^{-1}$ for local cultivars and 20 kg $ha^{-1}$ for selected cultivars. Because labor time to prepare fields before planting is an important constraint, breeders should consider zero plowing management as an integral part of the cropping systems into which these cultivars will be adopted. Alternatively, the response to improved soil tillage for new millet cultivars must be substantially increased to levels competitive with other major cereals in areas where farmers have diversified cropping systems.

### Actual Farm-Level Input Use Patterns and Yields

Farmers themselves recognize the low management responsiveness of the available millet cultivars, and allocate their resources accordingly. ICRISAT survey results show that in those zones where cropping options are widest all variable inputs complementary to land and labor—manure, chemical fertilizer, animals, and equipment—are used less intensively on millet than on either sorghum or maize (Table 3). As a result, average farmer grain yields for millet are extremely low, approximately 500 kg $ha^{-1}$, even dur-

Table 3. Input use and production for major cereals on an average farm in three zones of Burkina Faso, ICRISAT survey results, 1981.[1]

| | | Manual households | | | Traction equipped households | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Zone | Crop | Manure (kg $ha^{-1}$) | Chemical fertilizer (kg $ha^{-1}$) | Grain yield (kg $ha^{-1}$) | Manure (kg $ha^{-1}$) | Chemical fertilizer (kg $ha^{-1}$) | % area scarified | % area plowed | Grain yield (kg $ha^{-1}$) |
| Sahel | Millet | 200 | 0 | 570 | 390 | 0 | 70 | 8 | 450 |
| | White sorghum | 0 | 0 | 450 | 0 | 0 | 0 | 0 | 300 |
| | Maize | 11 960 | 0 | 400 | 1 660 | 0 | 40 | 15 | 500 |
| Sudan savanna | Millet | 160 | 9 | 480 | 660 | 2 | 0 | 13 | 870 |
| | White sorghum | 170 | 28 | 660 | 940 | 25 | 0 | 29 | 1210 |
| | Red sorghum | 1 270 | 55 | 1430 | 720 | 13 | 0 | 39 | 1520 |
| | Maize | 5570 | 53 | 1530 | 4800 | 67 | 0 | 17 | 1240 |
| Northern Guinea savanna | Millet | 0 | 0 | 420 | 0 | 0 | 0 | 0 | 430 |
| | White sorghum | 60 | 2 | 520 | 90 | 0 | 0 | 14 | 610 |
| | Red sorghum | 240 | 3 | 580 | 1 110 | 3 | 22 | 15 | 830 |
| | Maize | 11 280 | 68 | 1460 | 21 730 | 22 | 9 | 66 | 1770 |

1. Data are from the villages of Woure, Kolbila, and Sayero.

ing a relatively good year in the Sahel and Sudan savanna, the two major millet producing areas.

## On-Farm Performance of New Millet Cultivars

Between 1977 and 1984, more than 3000 millet entries were screened by 1CRISAT millet improvement researchers in Burkina Faso. Since 1981, cultivars showing the greatest promise in on-station trials have been advanced to on-farm, researcher-managed trials in villages in the Sahel and Sudan savanna zones. If performance at this stage of testing was encouraging, the cultivars were advanced to closely-monitored, farmer-managed tests for additional evaluation. During 1982-84, four promising millet cultivars were advanced to this stage: Souna 3, IKMV 8101, IKMV 8201, and IKMV 8202. However, once they were evaluated in the more stressed environments, all cultivars had a significantly different performance to that observed on-station.

## Yield Stability

The brief description of land-use patterns and management in the WASAT stressed the high degree of microvariability and the importance of risk. Because of farmers' risk aversion, the probability of wide adoption of a new millet cultivar will be greater to the extent that it has stable yield superiority, compared to locals, over a range of physical and management environments. Millet's role as the risk-reducing crop sown on the poorest land only emphasizes the importance of stability for that crop.

A commonly employed technique to compare yield stability across cultivars, which can be applied to data drawn from a large number of test sites, is to regress the grain yield of each cultivar at each site against the mean yield of all cultivars at each site (Hildebrand 1984). The mean site yield then represents a type of environmental index. A site (in this case a particular farmer's test block) where yields are low, due either to management or the physical site characteristics, is considered a poor environment, and vice versa.

We modified the standard approach by fitting the following regression model

$$Y_{ikj} = a_0 + b_1\overline{Y}_j + b_2X_1 + b_3\overline{Y}_jX_i$$

where

$Y_{ikj}$ = yields for the elite cultivar i and the control k at location j,

$\overline{Y}_j$ = the average yield of all cultivars at location j, and

$X_i$ = a dummy variable for elite cultivar i.

The regressions were fitted separately to data from zero fertilizer plots, and to data from test plots which received either 100 kg $ha^{-1}$ NPK (14:23:15) (1981-82) or 100 kg $ha^{-1}$ NPK (14:23:15) and 50 kg $ha^{-1}$ urea (1983-84) (Fig. 2). The number of observations at each level of fertilizer were as follows: Souna 3 (Sahel, 1982)-24; IKMV (Sudan savanna, 1983)-18; IKMV (Sahel, 1983)-20; IKMV (Sahel, 1984)-40. Results for 1984 are not presented due to extreme low yields caused by severe drought conditions. Results for the zero fertilizer plots show that over most environments all test cultivars yielded lower compared to local controls. Under fertilized conditions, the results were more mixed, with one selected cultivar (Souna 3, Sahel, 1982), projected to be superior but still low-yielding in better environments. Most importantly, none of the entries tested performed better than locals over the range of environments in any region.

### Response to Improved Management

Enhanced responsiveness to inputs is a common breeding objective aimed to increase.the profitability and thus the use of modern inputs. To compare responses to fertilizer and plowing for the improved and local cultivars, farmers' test data were fitted to yield function regression models:

$$Y = a_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_1X_2 + b_5X1X_3 \text{ x } b_6X_2X_3$$

where Y = grain yield,

$X_1$ = dummy variable for the elite cultivar,

$X_2$ = dummy variable plowing, and

$X_3$ = dummy variable for fertilizer

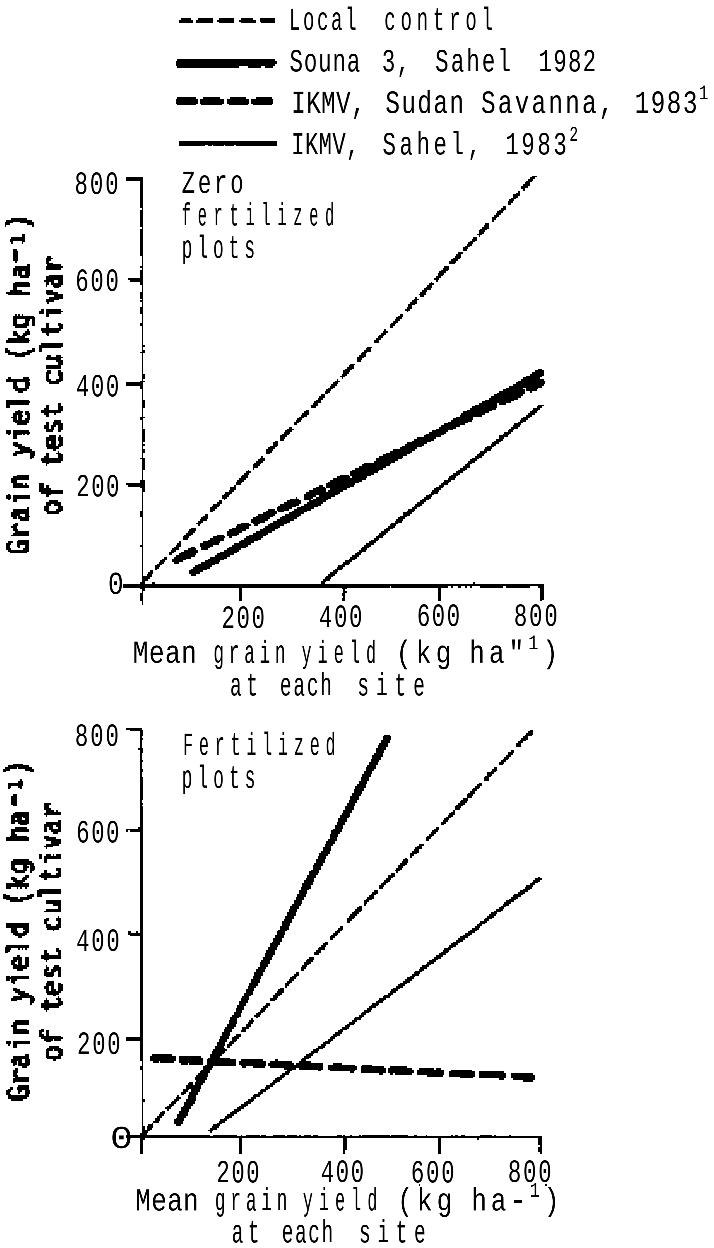


**Figure 2. Stability analysis of test millet cultivars in two zones, ICR1SAT farmers' test, 1982, 1983.**

(1. IKMV 8101, 8201, and 8202 are combined in these analyses.
2. IKMV 8201 and 8202 are combined in these analyses.)

Data from plots with zero fertilizer and 100 kg ha$^{-1}$ NPK (14:23:15) (1981-82) or 100 kg ha$^{-1}$ NPK (14:23:15) and 50 kg ha$^{-1}$ urea (1983-84) were employed in the analysis. Using the regression coefficients estimated yields were calculated at each input level for the local and elite cultivars.

Due to high variance (magnified by the extremely low levels of on-farm yields), no significant differences between the local and test cultivar responses to either fertilizer or plowing were found (i.e., neither $b_4$ nor $b_5$ were significant in any of the regressions). Moreover, at each level of input use for both fertilizer and plowing, predicted grain yields for the paired local cultivars were greater than for yields for each of the test cultivars.

## Yield Components

The separate components of grain yield were analyzed in an effort to identify how the elite cultivars were deficient when stressed by on-farm conditions. Plants per hectare, heads per plant, and grain yield per head were compared for each elite and local cultivar by using a t-test to determine the significance of mean differences. The analysis was done separately for the unfertilized and fertilized farmer test plots (Table 4).

All components tended to be inferior for the test cultivars, often at significant levels. Depending on the particular cultivar, low plant stand was due to poor seedling vigor, low survival for the more mature plants, or to a combination of both factors. The low number of panicles per plant was due both to poor head exertion under drought and fertility

Table 4. Comparison of yield components for local and test cultivars of millet in two zones of Burkina Faso, ICRISAT farmers' tests, 1982, 1983[1,2].

| | | | Unfertilized plots | | | Fertilized plots | | |
|---|---|---|---|---|---|---|---|---|
| Zone | Test cultivar | Year | Plants ha$^{-1}$ | Heads plant$^{-1}$ | Grain yield head$^{-1}$ | Plants ha$^{-1}$ | Heads plant$^{-1}$ | Grain yield head$^{-1}$ |
| Sahel | Souna | 1982 | | | +* | - | - | |
| | IKMV[3] | 1983 | | | -* | - | -** | -* |
| Sudan savanna | IKMV[4] | 1983 | | - | | -* | -*** | + |

1. A positive sign denotes those cases where the test cultivar surpassed the local control, and a negative sign the opposite.
2. Fertilizer rates were 100 kg ha$^{1}$ NPK (14:23:15) in 1982 and 100 kg ha$^{-1}$ NPK (14:23:15) plus 50 kg ha$^{-1}$ urea in 1983.
3. IKMV 8201 and 8202 are combined for these analyses.
4. IKMV 8101, 8201, and 8202 are combined for these analyses.
* = $P < .05$; ** = $P < .01$; *** = $P < .001$.

stress, as well as to genetic differences in tillering. Poor yield per head was due in part to bird damage, especially during the 1983 tests in the Sahel Zone when the recommended date of planting was too early for these early-maturing cultivars. In addition, barren heads were frequent in most of the cultivars tested, for which the causal factors have not yet been satisfactorily diagnosed.

These results are not final, and further testing of several of these cultivars in Burkina Faso is warranted. Nevertheless, several lessons can be learned from the poor performance. In part, these problems were due to recommended planting dates which were somewhat too early and which in a number of sites led to bird damage. However, in light of the results from the yield components analysis, (i.e., low plant stand and low number of heads per plant) delayed planting dates would not have entirely eliminated the performance gaps. Moreover, the planting date inflexibility of photoperiod-insensitive cultivars is itself a factor contributing to yield instability which can limit the general adoption potential of individual cultivars. More importantly the performance problems also reflect the poor adaptation of the test cultivars to conditions in farmers' fields. Because all test cultivars had been selected on the basis of consistent yield superiority on the research station, these results suggest that stresses present under the land-extensive management and on the marginal land types selected by farmers for millet cultivation are not adequately represented in on-station selection criteria and screening procedures.

## Conclusions

During the last two decades, climatic and demographic factors have combined to destabilize traditional farming systems in major portions of the WASAT, creating increasingly urgent pressures for technical change. One reflection of these trends is that lower and more variable rainfall, shorter cropping seasons, and the gradual expansion of cultivars onto less fertile and more drought-prone soils have reduced the suitability of traditional cereal cultivars which had been selected by farmers under more favorable conditions. Farmers have become increasingly active in selecting and experimenting with new cultivars, often outside formal agricultural extension programs. To allocate resources efficiently within modern millet improvement programs, it is clearly desirable to define goals which correspond to farmers' changing demands, and which satisfy the most probable current and future adoption conditions of specific target groups.

The most common characteristic of new cultivars demanded by farmers is earlier maturity to fit both the shorter rainy season and the more shallow soils into which millet cultivation is expanding. Medium-maturity millet cultivars maturing 10-30 d earlier than the most common full-season locals, and with an important degree of photoperiod sensitivity to give farmers sufficient planting date flexibility, have the greatest adoption potential. Well-adapted parent materials for breeding varieties of these maturity lengths can come in part from collections of early local cultivars. Very early, photoperiod-insensitive cultivars will have very little effect on total production in all zones unless cropping systems change radically.

Defining other appropriate objectives requires consideration of millet's role in the farming systems of distinct zones. Within the Sahel, where the extremely harsh environment limits farmers to millet as their only major cereal, the fundamental problems are low base yields, extremely low returns and high risk to new inputs. New cultivars must be more management responsive if production is to be increased in this zone. The obstacles and time required to introduce substantially improved complementary management in the Sahel however, should not be underestimated. In a country such as Burkina Faso, which includes higher potential agroclimatic zones, and where national resources are extremely limited, efficiency criteria will continue to lead policy makers to concentrate extension services and input supplies in the more humid zones where returns are higher and more assured. These factors, combined with the high risk aversion of Sahelian farmers, means that major management changes using purchased inputs will come more slowly in the Sahel than elsewhere. As a shorter-term objective, to ensure that the more management-responsive cultivars will not increase farmers' risk, millet improvement programs targeting that zone should place secondary emphasis on breeding for improved resistance to the major yield-loss factors.

The Sudan transition zone and the northern Guinea savanna pose a different set of problems in defining appropriate millet breeding goals. More favorable agroclimatic conditions support highly diversified cropping systems in which millet generally plays a particular but subsidiary role in meeting household food needs. Farmers allocate their resources among various cereal activities with the goal of efficiently reaching an aggregate production level which at least meets family food needs, but not to maximize the yields or even the production of any particular crop. Due to its better suitability to poorer soils, and its lower response to inputs, farmers cultivate millet in low-input systems on their least productive land as a low-cost, low-risk means of increasing their overall food security. Under conditions of input scarcity, they rationally apply inputs primarily to those crops which give them substantially higher response, sorghum and maize, with only marginal levels of inputs applied to millet.

This is the paradox facing millet improvement programs in the transition zone. It is clear that major increases in millet yields can only occur through higher input management systems. However, it is not clear that breeding for quantum yield increases within high input systems is a relevant or even realistic objective in this zone under current and foreseeable conditions. For farmers to justify applying inputs to millet, it is not sufficient that their use on millet be profitable, but that they be as profitable at the margin as when applied to other crops, such as sorghum or maize, which are substantially more responsive. Marginal improvements in the response of new millet cultivars will not be enough. Moreover, as sorghum and maize improvement programs succeed in producing improved cultivars with even higher response to inputs, the minimum target response rate will increase accordingly.

In short, unless transition zone breeders judge that it is possible to increase response rates to levels competitive with current and future sorghum and maize cultivars, then they should consider low-input management on marginal land types as the most probable adoption conditions for new millet cultivars in the foreseeable future. In this case, the major objective should be to improve yield stability by incorporating improved resistance to the major causes of yield loss at the farm level. It is not a coincidence that such a strategy corresponds best to farmers' own goals of including millet in their transition zone farming systems.

Implementing these objectives for both the Sahel and the Sudan and Guinea savanna demands a reassessment of present screening and selection methods on the research station, as well as giving greater accent to on-farm research. Priority now given to selecting for yield potential under high input management alone needs to be reconsidered. Only by screening at several input levels can cultivar differences in response to inputs be identified. Screening should also be conducted primarily on land types considered appropriate for millet cultivation in various regions. To achieve this, screening of advanced lines in well-controlled, researcher-managed on-farm trials may well need to be expanded. The major farm-level stress factors which contribute to the yield gap and to yield instability also need to be measured on farmers' fields, and systematically introduced on the research station at an early stage of selection.

Finally, it should be clear that this strategy for millet improvement requires a close interdisciplinary effort involving specialists in physiology, plant protection, agronomy, and economics, as well as breeding. The role of the physiologist is particularly important since crop mechanisms for tolerance or resistance to the major stresses, and interactions among environmental stresses, are not yet adequately understood. Knowledge in both of these areas is needed in order to develop reliable and efficient screening techniques. This approach also requires greater work with farmers themselves at several stages of the breeding and selection process, not simply at the final stage of pre-extension screening. An early and continuing interactive relationship with farmers to define appropriate breeding objectives and to test concepts and materials will substantially reduce the time necessary to arrive at improved cultivars which are well adapted to our clients' needs.

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# Management Practices to Increase and Stabilize Pearl Millet Production in India

**Rajat De[1] and R.C. Gautam[2]**

***Abstract***

*Pearl millet is a dominant crop of arid and semi-arid India with an average grain yield of only 650 kg $ha^{-1}$. With scientific management practices crop yields can be increased at least three-fold. Incorporation of rice-husks or farmyard manure (FYM) in sandy soils, the maintenance of an optimum plant population at 1.3 x $10^s$ plants $ha^{-1}$ in rows spaced at 50-cm intervals, and chemical weed control with triazine compounds are recommended. Responses to nitrogen of up to 137 kg $ha^{-1}$ N were obtained, with a response of 6.0-10.5 kg grain $kg^{'1}$ N applied. Grain legumes as preceding crops, or as mixtures, can increase the yield of pearl millet and the productivity of land. Azospirillum seed inoculation, and evapotranspiration reduction, either by the use of chemicals or by organic or polyethylene mulches, have also been reported to increase yields.*

**Résumé**

**Pratiques de culture visant à augmenter et à stabiliser la production du mil en Inde :** ***En Inde, le mil est une importante culture des zones arides et semi-arides où le rendement en grain ne dépasse pas 650 kg ha ¹. Ce rendement augmenterait au moins trois fois avec l'application des méthodes scientifiques de culture. On propose l'incorporation des balles de riz ou du fumier dans les sols sableux, une densité végétale de 1,3 × $10^5$ plantes ha ¹ en lignes à intervalles de 50 cm, et la maîtrise des mauvaises herbes par les composés de triazine. La réponse à l'application de l'azote a atteint 137 kg ha ¹, soit 6,0-10,5 kg de grain kg ¹ d'azote apporté. Les légumineuses à grain, en tant que culture précédente ou en associaton, permettent d'augmenter le rendement du mil et la productivité du sol. D'autres moyens d'augmenter le rendement sont : l'inoculation des semences par l'azospirillum ainsi que la réduction de l'évapotranspiration soit par l'utilisation des produits chimiques soit par celle des pailles organiques ou en polyéthylène.***

## Introduction

Pearl millet *(Pennisetum americanum)* is a staple food crop of arid and semi-arid India, grown on about 12 million ha, with a total production of nearly 7.5 million t. The crop is almost entirely grown under rainfed conditions (i.e., during the monsoon) using low managerial inputs with resultant low productivity not exceeding, on average, 650 kg $ha^{-1}$. Experimental evidence shows that given adequate attention, yield levels can be increased 2.5-3 times even on farmers' fields (Gautam et al. 1981). Inadequate plant populations, lack of fertilizer application and weed control measures, meager soil and water conservation practices, and the use of unimproved cultivars keep yields low.

In this paper, an attempt has been made to highlight management practices evolved from research at various agricultural research institutions in India. The main source of information is the work done under the All India Coordinated Millets Improvement Project (AICMIP).

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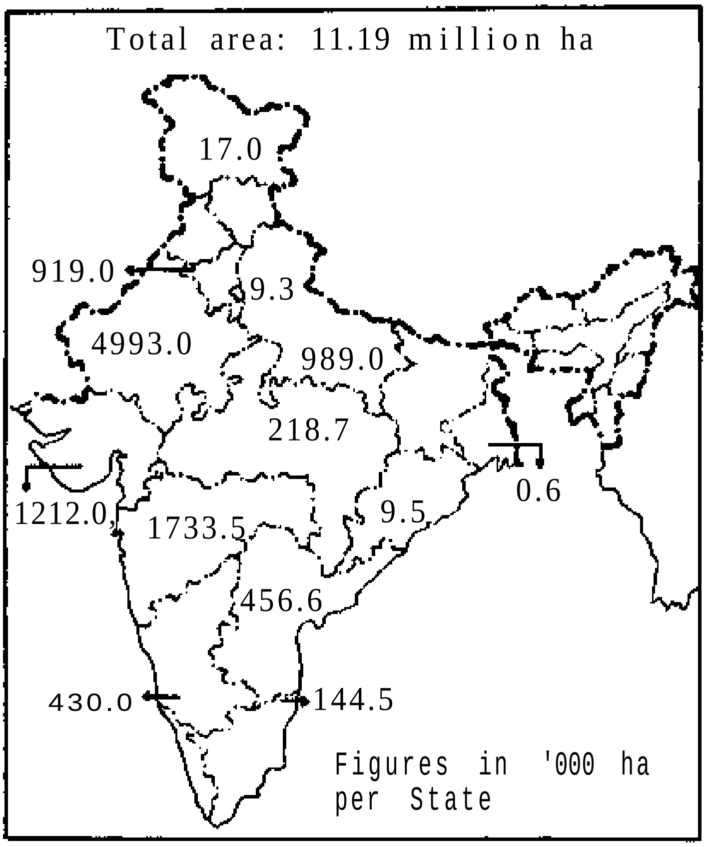


**Figure 1. Pearl millet distribution in different states in India.**

## Soil and Climatic Characteristics of Pearl Millet Growing Regions

In India, pearl millet is extensively grown in the northwestern, western, south central, and southern parts of the country (Fig. 1). Soils range from sandy to loamy sands in the alluvial regions of the west and northwest, but are sandy clay in the central, south central, and southern regions. Rainfall in these arid and semi-arid climates ranges between 190 mm $a^{-1}$ (at Jodhpur in western India) to 1000 mm $a^{-1}$ (at Nandyal in south central India).

Although the total rainfall in some pearl millet growing areas may appear to meet the moisture requirement of the crop, the intensity and duration of precipitation is often highly skewed so the crop may suffer from a water deficit at critical growth phases. If the monsoon rains start late and sowing is delayed, then critical moisture is often not available at the grain-filling stage because the rains stop early relative to the crop growth period.

## Preparatory Tillage

The water holding capacity of both the coarse-textured desert soils in western India, and the red sandy-loam soils of southern India is extremely low. Subramaniam et al. (1973) reported that materials such as rice husks or F Y M (251 $ha^{-1}$) incorporated to a depth of 20-45 cm 8 weeks before sowing improved the water-holding capacity of a red sandy-loam soil and thereby the yield of pearl millet.

## Plant Population

In a situation of limited moisture, the productivity of a crop is governed by the balance that may exist between the total quantity of available soil moisture and the plant population that it can sustain. Even a modification of the crop geometry may be able to optimize soil-moisture use. In a 2-year experiment at Coimbatore, India, on a laterite-loam soil, Gautam (1975) found that at a population of 1.3 x $10^5$ plants $ha^{-1}$, the best results were obtained when row-spacing was maintained at 50 cm rather than at 25, 75, or 100 cm (Table 1). In an earlier experiment, Gautam (1970) found that for a loamy-sand soil of Delhi, the optimum planting geometry was 45 cm between rows and 15 cm within the rows at a population of 1.41 x $10^5$ plants $ha^{-1}$ (Table 2). Patil and De (1978) noted that widening the row distances in a rainfed situation decreased the preflowering moisture use. The conserved water was utilized at the grain-filling stage.

## Weed Management

As a crop grown predominantly in the hot and moist rainy season, weeds deprive pearl millet of vital nutrients and moisture. Gautam and Kaushik (1980a) estimated that competition from weeds could reduce

Table 1. Effect of row spacing on grain yield of pearl millet.

| Row spacing (cm) | Plant population observed ('000 $ha^{-1}$) 1972 | 1973 | Grain yield (kg $ha^{-1}$) 1972 | 1973 |
|---|---|---|---|---|
| 25 | 142 | 133 | 1630 | 1560 |
| 50 | 135 | 126 | 2000 | 1960 |
| 75 | 136 | 101 | 1610 | 1760 |
| 100 | 128 | 99 | 1250 | 1700 |
| CD 5% | | | 520 | 270 |

Source: Gautam (1975).

Table 2. Grain yield (kg $ha^{-1}$) of pearl millet as affected by different interrow and intrarow spacing.

| Intrarow spacing (cm) | Interrow spacings (cm) 75 | 60 | 45 | Mean |
|---|---|---|---|---|
| 30 | 2440 | 2680 | 2400 | 2503 |
| 15 | 3080 | 3260 | 3750 | 3363 |
| 10 | 3550 | 3650 | 3310 | 3501 |
| Mean | 3020 | 3190 | 3150 | 3122 |

| | Interrow | Intrarow | Interaction |
|---|---|---|---|
| CD 5% | | 520 | 500 |

Source: Gautam (1970).

yields 25-50%. Dicotyledenous and monocotyledenous weeds of several species, including sedges, infest pearl millet fields. Manually uprooting them becomes rather difficult because of the soggy nature of the soil during the rainy season, so chemical weed control has been recommended (Gautam and Kaushik 1980b). In experiments conducted between 1970 and 1973 at 15 locations in India, triazine compounds (propazine and atrazine) when applied at the preemergence stage controlled 71-96% of the weeds, increasing the yield by almost 30-40% over the unweeded control. Chemical weed control (Table 3) was more economic than manual weeding (AICMIP 1970-73).

## Fertilizer Use

Tandon (1980) estimated the nutrient removal by different crops grown in rainfed situations, and reported that at the present productivity level, pearl millet removes 72 kg of N + P + K $ha^{-1}$ $a^{-1}$, whereas only 10-11 kg of these nutrients are actually applied. It is estimated that for the production of 100 kg of grain, pearl millet requires 3.6 kg of N, 0.8 kg of P, and 3.4 kg of K. Fertilizers not only increase above-ground growth, but also below-ground root proliferation. In this way replenishment of the soil nutrients encourage more efficient water use.

## Nitrogen Fertilizers

Of the three macronutrients, response to N has almost been universal in all regions of the country where pearl millet is grown. The optimum rate of N fertilization in experiments averaged over 5 years and 30 locations (Gautam et al. 1981) ranged from 92-137 kg $ha^{-1}$ at a response level of 6.0-10.5 kg grain $kg^{-1}$ N applied. The output/input ratio of nitrogenous fertilizer ranged between 0.8 and 2.7 in different zones (Table 4).

Because rainfall distribution is not predictable, nitrogen application of about 100 kg $ha^{-1}$ is not advisable because of the high N losses associated with volatilization, leaching, ordenitrification. Splitting the N application, half at sowing and the balance 3 weeks later was reported to be beneficial at several locations in experiments conducted over 3 years (Fig. 2). In further experiments conducted by Gautam and Kaushik (1984), it was obvious that the omission of N at sowing is not advisable, because the later application did not compensate for the omission at the initial stage of crop growth (Table 5).

## Legumes as Preceding Crops

Legumes are reported to fix 45-217 kg $ha^{-1}$ N in their root nodules (LaRue and Patterson 1981), which is

Table 3. Effect of weed control treatments on grain yield of pearl millet.

| Treatments | Grain yield (kg $ha^{-1}$) | Mean dry weight of weeds (kg $ha^{-1}$) | Weed control efficiency (%) |
|---|---|---|---|
| Unweeded control | 1870 | 1610 | - |
| Hand weeding (3 times) | 2670 | 60 | 96 |
| Propazine 0.5 kg a.i. $ha^{-1}$ | 2410 | 470 | 71 |
| Propazine 0.5 kg a.i. $ha^{-1}$ + Hand weeding (1 time) | 2530 | 500 | 69 |
| Atrazine 0.5 kg a.i. $ha^{-1}$ | 2310 | 460 | 71 |
| Atrazine 0.5 kg a.i. $ha^{-1}$ + Hand weeding (1 time) | 2490 | 450 | 72 |

Source: AICMIP (1970-73).

Table 4. Economics of pearl millet N fertilization in different agroclimatic zones of India.

| Agroclimatic zone | Optimum dose of N (kg ha$^{-1}$) | Response at optimum rate of N application (kg grain per kg N) | Output/ input ratio |
|---|---|---|---|
| South central zone | 137 | 5.0 | 0.8 |
| Northwest zone | 100 | 10.5 | 2.7 |
| Southern zone | 92 | 6.4 | 1.3 |
| Western zone | 120 | 6.2 | 1.2 |

Source: Gautam et al. (1981).

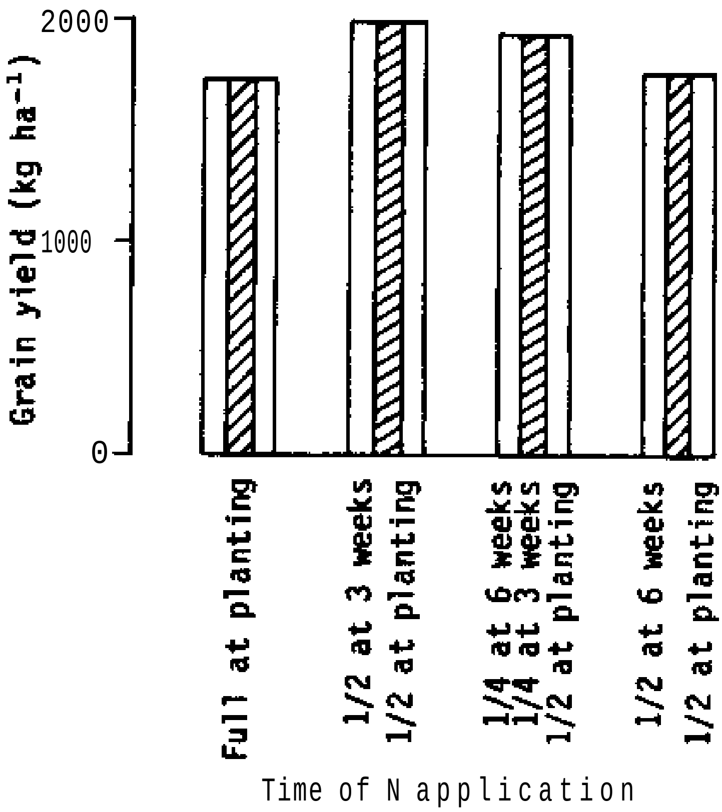


**Figure 2. Effect of time of N application on grain yield of pearl millet hybrid (mean of 4 centres).**

often in excess of their own growth requirements. The excess fixed N can be utilized by a subsequent crop grown on the same field (Giri and De 1979). In experiments conducted over 3 years, the grain yield of pearl millet was increased by 23% when grown after groundnuts, 24% after cowpeas, and 12% after pigeonpea. These pearl millet yield increases after groundnut or cowpea were equivalent to about 60 kg ha$^{-1}$ N applied to pearl millet following a previous pearl millet crop (Fig. 3).

The advantage following legumes was due to increased N removed by the pearl millet crop: 40 kg ha$^{-1}$ N after groundnuts and 33 kg ha$^{-1}$ N after cowpeas, compared with 19 kg ha*$^{1}$ N removed by

Table 5. Effect of time of N application on grain yield of pearl millet.

| Treatments (N kg ha$^{-1}$ and splits)[1] | Grain yield (kg ha$^{-1}$) 1981 | Grain yield (kg ha$^{-1}$) 1982 |
|---|---|---|
| 30(15-15-0) | 1400 | 2042 |
| 60 (30-30-0) | 1836 | 2528 |
| 90 (45-45-0) | 1867 | 2792 |
| 30 (0-15-15) | 1139 | 1472 |
| 60 (0-30-30) | 1249 | 1894 |
| 90 (0-45-45) | 1267 | 2074 |
| 0 | 976 | 1278 |
| CD 5% | 150 | 180 |

1. At sowing and 3-6 weeks after sowing.
Source: Gautam and Kaushik (1984).

the crop grown after a preceding pearl millet crop (Giri and De 1980).

## Legumes in Intercropping Systems

Pearl millet is seldom grown as a sole crop in India. Crops are mixed primarily as an insurance against bad weather (Raheja 1973). With advances in agronomic management practices, pearl millet is increasingly being grown as a row crop, which affords the possibility of planting low-growing legumes between the rows. De et al. (1978) and Gautam and Kaushik (1980a) showed that by modifying the planting geometry in a 30/90 cm row arrangement (three rows of pearl millet 30 cm apart and two such three-row blocks 90 cm apart) left considerable space for including three rows of mungbean (*Vigna radiata* [L.] Wilczek) as an intercrop. By adopting this technique, not only was the pearl millet yield significantly increased, but the additional yield of mungbean made this system economically advantageous (Table 6). Singh et al. (1978) found that a paired-rows system of planting increased the utilization of moisture from deeper layers. In the arid regions of Jodhpur in western India, Singh and Joshi (1980) found no significant difference in pearl millet yield grown as a sole crop or as an intercrop with any legume. But the incorporation of a legume increased the land-equivalent ratio up to 54% in some cases, and the monetary returns increased considerably.

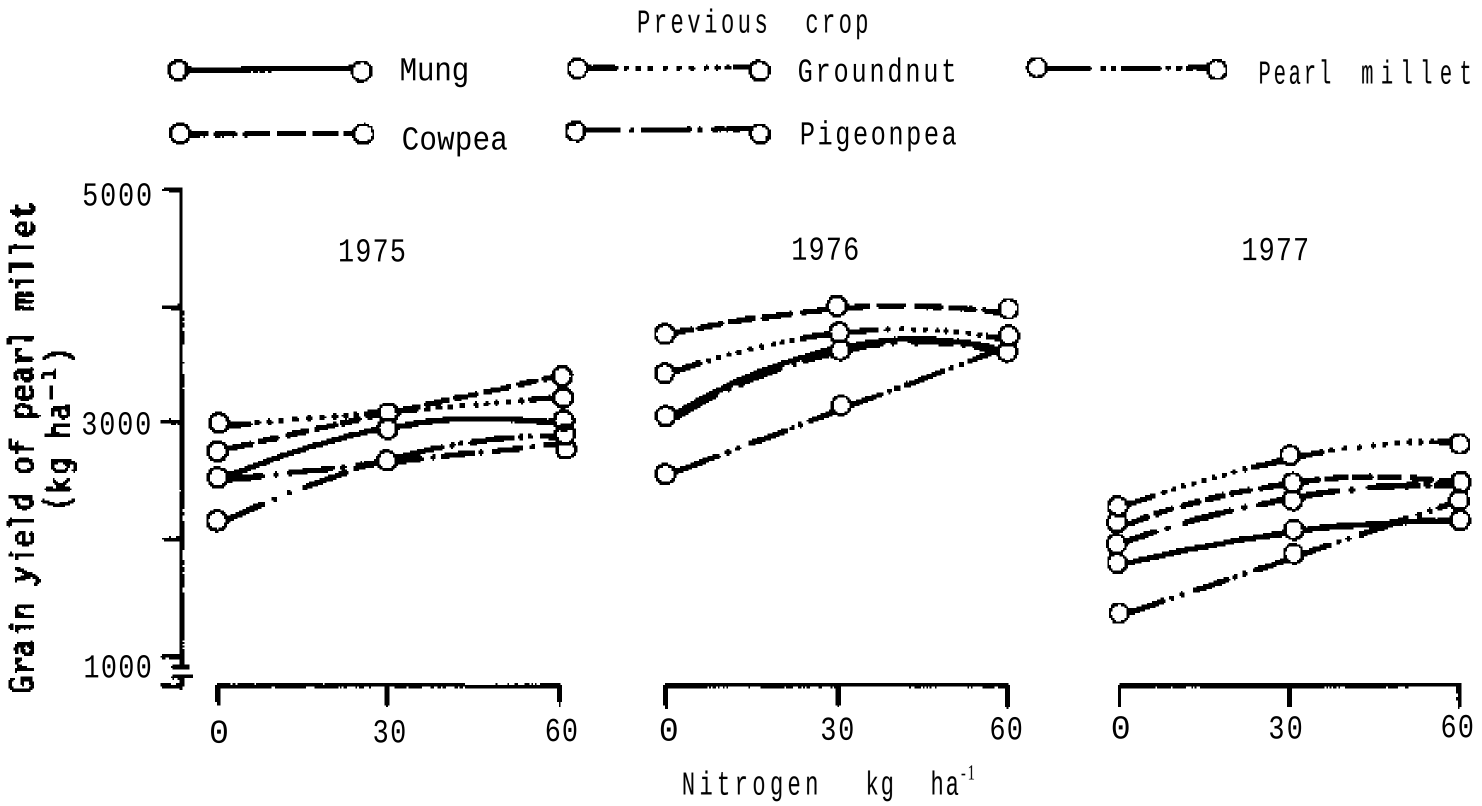


**Figure 3. Response of pearl millet to nitrogen when grown after various rainy season crops.**

Table 6. Effect of time, technique, and planting pattern on the productivity of pearl millet and mung.

| Treatments | Grain yield (kg ha$^{-1}$) Pearl millet | Grain yield (kg ha$^{-1}$) Mung | Pearl millet equivalent (kg ha$^{-1}$) |
|---|---|---|---|
| Paired-row 30/70 cm | | | |
| Direct seeded, 9 July | 2460 | 100 | 2670 |
| Direct seeded, 29 July | 2080 | 250 | 2880 |
| Transplanted, 29 July | 2580 | 260 | 3100 |
| Direct seeded, 18 August | 850 | 320 | 1480 |
| Treble-row 30/90 cm | | | |
| Direct seeded, 9 July | 2680 | 200 | 3070 |
| Direct seeded, 29 July | 2210 | 420 | 3050 |
| Transplanted, 29 July | 2400 | 490 | 3380 |
| Direct seeded, 18 August | 790 | 420 | 1630 |
| Transplanted, 18 August | 1550 | 650 | 2850 |
| Uniform-row pearl millet 50 cm | | | |
| Direct seeded, 9 July | 2460 | - | 2460 |
| Uniform-row mung 30 cm | | | |
| Direct seeded, 9 July | - | 700 | 1400 |
| SE | ±73 | ±23 | |

Source: De et ai. 1978.

## *Azospirillum* as a Seed Inoculant

*Azospirillum brasilence* is a free-living bacterium which exhibits associated symbiosis when present in the rhizosphere. These bacteria are capable of fixing 10-28 mg $g^{-1}$ N of calcium malate in pure culture. In experiments conducted at seven locations over 3 years, inoculation of pearl millet seed with the local strains of the bacterium has increased yields markedly. According to Gautam (1984), the effectiveness of the bacterium increased considerably when it was applied in addition to low rates of N at 10-40 kg $ha^{-1}$ (Table 7).

## Control of Evapotranspiration

A widely-spaced pearl millet crop grown in the hotter parts of the year can lose considerable soil moisture. Organic mulching was tried by Dahiya and Singh (1977) and Malik (1979) at Hisar. They found that application of wheat or rice straw increased the pearl millet yield about 25%. This decreased the soil temperature by 4°C and increased the soil moisture content by 3%. Dauley et al. (1979) reported from Jodhpur in western India that polyethylene film was as good as organic mulches, but both were effective only in years when rainfall distribution was not uniform.

Transpiration control as a means of decreasing soil moisture loss was studied by Kaushik and Gautam (1984), who found that grain yield was increased considerably by removing the upper one-third of the plant or foliar application of chemicals such as borax, kaolin, or atrazine, or by presowing treatment with 0.2% solutions of $KNO_3$ or NaCl. These chemical treatments were as good as straw mulch applied at the rate of 5 t $ha^{-1}$ (Table 8).

Table 7. Effect of N application and Azospirillum seed treatment on the grain yield of pearl millet.

| Treatments | Grain yield (kg $ha^{-1}$) (Mean of 6 locations over 3 years) |
|---|---|
| Control | 1150 |
| Azospirillum | 1390 |
| 10 kg $ha^{-1}$ N | 1450 |
| 20 kg $ha^{-1}$ N | 1650 |
| 40 kg $ha^{-1}$ N | 1910 |
| 10 kg $ha^{-1}$ N + Azospirillum | 1560 |
| 20 kg $ha^{-1}$ N + Azospirillum | 1840 |
| 40 kg $ha^{-1}$ N + Azospirillum | 2100 |

Source: Gautam 1984.

Table 8. Effect of treatments on grain yield of pearl millet.

| Treatments | Grain yield (kg $ha^{-1}$) |
|---|---|
| Untreated control | 1600 |
| Topping (30 days growth) | 1880 |
| Borax spray on plants (0.2% solution) | 2100 |
| Kaolin spray on plants (6% suspension) | 1930 |
| Atrazine spray on plants (100 ppm) | 2050 |
| Presowing treatment with 0.2% $KNO_3$ | 2370 |
| Presowing treatment with 0.2% NaCl | 2050 |
| Skipping alternate rows | 1250 |
| Dry straw mulch at 5 t $ha^{-1}$ | 2300 |
| CD 5% | 230 |

Source: Kaushik and Gautam 1984,

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# Management Practices to Increase Yield and Yield Stability of Pearl Millet in Africa

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### *Abstract*

*Pearl millet is a staple cereal adapted to the poor soils and low rainfall areas of the semi-arid tropics. The low annual production growth rate in the West African region is attributed to three factors: inherent low soil fertility, limited and untimely cultural operations, and frequent drought periods. Improved millet production depends on plant material and management practices that overcome these limitations while providing stable yields and maintaining or improving the production resource base. Production systems should maximize yield in the good years and guarantee some yield in unfavorable years.*

*This paper describes fertility, soil, and crop management practices that could have an impact on improving millet production in the major millet growing areas of Africa. These factors are examined in terms of their potential impact on production and their availability to the resource-poor farmer. Important practices that optimize the use of available water are discussed. If farmers of the semi-arid tropics of West Africa improve the fertility of their soils and move from hand tools to using animal traction, increased and stable yields are possible in this drought-prone region.*

### Résumé

**Pratiques de culture visant à augmenter et à stabiliser le rendement en Afrique** : *Le mil est une céréale de base adapté aux sols pauvres et à la faible pluviosité des zones tropicales semi-arides. Le faible taux de croissance annuel en Afrique de l'Ouest est attribué à trois éléments : la mauvaise fertilité inhérente du sol, des opérations culturales restreintes et non synchronisées ainsi que des sécheresses fréquentes. L'amélioration de la production du mil dépend du matériel végétal et des pratiques de culture qui permettront de surmonter ces contraintes tout en stabilisant le rendement et en conservant ou améliorant les ressources liées à la production. Les systèmes de production devraient assurer un rendement maximum en année favorable et garantir une production suffisante en année défavorable.*

*Cette communication décrit les différentes pratiques d'aménager la fertilité, le sol et la récolte, susceptibles d'améliorer la production dans les importantes zones de culture du mil en Afrique. Ces facteurs sont considérés en termes de leur impact potentiel sur la production et leur accessibilité au paysan démuni. Certaines pratiques d'optimisation de l'eau disponible sont étudiées. L'amendement de la fertilité du sol et le remplacement de la culture manuelle par la culture attelée permettra au paysan ouest africain d'augmenter et de stabiliser les rendements même dans cette région touchée par la sécheresse.*


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Submitted as CP 373 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

## Introduction

Pearl millet *(Pennisetum americanum)* is a staple cereal best adapted to the low fertility soils and frequently drought-prone semi-arid tropics of Africa and India. It is grown on an estimated 27 million ha in these two regions, with 56% of the production in Africa (FAO 1985a). In Africa, major pearl millet growing areas are in West Africa (83%) and the Sudan (8%), in the Sahelian (300-600 mm annual rainfall) and the Sudanian (600-900 mm) bioclimatic zones. Of the 14 million ha grown in West Africa, Nigeria (28%) is the largest producer, followed by Niger (22%), and Mali (10%). The discussion in this paper is confined to implications for these principal millet-growing regions of Africa.

Of all the regions of sub-Saharan Africa (SSA), West Africa has shown the slowest growth rate for total food production, mainly due to the very low production rate of the major staples, sorghum and millet, and the decline in the groundnut cash crop production (Spencer and Sivakumar 1987). The small increase in total food production has been almost exclusively due to increases in cultivated area (Swindale 1985). The new land tends to be in poorer, marginal cropping areas. This suggests technological change has had little impact on food production in general, and millet production in particular. Early descriptions (Dumas 1905) of millet farming systems in the region differ little from current farming methods. Pieri (1985a) cites FAO statistics that indicate for Africa to meet its food needs in the year 2000, increased production will have to come from increased yield per hectare (51%), rather than from expanded cultivated areas (27%), or from more than one crop per year on the same land (22%).

Millet is traditionally reserved for light, sandy, low fertility soils in areas where rainfall is low and drought common. Few yield-increasing inputs are used. Management strategies, using mainly hand labor, are extensive rather than intensive. The crop is grown with low plant populations, normally in association with other crops, particularly cowpeas (*Vigna unguiculata* [L.] Walp.) and sorghum *(Sorghum bicolor* [L.] Moench). Millet grain is used primarily for human consumption, however the straw is important for construction and as standing dry fodder for animal production system.

Improved millet production in the West African semi-arid tropics (WASAT) should rely on management practices that increase yields, when possible, while improving production stability in both good and poor rainfall years. Farmers' production can be stabilized through a reduction in yield variation from year-to-year, and by insuring a carryover of grain from good to poor years.

Although Egharevba (1979), Nwasike et al. (1982), and Njoku and Mijindadi (1985) have proposed other limiting factors, the authors consider the principal factors limiting millet yields in WASAT to be, in order of priority: (1) inherent low soil fertility, (2) limited and untimely cultural practices, and (3) the frequent occurrence of drought periods. The first two factors are more limiting than moisture in most years. In years when rainfall is inadequate, water-use efficiency and yields can be improved by inputs that address these two factors. The improvement of millet production will rely on management practices that overcome these limitations, while insuring yield stability and maintenance or improvement of the production resource base. Inputs, by necessity, will have to be available to the resource-poor farmer.

## Fertility Management of Millet Production Systems

The poor fertility of millet soils in WASAT is the principal limitation to increased millet yields. Organic matter (OM), available phosphorous (P), total nitrogen (N), and the cation exchange capacity (CEC) are all low (see Table 4, Spencer and Sivakumar, 1987). Consistently low yields per hectare in the region are indicative of this poor fertility. Traditionally, farmers have managed these poor soils, mainly Entisols and Alfisols, by extended fallowing. This permits build up of available N, P, and OM (Charreau 1972, Nye and Greenland 1960, Jones and Wild 1975). The increase in land use due to sedentarization and population growth has reduced or eliminated the fallow period, and farmers have been forced to cultivate marginal lands.

Millet production is largely determined by the availability of P and N in the soil, particularly P (Fig. 1), and moisture. The Dutch-Malian Projet de production secondaire (PPS) concluded that the principal limiting factor to animal and plant production in the Sahel region was low soil fertility. P and N deficiencies are more limiting than low and irregular rainfall (Penning de Vries and Djiteye 1982). Higher yields and intensified use patterns will remove more nutrients and deplete the resource base for the following crop, unless the nutrients are replaced. Surprisingly, this scenario has had little influence on national fertilizer use in sub-Saharan Africa, which is the lowest in the world at 6.4 kg $ha^{-1}$ (FAO 1985b).

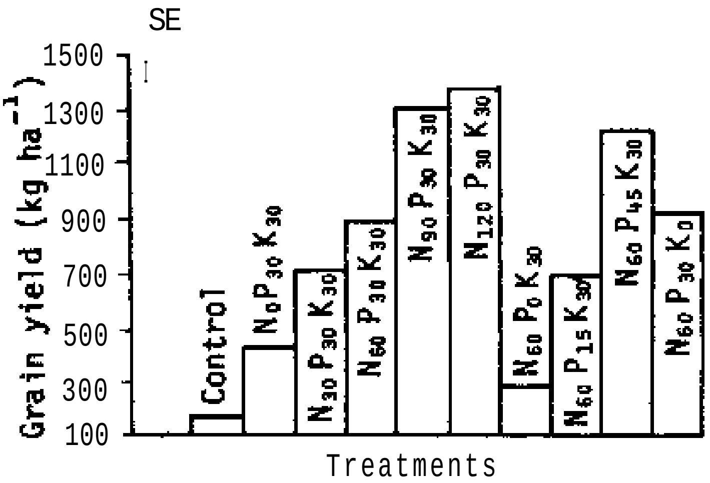


**Figure 1. Effect of different rates of nitrogen, phosphorus, and potassium on pearl millet grain yield (Sadoré 1985).**

Many fertilizer trials have shown that low P and N are major constraints to millet production in WASAT soils (Mughogho et al. 1985). The practice of recycling crop residue by incorporating it as compost, raw mulch, or manure does help to replenish P and N and maintain yields (Charreau and Nicou 1971, Tourte 1971, Pichot et al. 1974, Ganry et al. 1978, and Pieri 1985a, who cites Sedogo, and Ganry and Bertheau). Additional benefits occur when fertilizer use and OM maintenance techniques are used together (Fig. 2), but the limited availability of these products restricts the application of this strategy to

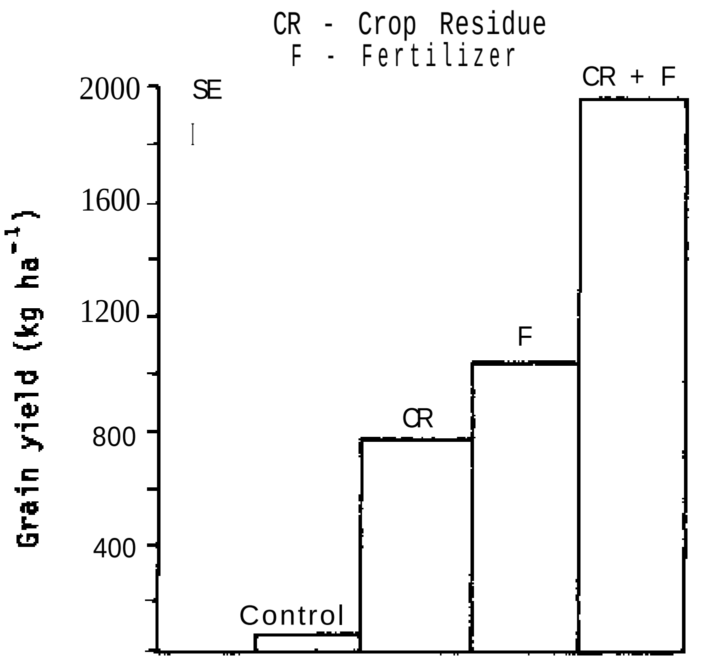


**Figure 2. Effect of pearl millet grain response to fertilizer and crop residue application (Sadoré, Niger 1985).**

maintain soil fertility. While immediate soil fertility improvement will largely come from added chemical fertilizers, the incorporation of crop residues and manure into the production system are needed to insure its stability (Pieri 1985a).

Although other nutrients, such as sulfur, may assume importance in some areas, only P and N will be considered because of the general and preponderant limitations they place on production.

## Phosphorous

Marked P deficiencies in the millet producing soils of WASAT are well documented. Research by the French government Tropical Agronomy Research Institute, Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres (IRAT) and the WASAT national programs, and more recently, work of the International Fertilizer Development Center (IFDC) and ICRISAT, shows that the major millet-producing soil groups are low in P (IRAT 1975, Bationo et al. 1985). During 1950-1980 millet responded well to imported, combined phosphate fertilizers (Bationo et al. 1985). A 1:5 fertilizer/grain yield ratio is possible (Fig. 3, and Pichot and Roche 1972). Such substantial yield increases have been achieved with local, improved, and exotic cultivars. Moreover, the yield superiority of improved cultivars generally occurs in the presence of adequate soil P (Fussell, personal communication).

Several countries of WASAT have natural rock phosphate (RP) deposits. The use of RP for direct application appeared to be an economic means of P fertilization. This encouraged early researchers to look at RP as a P source (Jones 1973, Truong et al. 1978). The effectiveness of RP depends on its chemical and mineral composition, soil factors, and the crop grown. Unfortunately, early research on the West African RPs found their agronomic effectiveness limited due to low reactivity, with a resultant inability to supply adequate P in the soil solution (Truong et al. 1978). Nonetheless, the RPs of Mali (Tilemsi RP) and Niger (Tahoua RP) are sufficiently soluble to be used for direct application. Lack of initial response to the added RP discouraged their use. In Niger, even though national production, distribution, and extension efforts have been established to market Tahoua RP, the adoption rate by farmers has been low.

Partial acidulation increases the solubility of RP and insures a better initial response by a short-season crop such as millet. Recent research in Niger

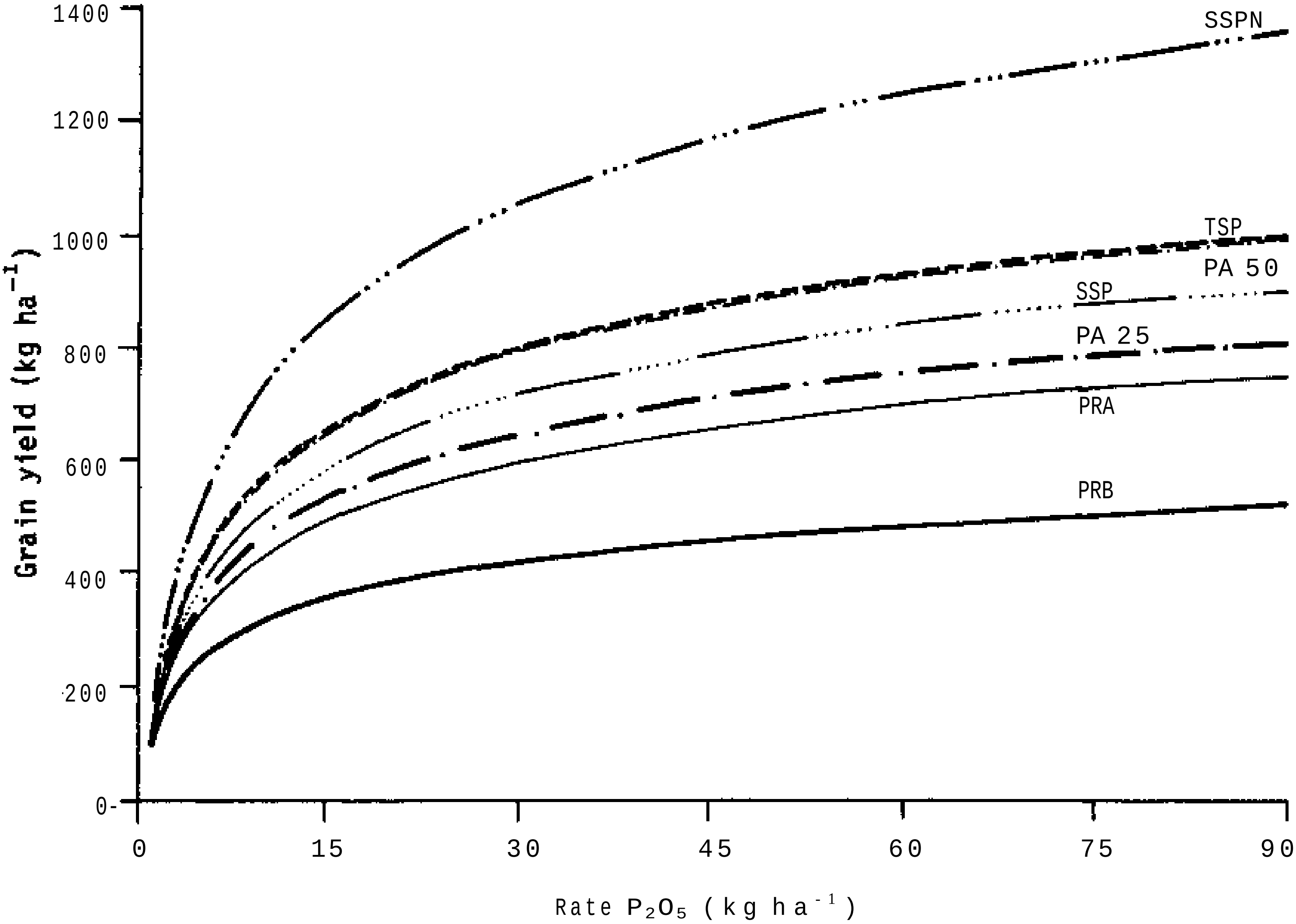


**Figure 3. Effect of phosphorus sources and rates on millet grain yield ISC, Niger, rainy season 1985. (SSP = single superphosphate; SSPN = SSP + nitrogen, TSP = Triple superphosphate; PA 50 and PA 25 = partially acidulated rock phosphate treated with 50 or 25% sulfuric acid; PRA = rock phosphate applied annually; PRB = rock phosphate applied as a basal dose triannually).**

shows that most RPs, such as found at Parc-W and Kpeme, increase yields up to 95±17.5% of Single Super Phosphate added (equivalent quantity of P) when they are 50% acidulated (Fig. 3, and Bationo et al. 1985). More than three-fold increases in millet yield have been produced on Entisols in Niger. Similar results have been demonstrated in Mali, Burkina Faso, and Senegal (Bationo et al. 1985).

Findings at the farmer level have been less spectacular (44-130% yield increases) but economical, even in the severest drought years (1CRISAT 1985). Financial returns were highest at 24 kg $ha^{-1}$ of acidulated RP when millet was sown with the first rains of 369 and 422 mm in two villages in western Niger. Moreover, there were important residual effects of P in the second year because unused P undergoes little leaching as compared to N. This is consistent with other results (ICRISAT 1985).

The importance of mycorrhizal activity to improve P availability in WASAT is under investigation by 1CR1SAT. Preliminary data indicate high levels of mycorrhizal activity. This research should receive a high priority in the light of the good crop responses to small applications of P. Better understanding of mycorrhizal effects on P uptake and its possible manipulation should lead to more efficient use of applied P.

Substantial, financially feasible, yield increases are possible at the farm level through the use of partially acidulated local RP. Adapted cultivars, with improved fertilizer-responsiveness, will enable the farmer to increase his return from fertilizer use. Moreover, because P fertilizers can be applied and incorporated before planting, the additional labor requirements do not interfere with critical planting or crop maintenance operations. Acidulated RP has a physical form similar to SSP and is easily applied. Currently, in Niger and Burkina Faso, local authorities are considering local production and distribution of acidulated RP.

## Nitrogen

Nitrogen improves millet yields in WASAT only in the presence of adequate P (Ganry et al. 1974, Troare 1974). Furthermore, the erratic rainfall and poorly buffered soil conditions increase the risk of losing applied N without any yield increase. But with adequate moisture and P, the judicious use of N on millet is an important management strategy. The following discussion considers only the use of chemical and plant nitrogen sources. This does not overlook the importance of mineralized N, especially early in the season, and the importance of timely planting with the first substantial rains to optimize mineralized N uptake and yields (Greenland 1958, Jones and Wild 1975, Egharevba 1979).

### Inorganic N Sources

A number of researchers in WASAT have demonstrated increased millet yields with the use of nitrogenous fertilizers (Ganry et al. 1974; Troare 1974; Egharevba 1979; FAO 1982; ICRISAT 1984, 1985, 1986; Mughogho et al. 1985; Pieri 1985a). With limited rainfall and newly cleared land, the response to N has been limited. With adequate rainfall and continuous cropping, the response to N is pronounced and varies with N source, application method, and timing (Fig. 4). However, the recovery rates are poor, as low as 26% (Mughogho et al. 1985). While it is possible that recovery efficiencies

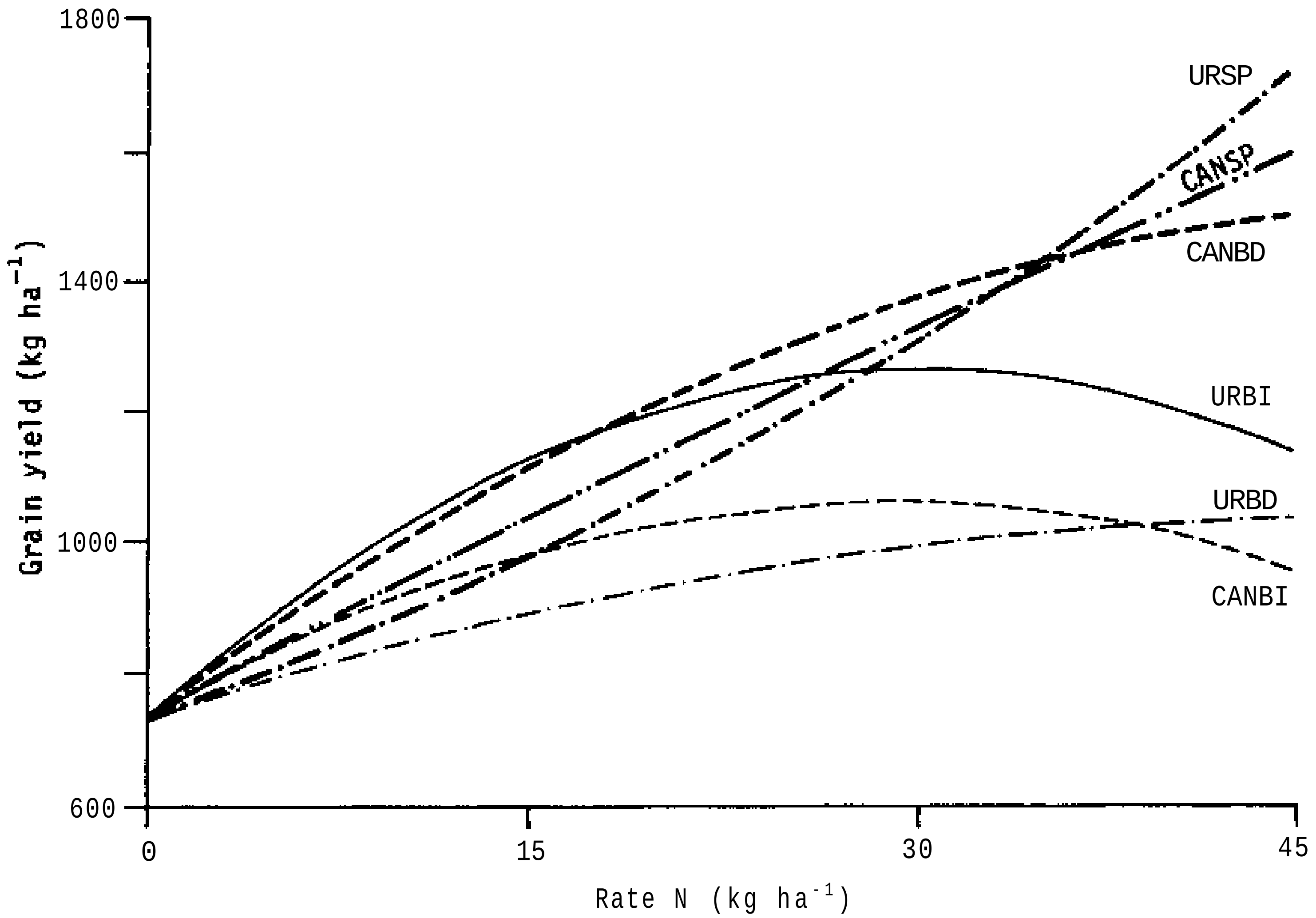


**Figure 4. Effect of different sources, rates, time, and methods of placement of nitrogen application on pearl millet grain yield, ISC, Niger, rainy season 1985. (URSP = urea split application; CANSP = calcium ammonium nitrate, split application; CANBD = CAN banding 30 DAE; URBI = urea broadcasting with incorporation 30 DAE; URBD = urea banding 30 DAE; CANBI = CAN broadcasting with incorporation 15 DAE).**

will improve when N is applied in split doses after planting (Fig. 4, and Mughogho et al. 1985), this may not always be the case (Egharevba 1978). Using split dosages can conflict with other activities, such as weeding, if there is a labor shortage at this time.

### Organic N Sources

The use of leguminous crop rotations (Pieri 1985a) and intercrop plantings with cereals to provide N are important fertility management practices. In Niger, millet yields increased more than two-fold where millet followed 1 year of groundnuts (Brown 1978). Similar observations have been made in the groundnut basin of Senegal. It is not clear whether the increased yields were due to the residual effect of N from the legume, or the residual P not used by the legume (Pieri 1985a). However, there is evidence of a combined residual effect of the two (ICRISAT 1985). In low rainfall years the amount of symbiotic N fixed is reduced by as much as 60% in a groundnut crop, but it still constitutes an important and inexpensive source of N (Pieri 1985a, who cites Ganry and Wey).

A viable management strategy is to apply P to a leguminous cash crop and follow this with nonfertilized millet. Such a legume/millet crop rotation has been widely practiced in Senegal for many years, and may in part account for the higher average millet yields in Senegal compared to Niger. It is possible that strip cropping cereals and legumes could contribute to improved wind erosion control as well as providing a workable crop rotation system.

Strategic management of a leguminous intercrop in a given year can also increase millet yields. In Mali total crop yield increased up to 100% with a millet/cowpea system where the cowpea intercrop was removed 60 d after the crops were sown. It appears that limited amounts of symbiotically fixed N may become available to the millet portion of the intercrop after the cowpea harvest.

The productivity of the pastoral system is important to the WASAT economy. The use of extended fallow periods has been an important fertility maintenance strategy. Research on the possible contributions of leguminous pastures to fodder and N fertility level has been neglected. Oversowing legumes, such as *Stylosanthes,* into a millet crop is a management strategy that merits study. It may contribute N to the following millet crop and provide high quality pastures as well.

Agroforestry is important as a source of N to millet cropping systems. Species such as *Acacia albida* Del. add up to 1 kg $ha^{-1}$ of N to the cropping system for every tree present. There are also important windbreak effects (Charreau and Vidal 1965). Such species are cultivated and encouraged in the traditional systems and crops under the trees yield much higher than those away from the trees (Charreau and Vidal 1965). However, this situation could be misinterpreted because of the scavenging nature of the roots that are away from the trees, and because the trees are used by birds for roosting and by cattle for shade, resulting in manure being concentrated around the trees (Breman et al. 1984, personal coniinunication). Nonetheless, because of the importance of agroforestry in reducing wind erosion and increasing yields (see later sections), the use of leguminous trees in association with millet production should be encouraged.

### Improved Fertility and Water-Use Efficiency

Improved fertility may or may not increase water use, but it does improve water-use efficiency (WUE). In two contrasting rainfall years at the ICRISAT Sahelian Center (ISC) (1984, 254 mm rainfall; 1985, 540 mm rainfall), millet crops with and without fertilizer used similar amounts of water within each year (ICRISAT 1984, ICRISAT 1985). The use of fertilizer produced up to 75% more total dry matter (TDM) and grain yield. As a result water-use efficiency was much higher under improved fertility. Improving the fertility of the soil will improve WUE, help stabilize production in poor years, and enable the crop to exploit good rainfall years.

## Soil Management of Millet Production Systems

The physical properties of the sandy-textured soils where millet is grown are poor. Low surface porosity, weak structure, susceptibility to crust formation, and low water-holding capacity are the important limiting properties. Improved cultivation practices enhance the benefits from the use of organic and inorganic fertilization (Tourte 1971, Charreau and Nicou 1971, IRAT 1975, Egharevba 1979, Pieri 1985a). Earlier researchers explored benefits from primary tillage, and in recent years, the positive effects of modifying the soil surface configuration have received attention (Nicou and Charreau 1985).

## Tillage

The beneficial effects of tillage result from reduced (soil) bulk density, which enhances root proliferation, thereby increasing fertilizer recovery and improving WUE. Tillage also incorporates organic matter, improves weed control, and improves soil moisture conservation. Yield increases due to tillage alone are quantitatively modest in the absence of other management techniques (Fig. 5). The synergistic effects of tillage with added fertility and improved genotype are critical to its value. When tillage was accompanied by other inputs, Nicou and Charreau (1985) reported an average 22% yield increase from 38 different experiments. Yield advantages from primary tillage are stable or increase in the driest years (Pieri 1985b; Pocthier, cited by Pieri 1985a).

Reduced bulk density and increased porosity, even in very sandy soils, improves root penetration (Nicou 1974, Chopart and Nicou 1976, Chopart 1983, Nicou and Charreau 1985). Porosity increases are normally in the order of 10-20% (Nicou and Charreau 1985), which doubles root dry weight during the first 50 d (Chopart 1983). Extensive rooting improves access to existing and applied fertility (Charreau and Nicou 1971). Since the plant can more fully exploit the profile, it can use more of the available moisture, and may be better able to resist drought (Chopart 1975). At the ISC, bulk densities prior to tillage are in the order of 1.55-1.65 t nrr$^{3}$. After tillage they are reduced to 1.30 t nr$^{3}$ (ICRISAT 1985). In 1984, an extreme drought year (240 mm), TDM yields increased by 17-29% due to plowing or ridging (ICRISAT 1985). In 1985, an average rainfall year (540 mm), the yield increase due to tillage in the presence of adequate fertility was 76% at the ISC, a result of increased rooting and improved moisture use (Fig. 5).

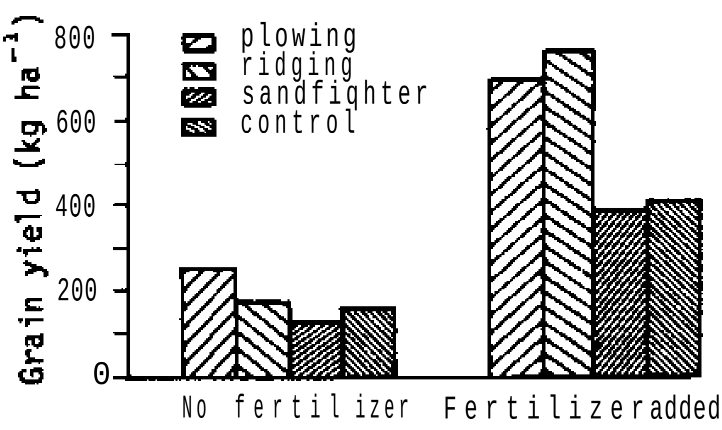


**Figure 5. Grain yield responses of pearl millet to fertilizer and presowing cultivation, ISC, Niger 1985. Standard error for comparing tillage means at same or different levels of fertility = ±66 kg ha$^{-1}$.**

Because the millet soils of WASAT are acidic, poorly structured and buffered, have low cation exchange capacity and water holding capacity, managing their organic matter status is important. The use of tillage to incorporate crop residue (Fig. 2), and animal manures, may improve organic matter status.

Weeds are controlled by primary and secondary tillage, as well as through weeding operations after the crop has emerged. Profile-inverting primary tillage, which buries weeds, or a thorough first weeding, or both operations combined, reduce the need for subsequent weedings, thus saving labor. Weeding is one of the critical labor bottlenecks in many WASAT traditional systems. With adequate weed control, competition for nutrients and moisture is reduced during the critical seedling establishment stage.

Soil moisture can be conserved at the end of the season with end-of-season tillage operations that eliminate weeds (Charreau and Nicou 1971, Jones 1975, Nicou and Charreau 1985). This may have an important beneficial effect on the following crop, if the season is dry (Dancette and Nicou 1974, cited by Dancette and Hall 1979; Chopart and Nicou 1976).

The benefits of tillage only become substantial in association with other improved practices like the use of important plant materials. A fertilizer-responsive genotype, grown with adequate fertility, improved tillage, and improved cultural practices will yield substantially higher than the traditional cultivars with traditional cultural practices.

## Land Forming

A variety of land forming techniques exist, including terracing, graded or nongraded benches, and leveling. Only three hold much promise as management practices for WASAT farmers: bedding, as practiced in the broadbed-and-furrow system; ridging, as traditionally practiced in Nigeria (Buntjer 1971), Mali, Senegal, and Niger; and hilling, as practiced in several locations in the Sahelian Zone, including the Seno Plain in Mali.

Only ridging is discussed here because on a micro level the effects of ridging, hilling, and bedding are similar. At the ISC, where infiltration rates are high (in excess of 150 mm h$^{-1}$), the effects of ridging on controlling wind erosion and protecting millet seedlings have been noteworthy. In 1984, a severe drought year, ridging improved the stand by 50%. The combination of ridging and the use of genetic material selected for better crop establishment will significantly improve yield. Where infiltration rates are lower and where ridges slope, ridges tend to concentrate water and increase both runoff and erosion. However, 'ridge-tying' and 'furrow-damming' reduce this problem, encourage uniform infiltration, and considerably increase yields, especially in the drier years (Lawes 1963, Kowal and Stockinger 1973, Nicou and Charreau 1985). In wetter years and heavier soils, erosion and water stagnation may be aggravated (Kowal 1970a and b).

Ridging concentrates fertility and organic matter in the ridge, increasing its availability to the seedling (Kowal and Stockinger 1973). Permanent bed or ridge systems also reduce the total area necessary to till, and limit the compacted area to the furrow.

Graded beds and furrows improve infiltration by slowing water movement down the slope. In addition, in permeable soils such as those found at the ISC, concentrating water in the furrow increases its effective head. Consequently, the moisture moves further down the profile (Klaij, personal communication), and is less subject to evaporation losses than at the surface. At the ISC in 1984, this partly accounted for the advantages that were observed in planting on ridges.

The effects of ridging on bulk density, organic matter incorporation, and improved rooting are similar to those of plowing or other primary tillage techniques.

### Animal Traction

The majority of tillage, planting, weeding, and farm transport in WASAT is done by hand. Developing adequate animal traction systems will increase human efficiency by improving farmers' ability to mechanize farm operations and transport capability. Animal traction use is relatively widespread in some areas of WASAT (e.g., the groundnut basin in Senegal). In the Sudanian Zone, there are several instances where its acceptance has been instrumental in intensifying the cropping system (e.g., the cotton zone in Mali). Due to the cost of tractors and their maintenance, it is only with animal traction systems that it is possible to replace the large scale use of human labor as a power source for basic farm operations. Furthermore, the advantages of primary tillage to crop growth may only be realized through the acceptance of animal traction on a widespread scale. Management options are increased by precision farming with improved animal-drawn tool carriers (ICRISAT 1983). Husbanding traction animals provides other benefits to the farmer, such as meat, skins, calves, milk production, and manure, all of which can improve farmer net worth and income.

Successful introduction of effective animal traction systems for the full range of crop operations will increase basic options available to WASAT farmers. However, there is a long learning curve for the use of animal traction, and providing the capital and developing the infrastructure to support animal traction systems are inherent problems. It is, however, the only practical means in the foreseeable future to increase the farmers' efficiency, and the timeliness and precision of operations.

## Crop Management of Millet Production Systems

Millet crop management based on the choice of an appropriate cultivar, cropping method, rotation, and cultural operations can increase production of the total cropping system, improve WUE, and provide a more stable return to the farmer.

### Cultivar Choice

Traditional millet cultivars used by farmers in WASAT are well adapted to the low fertility and low management production systems. With better management (e.g., P and tillage), the choice of a millet cultivar assumes importance. Synergistic effects occur with the use of management-responsive cultivars in these situations. Under conditions of good tillage and management, local cultivars maintain low harvest indices (HI <20%), yet increase leaf area and biological yield. Under these conditions, improved cultivars have less leaf production yet good biological yields with higher harvest indices (> 35%). Their lower and more efficient water use under improved conditions are a result of a close relationship to leaf area and TDM (Kowal and Kassam 1978, Azam-Ali 1983, Azam-Ali et al. 1984). Research into cultivars that have a higher WUE than cultivars of equivalent cycle length would be productive (Kassam and Kowal 1975). Initial results indicate at least a 20% difference in WUE between cultivars of equivalent duration (ICRISAT 1984).

Farmers need a choice of well-adapted millet cultivars of different maturity groups, because rainfall has been below average for the last 15 years in WASAT. Higher and consistently stable yields across these low rainfall seasons are the result of growing shorter duration varieties. This is understandable, as there is a positive linear correlation between crop-water requirements and the length of the growing period (Dancette and Hall 1979, Dancette 1983). In optimum growing conditions, a 75-day GAM dwarf variety (Group d'Amelioration du Mil) uses 390 mm of moisture whereas a 120-day sanio millet uses 630 mm. Short-duration cultivars of equivalent yield potential are an important management strategy in drought-prone WASAT, where the probabilities of drought are high at the beginning and end of the season (Spencer and Sivakumar 1987). Methods that predict the growing period will allow millet varieties to be tailored to specific agroclimatic conditions (Dancette 1976). Early-maturing millet also conserves moisture in the soil profile that may help the next seasons' crop (Hall and Dancette 1978).

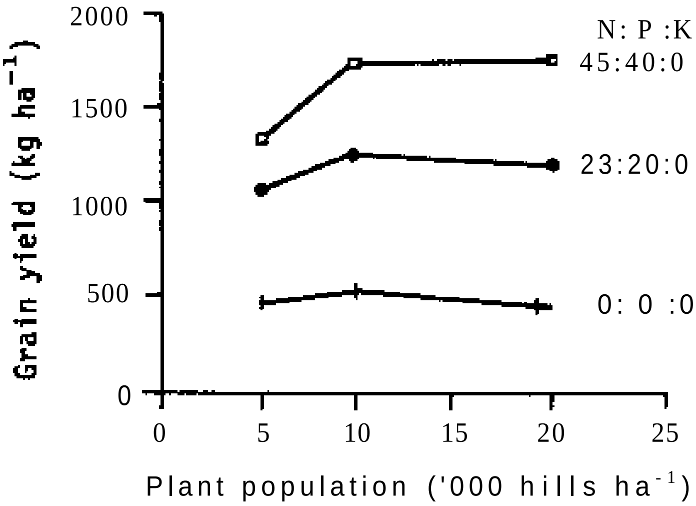


**Figure 6. Grain yield response to increases in plant population and fertilizer, ISC, Niger, rainy season 1985. Standard error for comparing plant population means at the same or different fertilizer level = ± 56 kg ha$^{-1}$.**

## Planting and Cultural Techniques

Timely crop management practices are necessary to sustain high millet yields (Ogunlela and Egharevba 1981). Planting with the first substantial rains maximizes grain production in most years. Early weeding and thinning contribute to good yields (Monnier 1976, Egharevba 1979). This is particularly important because there are positive synergistic effects between improved soil P and N, tillage, weed control, and higher plant populations (Fig. 6, Tourte and Fauche 1953, Tourte and Fauche 1955, Nebos 1970, Nwasike et al. 1982, Egharevba et al. 1984).

## Crop Associations

Millet is traditionally intercropped in WASAT. In Niger, up to 87% of the millet area is intercropped (Swinton et al. 1984), and similar figures are reported for Nigeria (Norman 1974) and Burkina Faso (Sawadogo and Kabore 1984). The most common associations are millet/cowpea, millet/sorghum, millet/maize, millet/groundnut, and millet/sorghum/cowpea. In these systems millet is normally sown first and acts as the dominant crop. The percentage yield contribution of the crop or crops grown with the millet decreases with decrease in rainfall.

Management strategies designed to increase and stabilize millet yields in WASAT must consider the advantages of traditional cropping patterns and the inherent production goals of the farmer. Studies of these traditional systems indicate that a total yield advantage exists and that intercrops are more stable than sole crops (Baker 1978, Baker 1979, Fussell and Serafini 1985). In general, millet yields are reduced in an intercrop, such as with rampant cowpea, but this is not always the case (Fig. 7, Fussell 1985, Serafmi 1985). Delayed planting of the intercrop consistently protected cereal crop yields (Serafmi 1985). The yield advantages of intercrop systems vary from 10-100% in millet (Fussell and Serafmi 1985).

Moreover, Norman (1974) concludes mixed cropping is a rational strategy both for profit maximization and risk minimization. Production and income stability are important features of the systems (Abalu 1976) which also alleviate seasonal labor peaks (Norman 1974).

The most advantageous millet intercropping systems exploit temporal differences between the crops. Millet is generally cropped with a later-maturing species, such as cowpea (Fussell 1985, Serafini 1985) or sorghum (Baker 1979). There is a temporal separation of the most competitive growth periods, and the intercrop is able to utilize those resources not fully used by the millet. During the 1985 cropping season at ISC, there was little reduction in millet yields, while cowpea hay yields increased substantially (Fig. 7). Cowpea, planted a week later than

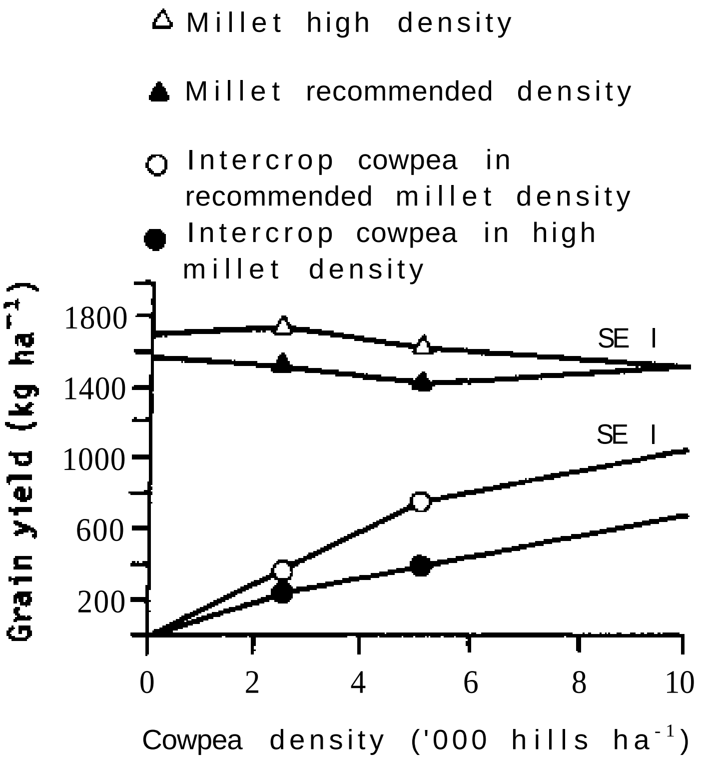


**Figure 7. Pearl millet grain yield and cowpea hay responses in a pearl millet/cowpea intercropping system at three cowpea densities, ISC, Niger, rainy season 1985.**

millet, exploited the moisture and nutrients not used by the millet without a large reduction in the millet yield because the cowpea had a longer growth duration than the millet. Such systems use water more efficiently than sole millet (Fussell 1985). In a year when drought occurs early in the season, the crop planted first, millet, will substantially suppress the non-millet component. This protects the production of the staple cereal.

Millet/intercrop genotypic interactions have not been adequately investigated. There should be plant types of both the cereal and the legume that will contribute to increased efficiency and production of the intercrop.

The inherent flexibility of millet intercropping systems is an important aspect of their use. The producer is able to decide when and how much of the second crop should be planted because millet is planted first. Should there be an early-season drought, the density of the intercrop can be reduced, or eliminated. On the other hand, if millet establishes poorly, the density of the second crop can be increased, a traditional practice the authors have observed in farmers' fields in Niger and Mali.

Considering these aspects, intercropping millet with other crops is consistent with other management strategies, such as animal traction, designed to increase yields and stabilize production (Mclntire 1983).

## Agroforestry

The importance of trees in traditional agriculture of WASAT was highlighted by Charreau and Vidal (1965) in research on the role of *Acacia albida* Del. Other frequently encountered species include *Butyrospermum parkii (G.* Don) Kotschy (karite), *Parkia biglobosa* (Jacq.) Benth (nere), *Adansonia digitata* L. (Baobab), and *Ballanites aegyptiaca(L.)* Del (dattier sauvage). These trees contribute substantially to the diversity and productivity of the farm enterprise through production of oil (karite), fodder *(A. albida* and others), firewood (all), fiber (Baobab), food (Baobab, Nieri, and others), medicine, repellants, and poisons (von Maydell 1983, Weber 1977, Weber and Hoskins 1983). Browse should contribute 20-25% of the fodder intake in the transhumant pastoral system for cattle, sheep, and goats (Le Houerou 1980). Balanced and productive millet-based systems for the Sudanian and Sahelian Zones are those that exploit the agroforestry and livestock contributions to the system (Taylor and Soumare 1983).

Trees may beneficially affect the microenvironment of a millet crop by having different growing cycles, and using the resource base differently than millet. *A. albida* is a classic example: it is deciduous during the rainy season (Charreau and Vidal 1965, Dancette and Poulain 1969), and is deep-rooted, exploiting moisture in the profile below that is used by the cereal. Using the Bambey (Senegal) region as an example, Dancette and Hall (1979) estimate that 650 mm of annual rainfall could support a millet crop which uses 400 mm of water, weeds, and groundwater rechange of 100 mm, leaving 150 mm of water that would support 22 *Acacia* trees $ha^{-1}$. Trees create air turbulence that lowers evaporative demand by reducing wind speed, provide some shade for the crop, and protect the soil from erosion (Dancette and Poulain 1969, Bognetteau-Verlinden 1980, Ujah and Adeoye 1984). Millet yields have increased by as much as 28% in the presence of adequate tree lines (Bognetteau-Verlinden 1980).

Trees are also important in nutrient cycling: leached cations are redeposited at the soil surface in the form of fallen leaves and fruits. For example, the practice of burning karite leaves just prior to the planting season releases K and Ca for the crop, which may have a critical impact on soil pH as well as fertility. The nitrogen contribution of leguminous trees has been discussed above, and is particularly important where the efficiency rates for applied N are low and the chemical forms of N are expensive, and difficult to procure.

A *aJbida* galleries cover many millet fields in WASAT. The authors have noted instances where they estimated that *A. aJbida* covered more than 50% of the crop surface. Alley cropping systems, as suggested by Dancette and Poulain (1969) using *A. albida,* as well as other adapted trees and shrubs are feasible, and may be an advantageous part of any millet management system in WASAT.

## Conclusions

The poor performance of the WASAT food production system is attributed in part to the very low production of the major staples sorghum and millet. For the region to meet its food needs in the year 2000, increased production must come from increased yields per unit area. Management practices must alleviate the effects of the principal factors limiting millet yields: inherent low soil fertility, limited and untimely cultural operations, and frequent drought periods. The first two factors are often more limiting than irregular and insufficient rainfall. Higher soil fertility and improved cultural practices will improve WUE and increase yields.

Sound management practices to alleviate the primary limitations include:

- the use of combined and acidulated rock phosphates;
- the use of biological sources of N, in particular, leguminous crop rotations, stable and efficient intercropping, and agroforestry;
- the incorporation of crop residues and animal manures;
- efficient primary and secondary tillage, using animal traction, including land forming techniques;
- the choice of management-responsive, water-use efficient varieties tailored to the current agroclimatic conditions;
- timely crop management practices; and
- maintenance and systemization of trees and shrubs as a part of the millet farming system.

The resource-poor farmer is not likely to adopt all these management practices. Previous experiences indicate that farmers tend to adopt and adapt parts of technical packages. Therefore, resource management systems need to be developed at a number of levels so farmers may choose strategies and techniques appropriate to their specific situations. In some cases, infrastructure improvements need to be encouraged and even subsidized by the governments of the region (e.g., rock phosphate industries). Improved soil fertility is the starting point of any management strategy to increase millet yields in the region. Other management options will have positive synergistic effects with improved fertility.

Additional management options may result from further research:

- increasing the effect of mycorrhizal associations on P uptake;
- use of leguminous pastures as a source of N and animal feed;
- the examination of the long-term effects of tillage and land forming techniques;
- choice of varieties both in sole and intercropping systems that maximize production and WUE; and
- development of efficient, integrated, agroforestry systems.

Low rainfall does mean lower millet yields. Nonetheless yields and WUE can be improved through the judicious use of fertilizers. In the presence of adequate fertility, other management practices will have a positive impact as well, and will improve stability over time. Current traditional management practices fail to take advantage of good years, because moisture is not the principal limiting factor. Management practices are available, which in some cases need to be refined, that guarantee production in poor years and take full advantage of better rainfall years.

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# Breeding for Adaptation to Environmental Stress?

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### Abstract

*Although breeding for adaptation to environmental stresses is a more complicated problem than breeding for adaptation to biotic stresses, the basic procedure is virtually identical. Initial steps include understanding the specific problems, and establishing methods to identify better-adapted materials. This is followed by determining if useful genetic variability for adaptation exists, and if so, deciding upon the best means to select for improved adaptation in a breeding program. The results of these steps then allow a rational decision on whether breeding for better adaptation is justified.*

*This procedure is illustrated using two different environmental stress problems in pearl millet: failure of stand establishment and drought stress during grain filling. Useful progress has been made on understanding the problems involved and developing screening and selection methods. Current efforts center on assessing the genetic variability for these traits and evaluating the response to direct selection for adaptation.*

### Résumé

**Sélection pour l'adaptation aux stress environnementaux :** *La sélection visant à l'adaptation aux stress environnementaux s'avère plus compliquée que celle pour l'adaptation aux stress biotiques. Cependant le processus de base pour ces deux types de sélection reste pratiquement le même. On commence par l'examen des problèmes particuliers et l'établissement des méthodes d'identification du matériel mieux adapté. Ensuite, il faut déterminer s'il existe une variabilité génétique intéressante et définir les moyens les plus efficaces de sélectionner ce matériel en vue d'améliorer son adaptabilité. Les résultats obtenus permettront d'établir dans quelle mesure la sélection pour l'adaptation se justifie.*

*Ce processus est explicité à l'aide de deux exemples des problèmes de stress environnementaux : l'échec de l'établissement des plantules et la sécheresse advenant pendant la formation des grains. L'étude des problèmes donnés et la mise au point des méthodes de criblage et de sélection sont déjà bien avancées. L'évaluation de la variabilité génétique et de la réponse à la sélection directe est actuellement en cours.*

## Introduction

The title of this paper has been deliberately phrased as a question because there has traditionally been considerable skepticism about breeding for 'resistance' to environmental stresses. Selection for tolerance to certain stresses—such as freezing temperatures, low pH, and aluminium-toxic soils—has been effective (Blum 1985), but plant breeders have been far more willing to devote resources to breeding for disease and insect pest resistances than to breeding for adaptation to environmental stress.

Research on environmental stress is admittedly more complex than research on biotic stress. While

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Submitted as CP 372 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Proceedings of the International Pearl Millet Workshop, 7-11 April 1986, ICRISAT Center, India. Patancheru, A.P. 502324, India. ICRISAT.

biotic stresses exist as discrete entities—individual species, races, or biotypes—variation in environmental stress is continuous. Usually, biotic stress is also easier to manage experimentally. Finally, immunity, and possibly even true resistance to environmental stress, is not possible. The choice is among degrees of tolerance or adaptation. Nonetheless, breeding for adaptation to environmental stress is still a conventional scientific problem, to be attempted by conventional scientific methods. Plant breeders have, in the past, produced genetic materials with a wide range of traits using such standard methods. It is the contention of the authors that a similar approach is equally appropriate to increased tolerance to environmental stresses.

## General Framework

There are two parts to the question of breeding for adaptation to environmental stress. (1) What methodology to use, and (2) what evidence is there to justify the investment of resources? Although there have been a number of reviews of this topic recently, particularly on breeding for drought resistance (Blum 1985, IRRI 1982, Christiansen and Lewis 1982), the literature does not provide a consensus on either methodology or probability of success. Many reviews, in fact are little more than a discussion of possibilities. These are specified (Table 1) following Khalfaoui (1985). The steps themselves involve first understanding exactly what the problem is (I and II), establishing the basic requirements to employ plant breeding as a solution (III and IV), and finally, deciding whether breeding for improvement is a realistic solution (V and VI). The remainder of this paper covers each of these in turn, using two particular problem areas for pearl millet as examples: poor crop establishment and drought stress during grain filling. In most cases, illustrations presented are from work by the authors.

Table 1. A logical framework to consider breeding for adaptation to environmental stress.

| | |
|---|---|
| I. | What is the specific stress for which improved adaptation is needed? |
| II. | What factors are responsible for observed differences among cultivars under this stress? |
| III. | How can systematic screening for genetic differences in adaptation be done? |
| IV. | Is there useful genetic variation for adaptation in breeding materials? |
| V. | How can the breeder best select for improved adaptation? |
| VI. | Is breeding for adaptation justified? |

## Concrete Definition of the Problem

### Failure of Crop Establishment

Pearl millet is particularly subject to poor stand establishment. The seed has limited reserves for early growth, and is generally grown in harsh climates by farmers who have limited land preparation and sowing methods. Failure of stand establishment, however, can occur for a wide variety of reasons: seed quality, sowing methods, seedbed environment, and the subsequent seedling environment.

Comparative studies of reasons for stand failure in India and Niger (Soman et al. 1984b; P. Soman and L.K. Fussell, ICRISAT, personal communication), illustrate differences between areas. In both countries the emergence of seedlings as a percentage of seeds sown was low (<25%) (Fig. 1). In Niamey Department, Niger, where sowing is done in hills, initial stands on a hill basis (at least one emerged plant per hill), averaged 80% of those hills sown. By 12 d after emergence however, hill populations were reduced by >50% and hill stands were poor; due to very high soil surface temperatures (>50°C at midday) which occurred in the absence of rain following emergence. In contrast, in Sikar district, India, where sowing is done in rows and desired plant population are higher, initial plant populations were very poor (<10% of seed sown in most fields), because low seedbed moisture and high seedbed temperature killed most seedlings before they emerged. Breeding to improve the stand establishment capability in these two situations would therefore involve breeding for tolerance to different conditions.

## Drought Stress

Drought stress is notorious for the near-infinite number of combinations of timing, duration, and intensity in which it can occur. Adaptation to drought stress (as measured by grain yield), depends on different traits, responses, etc., for the different times and intensities of its occurrence. An attempt to breed for improved adaptation to stress makes *sense* only if the stress is reasonably well defined.

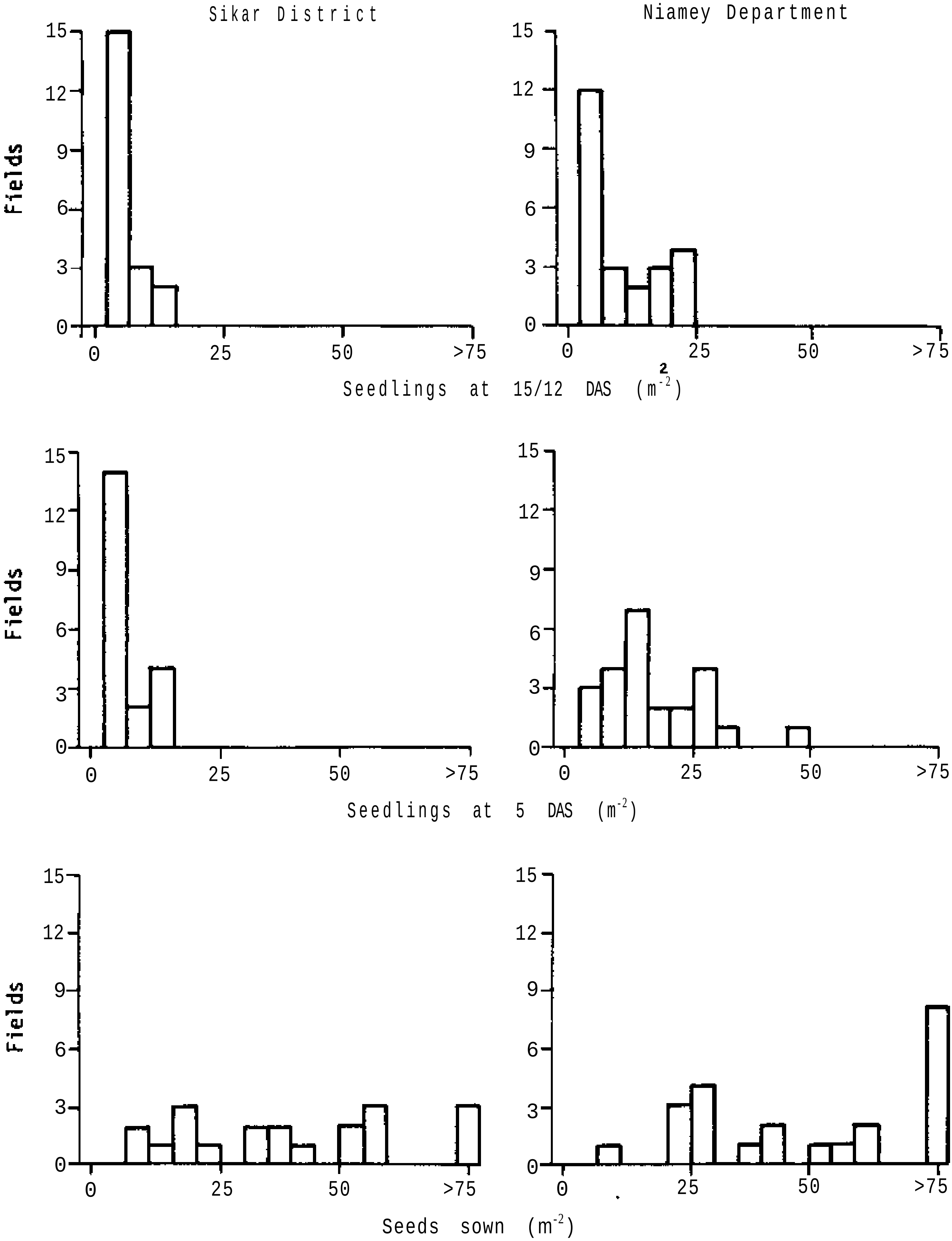


**Figure 1. Distribution of seeds sown (bottom), emerged seedlings (center), and surviving seedling (top) in farmers' fields in Dhandhan village, Siher District, Rajasthan, India in 1983, and in Niamey Department, Niger in 1985. (Source: Soman et al. 1984 and Soman and Fussell, ICR1SAT, Personal Communication).**

Analysis of climatic data for occurrence of drought periods can be complex when done at the soil water balance level, but useful information is available from long-term rainfall probability analyses. Across an east-west (Alwar- Bikaner) transect in the state of Rajasthan, India, based on long-term rainfall records, total rainfall not only decreases markedly, but the probability of adequate rainfall from flowering onwards falls precipitously (from 117, to 55, to 19 mm at a 50% level of probability) (Fig. 2). Whereas some adjustment for the generally lower rainfall level in the west is possible through crop management, little can be done to compensate for lack of rainfall during grain filling. Given that stress at this time is the most damaging to yield (Mahalakshmi et al. 1987), drought tolerance during grain filling is clearly the main objective for a breeder working in western Rajasthan.

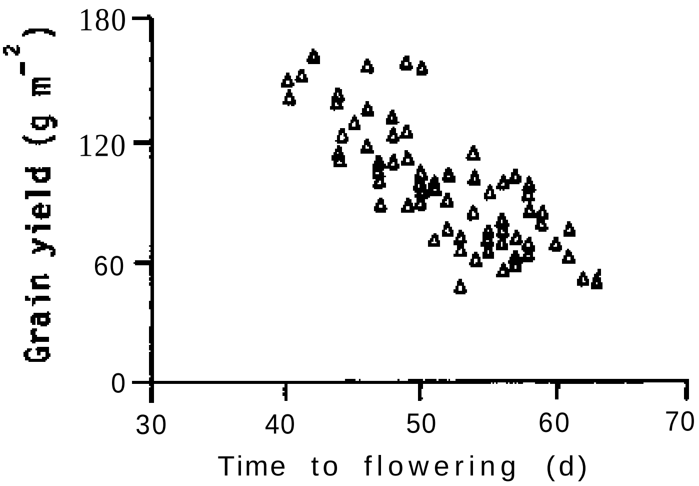


**Figure 3. Cultivar grain yield under conditions of terminal drought stress in relation to time of flowering (Source: Bidinger, Mahalakshmi, and Rao 1987a).**

## Analysis of Factors Affecting Genotype Performance During Stress

### Drought Stress During Grain Filling

A 'successful' genotype in case of drought stress during grain filling is one which produces an acceptable level of grain yield. While it is possible to select for grain yield under conditions of terminal stress, it may be much more useful for the plant breeder to know more about why a successful genotype is successful. There are complex hypotheses (e.g., Paleg and Aspinall 1981), but again, a simple framework of analysis is useful. Repeated, large-scale comparisons of cultivars under terminal drought conditions (Bidinger et al. 1987a) have indicated that the largest factor in yield differences among cultivars is drought escape, due to time to flowering differences relative to the beginning of the stress (Fig. 3). In comparisons over a number of years, drought escape has accounted for nearly 50% of the total variation in grain yields in severe terminal stress, a much greater proportion than either differences in yield potential or drought resistances among cultivars (Table 2).

Any attempts to improve cultivar adaptation to terminal drought must obviously consider drought escape, either by capitalizing on it to breed shorter-duration cultivars, or by excluding it, if drought resistance or tolerance is the objective of selection. These alternatives will be discussed in more detail.

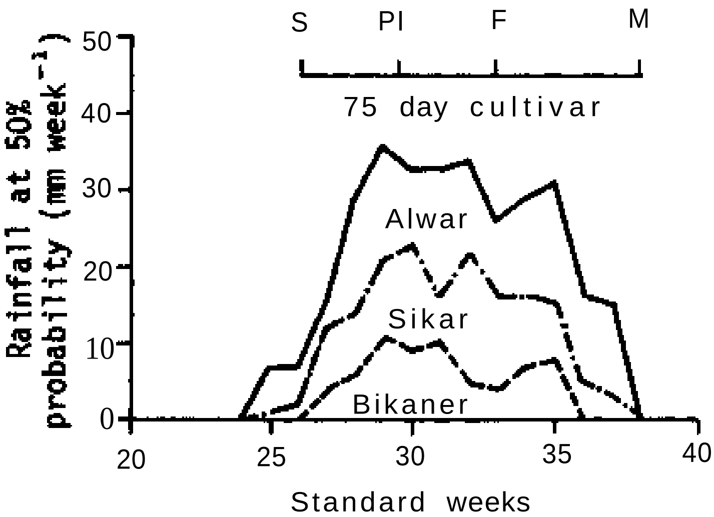


**Figure 2. Experimental weekly rainfall during the growing season, at a 50% level of probability for Alwar, Sikar, and Bikaner, Rajasthan, India. The duration of a typical 75 day variety is indicated in the figure, where S = sowing, PI = panicle initiation, F = flowering, and M = maturity. The sowing week (week 26) is June 25 to July 1. (Source: Biswas et al. 1982).**

### Failure of Crop Establishment

A 'successful' genotype in this case is simply one that establishes well under a variety of conditions. A knowledge of why genotypes differ in their capacity to establish would obviously help when selecting for improved establishment. Although differences for such factors as high temperature tolerance during germination are undoubtedly at the metabolic level, understanding these may or may not simplify the

Table 2. Percentage of variation in cultivar grain yield under terminal stress due to variation in yield potential, time to flowering (drought escape), and drought response index (drought adaptation). (Data from Bidinger, Mahalakshmi, and Prasada Rao 1986b; and Mahalakshmi and Bidinger, personal communication).

| | | Percentage variation in yield[1] due to: | | |
|---|---|---|---|---|
| Year | No. of cultivars | Yield potential | Time to flowering | Drought response index |
| 1981 | 72 | 1 | 64 | 30 |
| 1982 | 72 | 4 | 40 | 50 |
| 1983 | 72 | 1 | 65 | 29 |
| 1984 | 54 | 0 | 56 | 40 |
| 1985 | 90 | 14 | 25 | 54 |
| Mean | 72 | 4 | 50 | 41 |

1. From the following regression model:

$$Ys = a + bYp + CTF + DRI$$

Where: Ys = yield in the stress; TF = time to flowering; Yp = yield potential; DRI = drought response index

breeding process. Very little research has been done on the reasons for differences in crop establishment capability in millet, partly because direct screening for differences usually appears to be relatively simple and economical.

## Screening Techniques for Evaluating Genotype Differences in Adaptation

Screening techniques for adaptation to stress are similar to those for resistance to biotic stresses: they must be capable of applying uniform and repeatable selection pressure, and able to economically screen relatively large numbers of breeding lines. This obviously implies an ability to exercise some control over temperature and water, either by the selection of seasons and locations where these factors are at the desired level (or absent in the case of rainfall, allowing control of water availability by irrigation), or else through the use of controlled environment facilities. The particular response or parameter measured in such screening must also be directly related to field performance (often yield differences under stress conditions), and be as free from the influences of confounding factors as possible.

## Crop Establishment Ability

Screening for crop establishment ability is not too difficult. Success or failure is obvious, and the screening procedures require relatively little land and time. Techniques are available to screen for ability of pearl millet to emerge through a crusted soil surface (Fig. 4, and Soman et al. 1984a), and to germinate and emerge in high temperature conditions (Soman and Peacock 1985). Techniques to screen for the ability to emerge under conditions of low seedbed moisture (P. Soman, ICRISAT, personal communication), and for seedling survival under low moisture and high temperature (L.K. Fussell, ICRISAT Sahelian Center, personal communication) have progressed to the point where they are being used to evaluate genetic materials. Not all of these techniques are adaptable to screening as large a number of lines as desired, but all produce repeatable evaluations of genetic differences.

### Adaptation to Drought Stress During Grain Filling

Screening for adaptation to stress during grain filling is a much more complex problem than screening for seedling establishment. Neither the choice of a criterion for relative success or failure, or its measurement are as simple. The use of grain yield as a criterion is not adequate because it depends on factors other than adaptation to drought, assuming that adaptation rather than escape is the objective of the breeding program (Table 2).

It is possible to derive an estimate of genotypic drought response (adaptation) based on the unex-

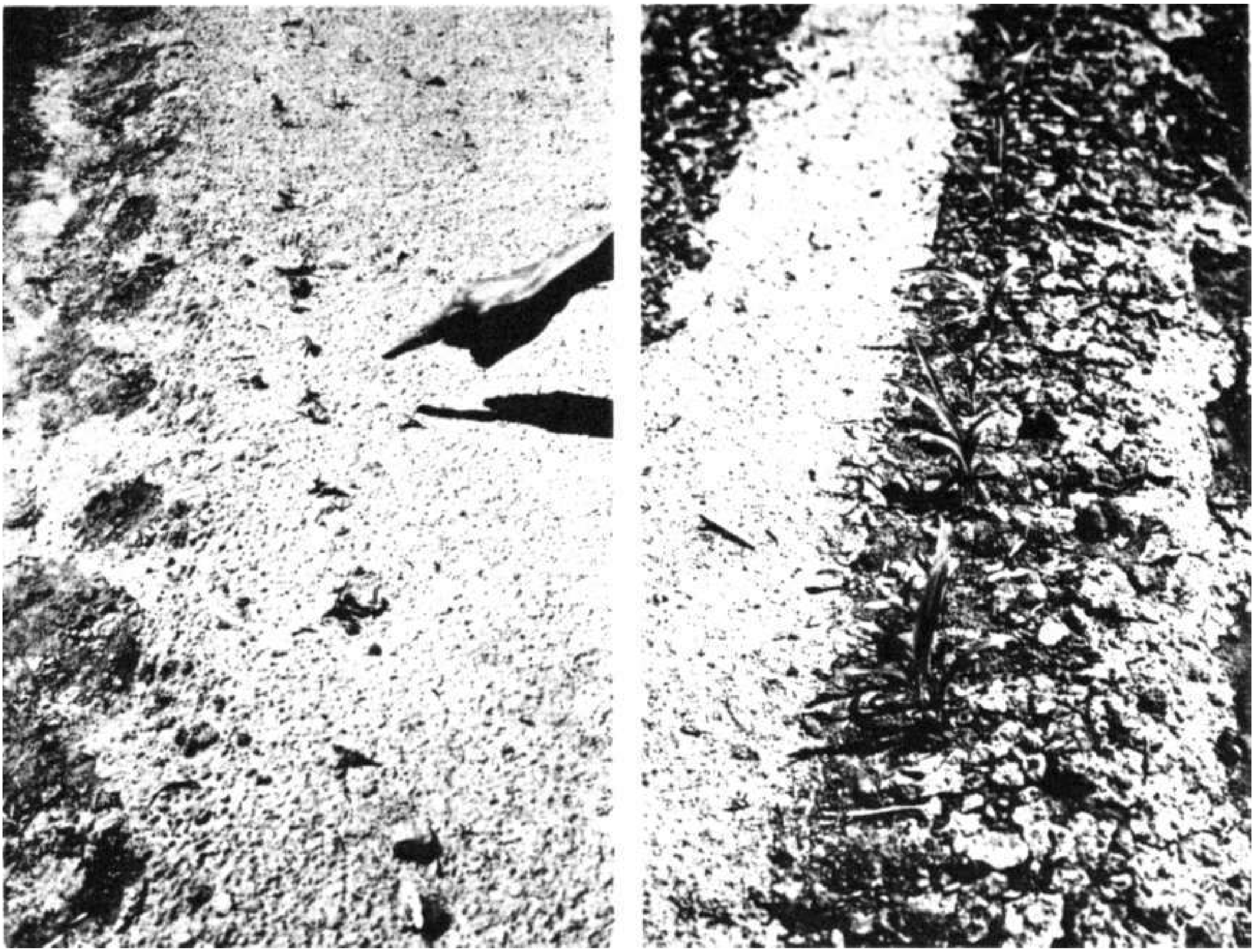

**Figure 4. Screening for ability to emerge under crusted soil surface conditions (a) in which the crust was broken before emergence and (b) in which the crust remains intact.**

plained variability in grain yield once the effects of drought escape and yield potential differences are removed (Bidinger et al. 1987b). This procedure involves three steps, using data from paired irrigated and drought-stressed plantings during the dry season:

1. Establishing the relationship of yield in the stress to time to flowering (drought escape) and yield potential (yield in the same test environment but in the absence of stress). These two factors generally account for 50-60% of the grain yield variation in the stressed planting (Table 2).
2. Using this relationship to establish an expected grain yield based on the above two factors for each genotype.
3. Comparing the differences between the expected yield in the stressed planting for each genotype, and the actual measured yield. If this difference is less than the experimental error, the genotype is considered to have no specific response to stress. If this difference is greater than the experimental error, the entry has a stress response (drought response index) that is either positive (measured yield > predicted yield) or negative (measured yield < predicted yield).

This index of drought response is significantly, positively correlated to grain yield in the stressed planting, but is independent of the effects of both drought escape and irrigated yield potential (Table 3). It thus provides an indication of drought adaptation, although adaptation is only one contributing factor to actual yield. However, the other two factors, yield potential and drought escape, are characteristics which can be assessed without using a specific drought screening methodology.

Table 3. Correlation of the drought response index (DRI) with yield potential, time to flowering (drought escape), and grain yield in the terminal stress. (Data from Bidinger, Mahalakshmi and Prasada Rao, 1986b; and Mahalakshmi and Bidinger, personal communication).

| | Correlation of DRI with: | | |
|---|---|---|---|
| Year | Yield potential | Drought escape | Yield in stress |
| 1981 | 0.05 | 0.00 | 0.55*** |
| 1982 | 0.05 | -0.05 | 0.72*** |
| 1983 | 0.06 | -0.01 | 0.54*** |
| 1984 | -0.07 | 0.06 | 0.65*** |
| 1985 | 0.00 | -0.10 | 0.74*** |

*** $P < 0.001$

## Evidence for the Existence of Genetic Variability for Adaptation to Stress

The existence of genetic variability for adaptation to stress—statistical, repeatable differences among genotypes—is obviously essential to the possibility of breeding for adaptation to stress. Unfortunately, there has not been sufficient research done on pearl millet to assess whether sufficient variability exists in this species. This is therefore the key question to be answered in deciding on the feasibility of breeding for adaptation.

### Adaptation to Drought Stress During Grain Filling

Several control cultivars used in dry season drought nurseries habitually rank among the best entries in the trial, but the reason is inevitably their earlier maturity, i.e., escape from drought rather than drought tolerance.

There has been interest, recently, in the possible drought tolerance in the Iniadi germplasm from northern areas of Togo and Ghana. Representatives of this landrace that have been tested frequently yield well in severe terminal stress situations (Mahalakshmi and Bidinger, ICRISAT, personal communication), but it has not been clear if this advantage is simply a function of their earliness or if they do in fact possess some adaptation to stress. Experiments in which the drought escape factor was removed by comparing only materials of similar early maturity have indicated a possible additional advantage to the Iniadi types. The five Iniadi entries improved their basic yield advantage by 4% of the trial mean (from 108% to 112%), in two trials conducted under terminal stress, due to a combination of their ability to maintain their considerably larger grain mass (125% of the trial mean) while actually filling relatively more grains per panicle than in the nonstressed control (Table 4). While the advantages indicated are not large, there is the possibility that specific selection within Iniadi types might further reinforce these differences. These data also clearly show how a useful yield difference under stress (12%) is possible from a combination of an initial yield advantage (8%), plus some degree of adaptation to the stress condition.

### Crop Establishment Ability

There is better evidence for genetic differences in adaptation to stress during emergence and establishment than for adaptation to drought stress during grain filling. This evidence is primarily repeatable differences among control cultivars employed in the development and subsequent use of various screening techniques. An illustration is the different emergence percentage between two commercial Indian hybrids when evaluated across a range of low-moisture, high-temperature seedbeds (Fig. 5). Emergence of these two hybrids differed little under favorable seedbed conditions but MBH 110 was considerably more tolerant to stress conditions than BJ 104. If differences of this magnitude exist in breeding materials, the scope for improvement of emergence ability should be large.

Table 4. Mean of five Togo varieties as a percentage of 25 entry trial mean under nonstressed (ICRISAT, dry season 1985) and stressed conditions (ICRISAT, dry season 1985, and Anantapur, rainy season 1985) (Data from Bidinger and Mahalakshmi, personal communication).

| | Non-stressed | Terminal stress | |
|---|---|---|---|
| Variables | ICRISAT | ICRISAT | Anantapur |
| Grain yield | 1.08 | 1.11 | 1.13 |
| Panicle $nr^2$ | 0.87 | 0.86 | 0.84 |
| Grain mass panicle $^{-1}$ | 1.23 | 1.25 | 1.28 |
| Grains panicle$^{-1}$ | 0.97 | 1.03 | 1.05 |
| Grain mass | 1.25 | 1.23 | 1.21 |

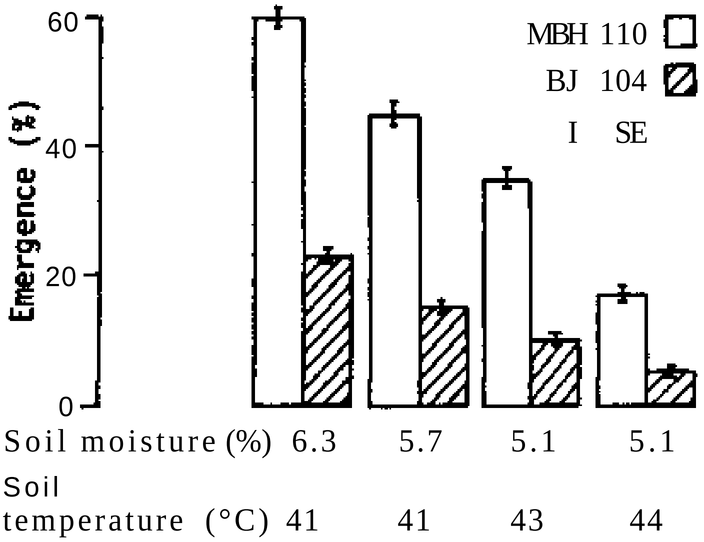


**Figure 5. Emergence of control cultivars MBH 110 and BJ 104 from seedbeds with below-optimum seedbed and temperature conditions, measured at midday on the day following sowing. (Source: Soman, ICRISAT personal communication).**

## Selection Methodology to Breed for Adaptation to Stress

### Crop Establishment Ability

Direct selection for emergence and survival using the screening methods described above should be adequate to breed for crop establishment ability. These techniques fulfill the requirements outlined in the section on screening methodology and, as they are generally conducted during the dry season (when temperatures are high and rainfall absent), they can be readily integrated into a breeding program. In fact, such methods can be useful as initial selection criteria to reduce large numbers of progenies to more manageable numbers. The selected progenies can then be evaluated for characters such as yield and disease resistance, which are more expensive to screen for than seedling emergence. The large numbers of seed produced by individual millet plants allow replicated selection for crop establishment ability without depleting seed quantities needed for subsequent evaluations.

### Adaptation to Drought Stress During Grain Filling

The use of the procedure described above to estimate genotype drought response is not practical as a selection procedure because it requires replicated yield trials in both stressed and nonstressed environments. Two alternatives are possible: direct selection for performance under terminal drought conditions (in a managed drought nursery) with control of drought escape, and selection for a positive drought index by selection for a response or trait correlated to the index.

**Selection for yield with control of escape.** Selection for grain yield under terminal stress, with elimination of drought escape (by either rigorous blocking of materials by time to flowering in the field, or statistical adjustment for the effects of time to flowering), is effectively selection for a combination of higher yield potential and adaptation to terminal drought. These are both desirable characteristics. Such a procedure has been used experimentally to select among inbred lines derived by selfing good but variable pollinators (B.S. Talukdar, ICRISAT, personal communication). One hybrid made using a pollinator selected in such a procedure performed well in a number of trials conducted under terminal drought conditions (Fig. 6). This procedure is being tested to reselect several high-yielding, open-pollinated varieties for better adaptation to terminal stress.

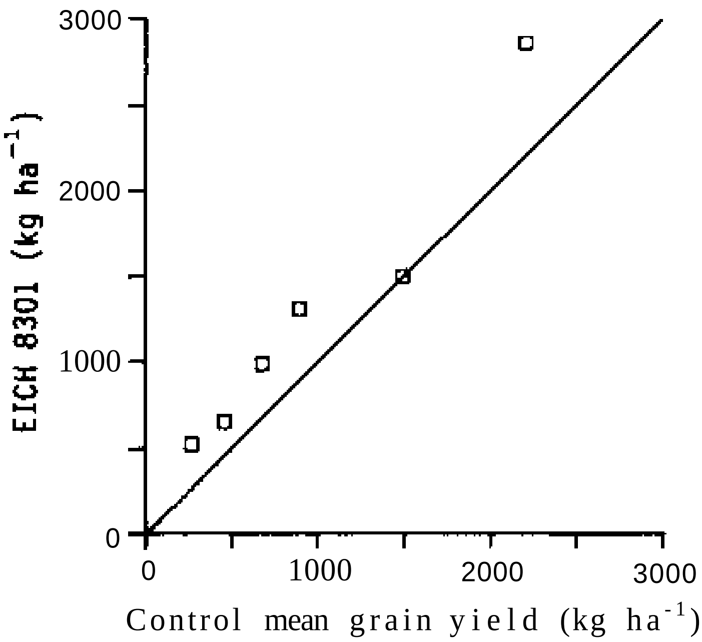


**Figure 6. Grain yield EICH 8301 in relation to the yield of two standard control varieties (WC-C75 and ICMS 7703) in five trials conducted under varying levels of drought stress during grain filling. (Source: Talukdar and Mahalakshmi, ICRISAT, personal communication).**

**Selection for Traits Correlated to Drought Adaptation.** Correlation studies with the drought response index described above indicate that grain yield per panicle in terminal stress could potentially serve as a selection criterion for adaptation to terminal drought (Bidinger et al. 1987b). The relationship of these two parameters is not exceptionally strong, from r = 0.28 (P<0.05) to r = 0.72 (P<0.001), over 5 years. However, selecting entries with grain mass per panicle greater than the population mean is generally effective to identify entries with a positive drought response index (Fig. 7). Where selection intensity for adaptation to drought is to be applied regularly, for example, in a population breeding program, selection of the best 50% of the entries based on grain yield per panicle in the stress should be an effective procedure to gradually improve adaptation to terminal drought.

## Justification to Breed for Adaptation to Environmental Stress

Whether or not the investment of resources to breed for adaptation to environmental stress is justified depends on the answers to questions specific to individual breeding programs. Adding additional selection criteria or breeding objectives to any breeding program will be at the expense of other efforts and therefore must be justified. First, the relative importance of environmental stress problems as factors in low pearl millet production must be established. How do these compare to the problems from diseases or pests, on which the breeder might also concentrate? How do the limitations on production caused by environmental stress compare to those due to poor management, lack of inputs, markets, etc.? The second, and perhaps most pertinent question, is whether or not there are other, simpler solutions to improve production in areas where it is limited by environmental stresses. Could crop establishment be improved by better land preparation or sowing methods? Could production in drought areas be increased by shorter-duration cultivars, or by the use of management techniques which improve rainfall use efficiency? The third and final question is whether or not the breeder can expect sufficient progress in breeding for environmental stress tolerance to justify the resource allocation. Will this produce varieties with higher yields on farmers' fields? Or more critically, will it produce varieties that will survive in national variety testing systems, which frequently emphasize yield potential rather than adaptation to stress environments?

The answers to these questions will ultimately determine whether or not breeding is attempted as a solution to environmental stress problems. The authors believe that not only is there a logical framework, but that there has been considerable success in developing screening and selection methods. There is some evidence of genetic variability in responses to at least some of the environmental stresses facing pearl millet. Not enough work has been done however, to estimate the progress that might be made. As indicated in the introduction, immunity to environmental stress does not exist, only relative degrees of adaptation. Evidence from screening genetic resources accessions and breeding lines for adaptation to these stresses suggests that differences are large enough to be of real value, if they can be incorporated with otherwise elite materials.

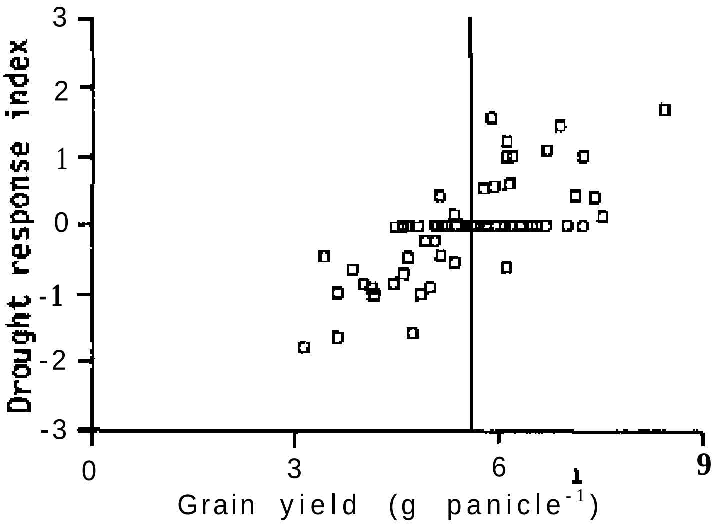


**Figure 7. Relationship of drought response index (drought adaptation) and grain mass per individual panicle (r = 0.58, P < 0.001), based on a replicated evaluation of 72 genotypes under terminal stress in 1982. The vertical line represents the mean grain mass per panicle (Source: Bidinger, Mahalakshmi, and Rao, 1987b).**

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# Discussion

Squire's paper drew on data from India, West Africa, and controlled environment conditions in the UK, and provided a review of the relationships between many of the important environmental variables, and pearl millet growth.

The discussion centered around the usefulness and application of these data, on the simple model presented, and the general acceptance of the root growth data and its measurement. The overall opinion was that the model was flexible, but the speaker admitted that more good data were required, particularly in relation to roots. The importance of saturation deficit was not challenged, and the speaker agreed that traditional methods for the measurements of roots and soil-water such as potentiometers and the neutron probe were probably better than sophisticated tracer methods.

Matlon's paper clearly showed that interpretation of experiment station data, generated utilizing many inputs not available to West African farmers, should be done cautiously. Similar caution should be observed when comparing data from the three climatic zones, the Sahel, the Sudanian, and the Northern Guinean Zones. The discussion centered around these two issues.

The poor response of new cultivars compared to locals under both low- and higher-input conditions on farmers' fields was clearly disturbing to the audience, but the consensus, substantiated by the data presented, was that this is a problem, and ICRISAT should concentrate on solving it. There was some disagreement about the statement that very early-maturing cultivars will have no impact unless management practices change.

There was general acceptance that the primary goal in the Sahel is to increase the responsiveness of new cultivars to improved management, but that in the other two zones, the goal is to improve yield stability. The group endorsed a comment that more emphasis should be put on soil and water management in West Africa.

Fussell's paper provided potential solutions to the problems outlined in Matlon's paper. Little progress would be made in increasing grain yield unless fertilizer is used, particularly phosphate. This was accepted with the proviso that the importance of water and soil management should not be completely dismissed.

Gautam's paper described the management practices to increase and stablize production in India. The discussion centered on matching plant populations to different environments, and the placement and timing of fertilizer applications.

Bidinger's paper, which acknowledged that plants have no immunity to environmental stresses, presented a physiological approach to breeding for 'resistance' to such stresses. A stepwise approach, using data from Niger and India, was used to illustrate the approach. Poor crop establishment and inadequate grain filling were used as examples. The discussion centered on whether the approach was over simplified, and whether there was a danger in examining growth stages or stress periods separately.

Bidinger argued that understanding each stage separately and clearly defining the problems in a particular climatic zone was necessary. It was agreed that stress incurred in the seedling stage, provided the seedling survived, could be advantageous to a plant subjected to stress in the later stages of development.

# Short Communications

# Androgenesis and Enzymatic Diversity in Pearl Millet

## Androgenesis in Pearl Millet
## (Androgenese chez le mil)


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Rice, barley, rye, wheat, maize, potato, and tobacco are often cited as examples in which haploids have not only been produced but are being routinely used in crop improvement programs. However, the production of haploids in semi-arid tropical crops such as pearl millet, sorghum, groundnut, chickpea, and pigeonpea, has had little investigation.

For pearl millet, there are only two reports on the production of haploids (Ha and Pernes 1982, Nitsch et al. 1983). Both produced plantlets from microspores, but there was no indication of efficiency of the breeding method.

Panicles with uninucleate microspores of three pearl millet cultivars were cultured on four different standard basal media: MS, N6, B5, and Nitsch with 3% sucrose, 0.66% agar, and 1 ppm 2,4-D. The responses of the cultivars differed, but WC-C75 was the most responsive.

Of the four different basal media, MS medium was the best for this cultivar. It induced androgenesis in more than 50% of the anthers cultured. After 10 d of culture, divisions in microspores were observed. An average of 36 embryogenic microspores per anther were observed after 16 d of culture. The maximum number of embryoids observed in one anther was 134. Acetocarmine squashes of the embryoids showed that they were haploid with seven chromosomes.

Investigations on the subsequent development of the embryoids are in progress.

## General Survey of Enzymatic Diversity in Pearl Millet
## (Etude generate de la diversite enzymatique chez le mil)


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Exactly 130 accessions of pearl millet from West Africa, East Africa, India, and eight samples of wild millet *(P. violaceum)* from Mali and Niger were analyzed by electrophoresis, for eight enzymes: alcohol dehydrogenase (ADH), catalase (CAT), B-esterase (EST), glutamate oxaloacetate transaminase (GOT), malate dehydrogenase (MDH), phosphogluconate dehydrogenase (PGD), phosphoglucoisomerase (PGI), and phosphoglucomutase (PGM).

These enzymes are coded by 12 genes and 46 alleles. Measurements of genetic diversity, using principal component analysis and discriminant function analysis, have shown that the eight wild accessions form a distinct group. Among the cultivated accessions, four separate groups, presented in order of decreasing genetic diversity have been identified: early millets from western and central Africa (from Senegal to Sudan), late millets from the same area, Indian millets, and southeastern African millets. Within the early group, a west-east cline has been observed for the allozymes PGM A1, PGI A3, ADH A4, and EST A4. A second set of allozymes separates the early and late groups: CAT A1, ADH A7, EST A3, EST A6, and EST A7. Millets from central Africa (Sudan and Chad) form a bridge between Indian and southeastern African groups. From these data, it can be inferred that early millets were formed by several independent domestications of the wild forms scattered along the southern margins of the Sahara. All the late millets from West Africa probably descend from a common, single, early, founder population. Millets from India and southeastern Africa were derived from central African forms by independent migrational events.

# Possibilities for Pearl Millet Hybrids in Africa

## Brief Overview of Pearl Millet Hybrids in Africa (Examen recapitulatif des hybrides de mil en Afrique)

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The discovery of cytoplasmic male-sterility in pearl millet and the breeding and release of Tift 23 A made the production of hybrids possible in India, and lead to spectacular yield increases. Although Tift 23A was made available to breeding programs in West Africa in the early 1960s, pearl millet hybrids were not tested extensively. Tift 23A was not adapted to the environments in West Africa: it was too early, downy-mildew susceptible, and shed pollen. Therefore, research was directed towards intervarietal or topcross hybrids, and yield advantages over the local controls were from 12-90%. In eastern Africa, efforts were made to convert locally-adapted material into male-sterile lines using the cytoplasm of Tift 23A, but further hybrid breeding was discontinued.

Recent research in Senegal and Niger shows that hybrids using male-sterile lines have shown yield advantages over the improved control of up to 60%. Work is in progress to breed male-sterile lines adapted to West Africa. Hybrids will find a place in southern and eastern Africa, and in areas with dependable rainfall in West Africa, but their introduction needs to be coupled with the adoption of improved management practices.

It is hoped that current research will lead to hybrids with substantially increased yield potential that will be cultivated by African farmers by 1995.

## Pearl Millet Male-Steriles and Hybrids in Nigeria (Lignees males steriles et hybrides de mil au Nigeria)

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Even though millet is grown on about 5 million ha and the annual production is approximately 3 million t, the average farmer's yield is about 0.641 $ha^{-1}$. Open-pollinated varieties—both local unimproved and improved—predominate. Research indicates that the available male-sterile lines from India and the USA used in hybrid millet combinations are highly susceptible to downy mildew, ergot, and smut. Disease incidence on the hybrids exceeded 30%.

The mean yield of hybrids in Kano was 0.73-1.75 t $ha^{-1}$, while at Samaru it was 0.18-1.08 t $ha^{-1}$. The best hybrid, with 5141A as the seed parent, yielded 1.32 t $ha^{-1}$ in Kano and 0.73 t $ha^{-1}$ in Samaru.

# Research on Pearl Millet Hybrids in Senegal
# (Recherches sur les hybrides de mil au Senegal)


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**and**

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Among the cereals, pearl millet predominates in the north and central regions of Senegal where rainfall is low and erratic. At present, open-pollinated varieties which mature in 70-100 d are grown in these regions. It is possible to grow hybrids in irrigated areas of the northern region, and in the south-central region where rainfall is both adequate and assured, and where farmers are able to use high levels of inputs.

During the early 1960s, hybrids were produced by crossing a population and an inbred line. The best hybrid yielded up to 147% of the local population. Male-sterile line Tift 23A was introduced in the late 1960s but it was highly susceptible to downy mildew. Systematic hybrid breeding efforts recently began with the availability of new male-sterile lines such as 81A and 111A. The pollinators were selected inbreds from crosses between Senegalese genotypes and introductions. In over 250 initial testcrosses evaluated, 23 hybrids were retested last year at two locations. The highest yielding hybrid, ICMH 8512 SN (2700 kg $ha^{-1}$), yielded 30% more grain than the best control in the trial, IBV 8001, followed by ICMH 8418 SN, ICMH 8510 SN, and ICMH 8413 SN. During the last 3 years, the best hybrid was ICMH 8413 SN, which produced 31-52% more grain than Souna III, a common control in the different years. All these hybrids produced shorter plants and heads, but produced more heads per unit area than Souna III. These hybrids were highly resistant to downy mildew and moderately resistant to smut.

These preliminary results are encouraging, and therefore efforts will now be made to breed hybrids using new inbreds on 81A, 111A, and other male-sterile lines.

# Potential for Pearl Millet Hybrids in Southern Africa
# (Potentiel des hybrides de mil en Afrique australe)


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**and**

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The cultivation of maize, the most important cereal crop in southern Africa, has extended beyond its zone of adaptation. In the last few years, it has failed completely in certain areas due to low rainfall and dry weather. Governments and farmers are now looking for alternative crops. Pearl millet is a traditional crop of southern

Africa, where the largest area is grown in Zimbabwe, followed by Tanzania, Angola, Zambia, Malawi, Mozambique, and Botswana. In these countries, pearl millet and finger millet are grown on over 800 000 ha, and annual grain production is about 500 000 t. The average yield of pearl millet per unit area is low because the crop is grown largely by poor farmers in communal areas using unimproved seeds and low inputs. Recently efforts have been made to increase pearl millet production by initiating research on a regional basis.

Currently available hybrids produce 10-20% more grain than the best varieties available in the region. The hybrids can be grown in all millet-growing regions of the seven countries, except in Botswana and the southern part of Zimbabwe where the annual rainfall is very low (<400 mm). In the near future, hybrids are likely to be more successful in Zimbabwe and Malawi where both the seed industry and extension system are efficient. In Zambia, there is a good seed industry but seed distribution in remote areas seems poor. In Tanzania, farmers mostly grow photoperiod-sensitive cultivars, so more testing is required to compare the adaptation of medium-maturing hybrids with varieties.

Hybrids seem to have good potential in several regions of southern Africa, so 30% of our efforts will be to breed good pollinators and male-sterile lines for the production of high-yielding and disease-resistant hybrids.

## Discussion

Three major points emerged during the discussion following presentation of these papers.

- There is a need for more comparative studies on the relative disease reactions of hybrids and varieties to understand the differences.
- A warning against the assumption that hybrids would grow well only under high rainfall conditions and good management—there are examples of sorghum hybrids outyielding varieties even under poor conditions.
- Doubts were raised by some participants as to the likelihood of the required inputs for hybrids being used by very poor SAT farmers.

# Food Quality, Consumer Acceptance, and Storage Stability of Pearl Millet Grain

## Recherches sur les qualites organoleptiques au Niger (Grain Quality Research in Niger)

**Moussa Oumarou**

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Au Niger, le mil est de loin la principale culture vivriere. Produit largement, consomme aussi bien en zone rurale qu'en zone urbaine, il constitue en fait l'aliment de base du Nigerien.

Les varietes les plus couramment utilisees pour la confection du plat traditionnel sont les cultivars locaux epures ou ameliores : il s'agit du Haini Kirei (HK) et sa version precoce (HKP), du Guera Guera, du Zar farawa, de l'Ankoutess et du Composite Intervarietal de Tarna (CIVT).

La couleur des grains est variable. Elle va du jaune-or (HKP) au jaune (Guera-Guera). Signalons que pour la confection de certains plats, le paysan utilise selectivement certaines varietes plutdt que d'autres. Les techniques de transformation utilisees pour le decorticage et la production de farine sont basees sur la methode traditionnelle du mortier et du pilon. Cependant en zone urbaine, on utilise de plus en plus, les decortiqueuses et les moulins a grains au lieu de la methode traditionnelle.

Le Nigerien a developpe une gamme de produits varies a base de mil. Un de ces produits le plus couramment consomme au Niger est le foura (en Haoussa) ou Donou (en Djerma-Sorrai). Puis viennent par ordre d'importance le turvo, le couscous, les galettes (massa), la bouillie, etc.).

Pour la confection de ces produits, on utilise de la farine fraiche, (fourra, Tuwo), de la farine seche (Tuwo) ou de la farine legerement fermentee dans le cas de la preparation des galettes.

Vu le role que joue le mil dans l'alimentation du Nigerien et les efforts entrepris en matiere d'amelioration de cette plante, l'INRAN est en train de mettre en place un programme "Qualite cerealiere du mil" dont les objectifs principaux sont:

- Evaluation des caracteristiques morphologiques et physico-chimiques du grain de chaque variete.
- Evaluation de son aptitude a l'usinage.
- Evaluation de la qualite nutritive et nutritionnelle.
- Evaluation des qualites organoleptiques des produits finis.

Ce programme se propose egalement d'identifier parmi ces varietes celles dont les grains ont une aptitude generate ou specifique.

## Grain Quality Research in Niger
## (Recherches sur les qualites organoleptiques au Niger

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In Niger, pearl millet is the most important food crop and a staple food for people in both urban and rural areas.

The varieties commonly used for traditional preparations are improved local cultivars such as Haini Kirei (HK) and its early form (HKP), Guera Guera, Zar farawa, Ankoutess, and Composite Intervarietal de Tarna (CIVT).

Grain color varies from golden yellow (HKP) to yellow (Guera Guera). The varieties are chosen according to the type of preparation. The traditional mortar and pestle are used for hulling and making flour. In urban areas, however, hulling machines and flour mills are becoming popular.

A large variety of food is made from pearl millet in Niger, the most common being foura (in Hausa) or donou (in Djerma-Sonrai). Other important foods are tuwo, couscous, massa (pancakes), porridge, brabuska, and labdourou.

Freshly ground flour (fourra, tuwo) or dried flour (tuwo) is used for preparing these foods. Pancakes are made from slightly fermented flour.

Considering the importance of pearl millet in the local diet, the Institut National de Recherches Agronomiques du Niger (INRAN) is developing a food quality program as part of the large crop-improvement effort. Its main objectives are to evaluate:

- the morphological and physicochemical characteristics of the grain of different varieties;
- the dehulling quality;
- the nutritive value; and

• organoleptic evaluation of the finished products from the breeding program; the program also proposes to identify among those varieties with a general or specific ability to give food quality fourra, tuwo, etc.

Two traditional methods for preparing fourra and tuwo in certain parts of the Niamey district are described.

## Grain Quality Research in Mali
## (Recherches sur les qualites organoleptiques au Mali)


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**and**

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Price differences of pearl millet in urban markets reflecting consumer demand for quality characteristics were studied. Consumer preference tests were conducted in villages with ethnically different people to determine quality traits appreciated by rural consumers. Rural and urban consumers generally agree about millet quality. Ease of grain decortication was the single most important quality criterion for consumers. Large round grains were generally preferred to small elongated grains because decortication is easier.

Additional market price surveys revealed a consumer preference for pearl millet over sorghum and maize. Consumers especially complained about the difficulty of processing maize grain, and remarked on the relative ease with which pearl millet can be decorticated.

In a progressive decortication study consumers could differentiate food products *(td)* prepared from grain decorticated with less than 30% bran removal, compared to more completely decorticated grain. A comparative study of large versus small grains confirmed the importance of grain size and roundness for ease of decortication.

In studies with blends of millet and cowpea flour, consumers accepted blends containing up to 15% cowpea in gruels offered to infants. Flour from decorticated millet grain can be stored up to 15 d. Flour kept longer than this is unacceptable because of poor food keeping quality and flour beetle infestation.

## Food Quality and Consumer Acceptance of Pearl Millet in India
## (Qualites alimentaires et gouts des consommateurs en Inde)


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Rural people are the major consumers of pearl millet in India. The grain types, processing methods, and food habits vary considerably in different parts of India. Surveys on the traditional food preparation methods using pearl millet were carried out in 171 villages of 7 Indian states. Despite low yields, local cultivars are generally preferred by consumers due to their characteristic, unidentified, food quality attributes. The grain is initially processed in different ways depending on the need. Grains are commonly dry milled to produce flour or grits in several villages. In some cases, dehulling of grains is done using wooden or stone mortars with a wooden pestle, particularly for preparing dehulled grain or grits to be cooked in the same manner as rice. Other processing methods include wet milling, fermentation, roasting, and popping.

The most common products made from millet are roti or chapati, unleavened flat breads prepared from whole grain flour. Porridges, cooked grains, and other preparations are also common. In the Indian states of Rajasthan and Gujarat, millet is preferred during the winter, while wheat is used in the summer. Because food habits vary regionally, there are many different recipes that include pearl millet. Based on survey data, pearl millet food products were grouped into seven broad categories: bread, porridge, and gruel; boiled, steamed, and fried preparations; and other foods (snacks).

ICRISAT researchers have studied the role of certain physiochemical properties in the quality of roti, porridges, boiled products, and the grain factors that influence pearl millet dehulling quality.

## Traditional Food Preparations of Pearl Millet in Asia and Africa (Preparations traditionnelles du mil en Asie et en Afrique)


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Pearl millet is a traditional staple food of semi-arid tropical farmers in Asia and Africa. The spikes are threshed by pounding in a wooden mortar, beating with sticks, trampling by animals, or by mechanical threshers. The moistened grain is again pounded to remove the pericarp or husk. The pearled grain is further pounded to make flour using rectangular or circular granite stone grinders. The most common traditional preparation in much of Africa is a thick porridge made with millet flour called by different names in different countries such as mosokwane (Botswana), nsima (Malawi, Zambia), ugai (Tanzania, Kenya, Uganda), sadza or sitshwala (Zimbabwe), aceda (Sudan), *to* (West Africa), and mudde, sankati, or kuzh (India).

A thin, smooth, creamy, free-flowing porridge is called akamu, eko, ogi, kmu, or koko (Nigeria); uji, ogi, edi, or obushera (Uganda); bota or ilambazi (Zimbabwe); and ambali or kali (India). Unleavened bread made from millet flour and baked on a hot pan is an important millet preparation in much of India and Pakistan. It is called roti (northern India, Pakistan), and rotili (western India). At times, onions and chilies are added to the bread (roti), especially in southern India. The whole grain is cooked like rice in southern India. Almost throughout Africa, pearl millet is used to brew opaque beer, a prestigous beverage. Several snacks are also prepared, such as a ready-to-drink beverage called fura or chere, prepared by mixing steamed millet flour with sour milk, deep-fried pancakes called marsa, and a thick pancake called kamuzu. The pearled whole grain cooked with milk and sugar is called kheer, and when cooked with pulses and other vegetables it is called kichidi (India).

## Storage Quality of Pearl Millet (Capacite de conservation du mil)


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Most farmers grow pearl millet for their consumption and store the grain at home. Surveys conducted in the SAT areas of Andhra Pradesh on the quantity of pearl millet stored and its quality revealed that normally farmers in this region store 500-600 kg of the grain. More than half of these farmers store the grain in gunny bags. About 25% store it either in a "gade" (basket of woven bamboo strips), or in clay pots. Sun drying is the only pest control method used prior to storage. Grain stored in gunny bags was 66% insect damaged, while the grain stored in gades was only 47% damaged. Insect infestation levels as well as percentage of weight lost during storage was lower in pearl millet compared to sorghum. The weight loss after 9 months of storage was only 1% compared to over 2% in sorghum. Chemical analysis of nutrients indicated similar or somewhat higher losses of protein in pearl millet after storage (11% in pearl millet, 10.5% in sorghum), thiamine (39.4% in pearl millet, 25.1% in sorghum), and niacin (16.7% in pearl millet and 13% in sorghum). The loss was attributed to the higher concentration of these nutrients in the seed coat of pearl millet grain.

# Quantitative Genetics and Analysis of Multilocational Trials

## Studies on Adaptability and Gene Effects and their Implications in Pearl Millet Breeding

**(Etudes sur l'adaptabilite et les effets geniques—leur importance dans la selection du mil)**

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The analysis of genotype-environment interaction in a number of studies conducted at HAU, carried out using Eberhart and Russell (1966) adaptability parameters, revealed that both the linear regressions and deviations from them played an important role. The major portion of those interactions were accounted for by the linear regressions for most of the characters. However, for such characters as head length for which only the deviations from the regressions were found to be significant, predictions across environments for most of the genotypes could still be made as a large number of them either showed no genotype-environment interaction or had only the linear regression significant.

An inspection of behavior of the stability parameters (b and $s^2d$) of the parents and their arrays in a diallel analysis and the association between those parameters indicated that both the predictable and the unpredictable components of interaction were under the control of distinct genetic systems. There appeared to be no correlation between mean performance $(\bar{X})$ and responsiveness (b), in respect of grain yield and its components, in the parental material; conversely downy mildew showed association.

In one of the studies, nine environments, varying for the extent of artificially created drought stress, were grouped (stratified) into seven sets on the basis of environment or location. A correlation matrix between the performance of genotypes in the sets was determined. The mean performance of the genotypes for grain and dry fodder yield was positively correlated in all cases, but b value was correlated in 62% and $S^2d$ value in 45% of the cases. The proportion of genotypes showing instability was substantially lower when the test environments sampled included only the drought stress conditions as compared to nonstress and a range of stress and nonstress conditions. Thus, the stratification of environments for identification of suitable genotypes is helpful.

The genetics of quantitative characters was studied using diallel and line x tester analyses. Both additive and nonadditive gene effects were found to be important, in the expression of almost all the characters, in almost all environments. Both these components of genetic variation interacted with the environments for almost all the characters except seed size (500 grain mass). Breeding implications have been discussed.

## Genetic Divergence in Landraces of Pearl Millet in Rajasthan
## (Diversite genetique chez les races non ameliorees du mil au Rajasthan)

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About 300 local landraces of pearl millet were collected and evaluated in Rajasthan. The widest range of variation was observed for plant height, grain yield, 1000 grain mass, head length, and grain density. Using a cluster analysis, the landraces were classified into 23 genetically diverse cluster groups. Six of these were clearly in the arid zone, three in the semi-arid zone, five in the adequate moisture zone, and two were common to both semi-arid and adequate-moisture zones. Thus a meaningful distribution pattern of genetic clusters was observed in relation to the pattern of agroclimatic variation. The maximum divergence between clusters was created by time to flowering, plant height, and head length. However, out of the 12 characters studied, only one, number of nodes per plant, was not effective in separating the landraces into groups.

## Genetic Basis of Population Improvement in Pearl Millet
## (Base genetique de l'amelioration des populations de mil)

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Populations have multigenetic polymorphisms which from a plant breeding viewpoint are preferably "balanced". They are maintained in stable equilibria in the population mainly through the selective advantage of complex heterozygotes and they confer population homeostasis.

While composite populations cannot be regenerated, a synthetic can, in principle, be regenerated if its parental lines are inbred and can be maintained without excessive inbreeding depression. It is not essential to maintain the parental components of a composite. A number of alternatives to improve composites are discussed.

One method depends on constructing a base gene pool from which a potential gene pool is derived by a few cycles of large-scale intermating. It is important that low genotypes are not consciously eliminated during the process, since high x low crosses may generate and sustain heterotic effects in successive cycles. Composites can be derived from the potential gene pool by a process of intermating and mild selection in isolation. Since the polymorphic equilibrium associated with composite populations can break down due to forces such as small population size, various degrees of nonrandom mating, and natural selection (including biotic and abiotic stresses), the yields of composites are, at most, only acceptable. Care in seed production is critical to prevent the population from moving to another equilibrium associated with low yield, in which case replacement will be needed. These genetic principles behind breeding populations and maintaining their yield are highlighted with data on pearl millet composite populations.

# Quantitative Genetic Analysis in Pearl Millet
# (Analyse genetique quantitative du mil)

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Quantitative genetic studies in pearl millet are reviewed. The $D^2$ analysis has shown no relationship between geographic diversity, genetic diversity, or the expression of heterosis. The components of genetic variation from diallel, line x tester, and North Carolina designs revealed the predominance of nonadditive variance for a majority of traits. However, the use of selfing series and modified triple test cross revealed the importance of additive variation for many characters. The components of mean revealed the existence of epistatis for the majority of traits. In general, the dominance (h), component was greater than the additive component. Successive weighted analysis of means was done in a limited number of cases. The general and specific combining variance estimates from diallel and line x tester showed predominance of the latter for most of the quantitative traits. Correlation of grain yield with head number is most consistent over different groupings of germplasm. Path coefficient analysis has also highlighted the direct effect of a number of characters on yield which could be utilized in selection.

Stability analyses have revealed both linear and nonlinear genotype x environment interactions for grain yield. Varieties with general and specific adaptation could be be identified.

In general, the studies conducted or the analyses performed suffered from one or the other limitations. There is a need to follow the biometric analyses more appropriately.

# Essais regionaux du mil conduits par le CILSS, 1981-1984
# (Pearl Millet Regional Trials by CILSS, 1981-1984)

**G. Loynet, A. Kere et O. Sidibe**

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Une evaluation des meilleures varietes de mil disponibles dans la region sahelienne aete realisee de 1981 a 1984 dans le cadre du Projet d'amelioration des mils, sorgho, niebe et mais, gere par l'lnstitut du Sahel. Les resultats obtenus au cours de ces quatre annees d'experimentation ont permis d'isoler les varietes les plus performantes dans des contextes climatiques varies s'etendant depuis le Tchad dans Test jusqu'au Senegal, aux zones subdesertiques saheliennes et soudano-saheliennes dans l'ouest. Un groupement geographique des varietes a ete realise en decoupant la region en trois zones homogenes, representatives des conditions agro-ecologiques de la region. Les resultats font apparaitre que les zones a pluviometrie comprise entre 200 et 600 mm demeurent les plus favorables a la culture, celles a pluviometrie superieure presentant d'importants risques de maladies.

# Pearl Millet Regional Trials by CILSS, 1981-1984
# (Essais regionaux du mil conduits par le CILSS 1981-1984)

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Superior pearl millet varieties grown in the Sahelian region were evaluated from 1981 to 1984 as part of the Crop Improvement Project for pearl millet, sorghum, cowpea, and maize, directed by the Institut du Sahel. The best varieties were identified for different climatic situations extending from Chad in the east to Senegal and the subdesert, Sahelian, and Sudano-Sahelian Zones in the west. The varieties were grouped geographically by dividing the region into three agroecologically representative zones. Areas with rainfall between 200 and 600 mm are most suited to growing pearl millet; disease risks increase in high-rainfall regions.

# Analysis of the International Pearl Millet Adaptation Trial (IPMAT)
# (Analyse de l'Essai international du mil—objet adaptation (IPMAT))

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The International Pearl Millet Adaptation Trial (IPMAT), which includes both hybrids and varieties as entries, has been grown multilocationally in India and Pakistan. The grain yield data over 5 years have been analysed in a number of ways.

A regression analysis indicated that the breeder's procedure of selecting from among the highest-yielding entries across environments is satisfactory, as it also selects entries that perform well in poor environments. Selecting entries on predicted performance in the lowest-yielding environment appears to be a less reliable procedure.

The hybrids are generally higher-yielding than the varieties, but are less stable. The most important source of genotype x environment interaction in the regression analysis was due to the deviation from the regressions ($S^2d$ values), rather than variation between the regressions. The varieties were superior to the hybrids in this respect, with lower than average $S^2d$ values.

A mean-standard deviation analysis showed that the highest-yielding genotype would always be preferred by the average, risk-averse farmer.

## Discussion

Because composites may have high levels of variability, the suggestion was made to derive varieties by random mating a few selected progenies from the composite rather than using the composite itself as the finished product. It was pointed out that a few selection cycles in a diverse composite may result in reduced variability, so that the composite can be tested as the finished product.

It was suggested that analysis of variance and t-test may be better methods than regression analysis for stability analyses. Nearest neighbor analysis (NNA) and lattice designs were also suggested. In reply it was pointed out that mean-standard deviation analysis was proposed as a better alternative to conventional regression analysis, and that NNA and lattice designs were impractical for across-location analyses.

The comment was made that stability can be a property of individual genotypes. Varieties appeared to be more stable than hybrids for $s^2d$ values but this could be the result of a statistical artifact of the regression analysis.

## Insect Pests of Pearl Millet in Rajasthan
## (Insectes ravageurs du mil au Rajasthan)

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Pests recorded on pearl millet in Rajasthan, are mostly minor, except white grubs, red hairy caterpillars, leaf weevils, leaf rollers, rutelid beetles and sometimes, earworms.

Among root feeders, *Holotrichia consanguinea* B1. is the most dominant and important white grub. The presence of *H. reynaudi (Bren)* is not confirmed. *Aethus laticollis* Wagner is reportedly becoming a major pest.

*Myllocerus maculosus* Desb. is a regular moderately severe foliar pest throughout Rajasthan. The red hairy caterpillar, *Amsacta moorei* Butler, causes heavy losses in young crops but it has not appeared in large numbers after 1979. *Marasmia trapezalis* Guenn. is usually a moderately severe leaf roller in good rainfall years. Mirid, lygaeid and delphacid bugs are minor pests. Shootfly, *Atherigona approximata* Mall., though reported, is generally absent on pearl millet.

*Autoba silicula* (Swin.) and *Heliothis armigera* (Hb.) feed on ripening grains. *Rhinyptia* spp. beetles are important pests on milky grains of pearl millet. Maggots of *Anacamptoneurum obliquum* Becker breed in and damage grain in pearl millet heads.

*Rhizopertha dominica* Fab. and *Tribolium castaneum* Herbst. are the principal storage pests of pearl millet grain.

*Orius* sp. (Anthocoridae, Hemiptera) are predators of thrips and *Exorista xanthaspis* Wied (Tachinidae:-Diptera) is recorded as a larval parasite of *Amsacta moorei* Butl.

## Insect Pests of Pearl Millet in Peninsular India
## (Insectes ravageurs du mil dans la peninsule indienne)

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Pearl Millet in India is attacked by a few insect pests which are of local or endemic importance. In peninsular India, the shoot fly (*Atherigona approximata* Mall.), stem borer *(Chilo partellus* S.) and white grubs *(Holotrichia* spp.) are the key pests. The research findings on various aspects of the key pests carried out under the All India Coordinated Millets Improvement Project (AICMIP) are summarized.

Seasonal activity of the shoot fly indicated that the fly breeds practically throughout the year and is at its peak during July to September.

In studies of resistance sources to shoot fly and stem borer, 31 and 36 lines respectively were selected as less suceptible, of which populations coded by AICMIP as MP 9, 15, 16, 19, 35, 47, 53, and 63, and WC-C75 and PSB 3 showed resistance to both the pests. Seven accessions from the ICRISAT Genetic Resources Unit and 27 lines had also shown resistance to white grubs and grey weevils, respectively, in similar studies.

Genetics of pest resistance indicated a greater role of dominance for shoot fly resistance. In addition, cultural practices such as early planting to minimize shoot fly incidence, insecticidal controls (soil application of phorate 10 G and foliar sprays of endosulfan, penthoate) for controlling shoot fly have been suggested. Intercropping with pulses can reduce white grub damage in pearl millet.

Insects with a potential for becoming pests in the future have also been identified. Lastly, future lines of research were discussed.

## Pearl Millet Entomology Research in Senegal (Recherches sur l'entomologie du mil au Senegal

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**and**

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Pearl millet is a major food crop in Senegal, and is attacked by about 100 insect pests. The damage severity mainly depends upon the climatic conditions and coincidence between the abundance of pest populations and vulnerable growth stage of the millet crop. Surveys of insect pests and their natural enemies were undertaken and their importance under subsistence farming conditions was evaluated. The stem borers *(Acigona ignefusalis)* Hmps. and spike worms *(Raghuva albipunctella)* De Joannis are considered as key pests. Considerable losses caused by sporadic attacks of *Geromyia penniseti,* Felt. *Oedaleus senegalensis,* Krauss *Amsact a moloneyi Druce, Psalydolytta* spp., *Spodoptera exempta Wlk., Heliothis armigera Hb.,* and *Lema planifroms* have been reported.

Limited information on the biology and ecology of major insects has been obtained from three observation sites in the south-central region where a warning system for spike worm attack with the help of a model of moth flights and egg counts is underway. The pest management strategy would be applied through a pilot project. Therefore, various methods are being tested, for example, utilization of resistant varieties, biological control agents *(Bacillus thuringiensis* and *Bracon hebetor* Say against spike worms), and partial burning of millet stems against borers. Socioeconomic problems, changes in agricultural policies, farmers' reactions, etc., must be considered to implement an efficient, economical, and stable pest management strategy.

## The Status of Millet Entomology in Nigeria (Etat actuel de l'entomologie du mil au Nigeria)

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Extensive surveys have identified up to 161 insect species that are associated with the millet crop in Nigeria. The major pests are the millet stem borers, *Acigona ignefusalis* Hmps., *Raghuva graminivora* Lap., *Kraussaria angulifera* Krauss, *Oedaleus senegalensis* Krauss, *Meligethes* sp., and possibly *Dicraeus* sp. Sporadically

important pests include *Haspidolema melanophthalma* Lac., *Monolepta goldingi* Bry., *Anomala distingnenda* Blanch., *A. mixta* Fab., *A. tibialis* Lans, *Delia arambourgi* Sequy, *Dysdercus superstitio sus* Fab., *Zonocerus variegatus* Fab., and various species of *Psallydolytta.* The millet stem borer has been the most studied probably because its infestation and damage are the most widespread. Its life cycle, biology, population dynamics, and control measures, have been investigated; even integrated control is being considered. *Raghuva*, the millet head caterpillar, is a serious pest in areas above latitude 11° N. The major storage insect pests of millet have also been identified and some factors which affect their incidence have been investigated. Areas for future research are suggested.

## Host-Plant Resistance to Pearl Millet Insect Pests in India (Resistance des plantes-hotes aux insectes ravageurs du mil en Inde)

**Prem Kishore**

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In pearl millet, a crop of low economic value, the most practicable long range solution for insect control lies in breeding high-yielding, resistant cultivars. A systematic approach to host-plant resistance studies to major pests started in 1964 with the establishment of the All India Coordinated Millets Improvement Project (A1CMIP). Emphasis is on screening varieties and hybrids for their relative susceptibility to shoot fly *(Atherigona approximata)* Malloch, stem borers *(Chilo partellus* Swin., and *Sesamia inferens* Wlk.), white grub *(Holotrichia* spp.), grey weevil *(Myllocerus* spp.), leaf roller *(Marasmia trapezolis* Guen.), fulgorid *(Perigrinus maidis* Ashm.), earhead caterpillars *(Eublemma* sp.) and others. Exactly 2345 accessions from ICRISAT have been evaluated for resistance to these pests, and the IP numbers of the less susceptible entries identified were:

Leaf roller — 26, 366, 1176, 1178, 1289, 1302.
Fulgorid - 78, 103, 1307, 1362.
Earhead caterpillars — 57, 164, 326, 1130, 1316.
Whitegrub — 478, 501, 835, 1169.
Purilla - 79, 1307, 1395.

New sources of resistance such as populations coded by AICMIP as MP 9, MP 15, MP 31, MP 60, MP 80, MP 86, MP 95, MP 106, and PSB 8 have consistently shown lower levels of damage by shoot fly, stem borer and grey weevil in multilocational trials. Not much information is available on the mechanism of resistance, however, nonpreference for oviposition and antibiosis may be the major mechanism operating. Both nonadditive gene action and complementary gene action are responsible for inheritance of resistance.

Lines such as MP 60, MW 5 and MH 107 have shown resistance to stored grain pests.

Suitable techniques for screening under artificial infestation conditions and mass rearing of important pests need to be developed.

# Host-Plant Resistance to Insect Pests in Pearl Millet
# (Resistance des plantes-hotes aux insectes ravageurs du mil)


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Nearly 500 insect and other animal pests have been reported to feed on pearl millet, of which a few are serious or potential pests on a global or regional scale. Host-plant resistance is the most appropriate tool to keep insect populations below economic threshold levels. Resistance screening and breeding programs may be undertaken against pearl millet insects such as shoot fly *(Atherigona approximata* Malloch), stem borers *{Acigona ignefusalis* Hmps., *Chilo partellus* Swin., and *Sesamia inferens* Wlk.), armyworms *(Mythimna separata* Wlk., *Spodoptera exempta* Wlk., and *S. frugiperda J.E.* Smith), midge *(Geromyia penniseti, Raghuva albipunctella* de Joanis, and *Eublema* spp). A few other insects may be locally important.

A strategy to screen for host-plant resistance involving planting dates, use of infester rows, split plantings, hot-spots, controlling other insects interfering in resistance screening, and artificial or no-choice screening has been suggested and discussed. Rearing insects on artificial diets or collecting and carrying diapausing larvae in *2%* agar-agar has been suggested to augment natural populations. Sources of insect resistance identified under natural conditions have been listed, and need to be confirmed in multilocational trials. Oviposition nonpreference, and slower rates of development because of morphological barriers or antibiotic factors in the food source may contribute towards host-plant resistance to most insects. Early- and late-maturing cultivars escape *Raghuva* damage, while compact panicled cultivars tend to be damaged less. Cultivars with a thick cover of anthers suffer higher damage by *Heliothis armigera.* Presence of awns may be helpful in reducing oviposition and feeding by panicle feeding insects.


## Discussion

The presentations and discussions indicated that the most important insect pests of pearl millet are grey weevil and white grub in Rajasthan; shoot fly, stem borer, and white grub in peninsular India; and spike worm *(Raghuva albipunctella)* and stem borer *(Acigona ignefusalis)* in West Africa. Midges, headbugs, blister beetles, and army worms are considered minor pests.

Population monitoring of various insects has been conducted using light and pheromone traps, counting insect numbers (eggs, larvae, and pupae), as well as through damage surveys of crops. Peak activity of millet shoot fly *(Atherigona approximata)* has been recorded during Jul-Sep in peninsular India.

A number of alternate host plants have been report-ed for off-season carryover of insect pests. Paragrass is an alternate host of the leaf roller, and a number of grasses are hosts for grey weevils in India and stem borers in West Africa during the off season.

Among the various control measures, cultural techniques are advocated to reduce pest populations. Destruction of stems before the rainy season reduces the population carryover of stem borers. Early planting escapes shoot fly damage. A well-fertilized crop is generally attacked less by spikeworm, while the reverse is true for stem borer. Other cultural practices such as intercropping, mixed cropping, and crop rotation help reduce pest infestations.

Although a number of predators, parasites, and pathogens have been reported to attack millet pests, their role in reducing pest populations is limited. *Bacillus thuringiensis was* suggested as an alternative to synthetic insecticides.

Use of insecticides is a costly way to control insect pests of millet. Although granular application of carbofuran has shown promising results in controlling shoot fly and stem borers, the cost-benefit ratio is yet to be determined. Foliar applications of endosulfan and phosalone are also promising. Drilling BHC with farmyard manure (2:3) in the furrows before planting helps control white grubs. It was suggested that since a number of insects pollinate pearl millet, it is essential that these beneficial insects not be damaged by insecticides.

Host-plant resistance is the most cost-effective, long-term solution to pearl millet insect pest problems. It is compatible with other control measures, and there are no production costs to the farmer. The genetics of resistance to shoot fly and stem borers have been documented, and there are a number of shoot fly- and stem borer-resistant lines.

# Pearl Millet for Fodder and Forage Production

## Using Genetic Markers on Pearl Millet Chromosomes to Locate and Transfer Heterotic Blocks for Forage Yield (Utilisation des marqueurs genetiques sur les chromosomes de mil afin de reperer et de transferer les blocs d'heterosis pour le rendement fourrager)

**Glenn W. Burton**

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Fourteen recessive chlorophyll-deficient mutants (cd) induced in Tift 23 pearl millet were used to identify chromosome blocks heterotic for plant yield. Yields of spaced plants of large $F_2$ populations of crosses between the Tift 23 (cd/cd) mutant stocks and normal (Cd/Cd) inbreds 13, 18, 104, 106, and 186 were recorded, and a small $F_3$ progeny row derived from each spaced plant was used to separate the $F_2$ plants into Cd/Cd and Cd/cd groups. Among 69 such $F_2$ progenies, Cd/cd plants were heavier than Cd/Cd plants in 53 cases, 15 of which were significantly heavier ($P<.05$ or .01). In the large $F_2$ populations studied, the frequencies for all genes in the Cd/cd and Cd/Cd plant groups of any cross should have been essentially equal, except for the alleles of the genes linked to the cd mutants.

Tift 23 mutant, M5, that identified a high yield heterotic block in inbred 104 (+1510), also identified a low yield heterotic block (+122) in inbred 186. Transferring heterotic block identified by M5 from inbred 104 to inbred 186 by backcrossing should increase the plant yield of Tift 23A, x 186 (hybrid Gahi 3). Ideal genetic markers to identify and transfer heterotic blocks on chromosomes should be natural or induced mutants, be monogenic and recessive, be easy to identify when heterozygous, have little effect on fertility when homozygous, and be located on a chromosome site not occupied by others. At Tifton, we are now using such markers to identify and transfer heterotic blocks for high forage yield to Tift 383, (the $d_2$ dwarf version of inbred 186) by backcrossing. Thus, we hope to ultimately increase forage yields of Tift 23DA x Tift 383 (hybrid Tifleaf).

## Developments and Lacunae in the Genetic Improvement of Forage Pennisetums (Developpement et lacunes dans l'amelioration genetique des pennisetums fourragers)

**V.P. Gupta**

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Methods used in forage *Pennisetum* improvement include the improvement of local populations, varietal selection in exotic materials, use of $F_2$ hybrid populations, selection after intervarietal hybridization, breeding of synthetics and composite varieties, interspecific hybridization and species improvement.

Evaluation of a world collection of germplasm enabled the selection of an array of diverse lines which could be used for intra- and interspecific improvement. In the first phase, interspecific Napier-millet hybrids such as NB 21 were produced that were better in yield, nutritive value, regeneration capabilities, growth rate, acceptability, palatability, disease resistance, and suitability for mixed cropping. Because of high additive genetic variability and less inbreeding depression for vegetative traits, the use of hybrid $F_2$ populations was recommended, but all $F_2$ populations were not necessarily superior. Recently, a number of varieties and synthetics have been bred that have superior yield and quality. Elite types are evaluated for green fodder yield, dry matter yield, and crude protein yield per unit area per unit time, along with other biochemical traits such as oxalic acid, TDN, and IVDVD. Other traits considered are duration, plant height, tillering, leaf size and shape, and the leaf/stem ratio. Good performance under adverse environmental conditions and uniform yield over different growing periods are also useful features. In the search for lines that remain green at harvest physiological evaluation at different developmental stages may be required. Some biochemical parameters and activity of certain enzymes could be used effectively to screen for stable, highly-productive, input-responsive genotypes.

## Breeding Photoperiod Responsive Varieties of Forage Pennisetums (Selection des varietes de pennisetums fourragers sensibles a la photoperiode)

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Most pearl millet genotypes are day neutral, but much African material is photoperiod sensitive. Earlier studies have indicated that these lines flower in November, irrespective of a variable sowing time from April to August.

The inheritance of photoperiodism in pearl millet is controlled by many genes. Our studies on crosses of photoperiod-sensitive lines with two male-sterile lines indicated that the $F_1$ hybrids were day neutral, and did not possess any hybrid vigour for forage yield attributes. None of these hybrids was male-sterile, indicating that these lines were not maintainers of the A, male-sterile cytoplasm.

Forage breeders have exploited the longer growth duration of photoperiod-sensitive pearl millet to breed late varieties, e.g., Tiflate, at Tifton, and PSB 2, at Jhansi. Such varieties remain vegetative much longer, with a more uniform seasonal distribution of green fodder which extends up to Oct-Nov when farmers have the greatest need for fodder.

Photoperiod-sensitive pearl millet material has also been utilized in interspecific hybridization with *Pennisetum purpureum.* Several such hybrids have been bred at the Indian Grassland and Fodder Research Institute, Jhansi, and two of these have narrow leaves and upright growth, which offers the possibility of intercropping a legume component. Many interspecific hybrids have been synthesized in Nigeria by utilizing the male-sterile Maiwa line, and the possibility of hybrid seed production has also been demonstrated.

## Breeding Sweet Pearl Millet Dual-Purpose Varieties (Selection des mils sucres a double usage)

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Pearl millet straw, unlike sorghum straw, is not used as cattle fodder in Tamil Nadu because of its inferior quality. To produce varieties for dual purpose (grain and fodder), sweet pearl millet types were utilized. By population improvement, three populations, TNSC1, TNSC2, and TNSC3 were bred at Tamil Nadu Agricultural University, Coimbatore. They were also tested as parents in the hybrid breeding program. TNSC1 and TNSC2 maintained sweetness and showed complete restoration in the hybrid combinations with three standard male-sterile lines. They also possess good agronomic characters. They will be evaluated further before being released as varieties.

## New Approaches in Forage Breeding in Pearl Millet
## (Nouvelles approches a la selection des mils fourragers)

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An attempt was made to breed pearl millet hybrids exclusively for forage. Hybrid MBFH-1 (Mahyco Bajra Fodder Hybrid-1) has shown significant superior green fodder yield over improved varieties such as L-72 and L-74.

Pearl millet fodder type hybrids are fast growing, and in two cuts can give about 501 $ha^{-1}$ green fodder in 75-80 d.

## Breeding *Pennisetum pedicellatum* for Forage
## (Selection de *Pennisetum pedicellatum* pour le fourrage)

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*Pennisetum pedicellatum* Trin. is a grass species adapted to warm and humid conditions of the tropics and subtropics where its luxurious and nutritious herbage is used to feed animals. Both annual and perennial forms having 2n = 36, 48, and 54 were identified among 38 distinct morphological strains, although plants with 2n = 30 and 53 were also encountered during the course of detailed cytological and embryological investigations.

Since *P. pedicellatum* is essentially apomictic, varietal improvement programs were based on isolating types with more of the sexual rather than the usual aposporic embryo sacs among the facultative apomicts. Strains such as T22 were very promising and, as a result, are presently being extensively exploited to create the desired variability in forage attributes from among crosses between the so-called facultative apomicts with distinct genetic markers.

Other tools being adopted are the induction of sexuality by regulating photoperiod responses and mutation breeding. Meiotic irregularities in the progenies seem to be of very little hindrance in advancing the generations once heterotic vigor and desired types have been isolated by clonal selection. This is because apomixis causes the genotypes to breed true.

Correlation and factor analysis have indicated positive loading of factor 1 on fodder yield, branch number, tiller number, stem girth, and leaf number, while plant height and leaf length were influenced by factor 2.

## Potential of Associative Nitrogen Fixation in Rainfed Cereals (Potentiel de la fixation de l'azote par l'association racine-microbes chez les cereals pluviales)

**P. Tauro**

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Association between cereal plant roots and nitrogen-fixing bacteria has been well documented. Seed treatment with bacteria such as *Azospirillum* has shown to be beneficial. The mechanism by which cereals derive benefits from such association is, however, not very clear. In India, over 70% of the cropped area is rainfed agriculture, with little or no nitrogen inputs, so yields are low and variable. Pearl millet is grown on sandy soils, generally in rotation with chickpea. Average grain yields range between 200-300 kg $ha^{-1}$ in Rajasthan, and between 500-600 kg $ha^{-1}$ in Haryana, with about twice as much straw as grain. Recovered nitrogen under these conditions is 5-20 kg $ha^{-1}$. Any contribution from associative nitrogen fixation, however small, would have a greater meaning in this system than in irrigated cereals.

Our studies over the past few years have revealed varying levels of nitrogenase activity which differ with genotypes. Marginal yield increases have also been reported from seed treatment with bacteria.

## Factors Affecting Nitrogen Fixation Associated with Cereals (Facteurs influencant la fixation de l'azote chez les cereales)

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Nitrogen fixation is the result of interaction between the host plant, nitrogen fixing bacteria, and the environment. Nitrogen fixation associated with cereals may be improved by manipulating factors that affect the process either individually or in combination. Genotypic variation for stimulating nitrogen fixation has been observed in lines or cultivars of sorghum, pearl millet, and minor millets. Large variability from plant to plant in nitrogenase activity has been observed in the Ex-Bornu population of pearl millet. Work is underway to stabilize high and low nitrogenase activity in this population.

Diurnal variation in nitrogenase activity of plants grown in field or greenhouse was observed. The highest level of activity occurred toward the end of the photoperiod. However, such a variation was not observed with plants placed under a constant temperature in the glasshouse. Seasonal variation in nitrogenase activity of plants was also observed and coincided with the biomass development of the plant. Both were highest at flowering.

Environmental factors such as temperature, radiation, soil moisture, oxygen partial pressure, and soil factors (e.g., combined N and organic carbon levels) are known to affect nitrogen fixation. Significantly higher nitrogenase activity and better growth of sorghum and millet plants occurred when plants were grown in a mixture of sand and farmyard manure (FYM) than when grown in vermiculite, soil, or a sand and soil medium. Nitrogenase activity and plant growth were greater in a mixture of sand with 2 or 3% FYM than with 0.5 or 1% FYM. Activity was higher when the plants were incubated at 33°C or 40°C than at 27°C. Activity also increased with increasing soil moisture. Nitrogenase activity in sorghum plants grown in tubes filled with washed sand was drastically reduced when the plants were regularly fed with a solution of combined nitrogen above 15 ppm. Nitrogenase activity of millet and sorghum plants in the greenhouse was stimulated by the addition of 20 kg $ha^{-1}$ N over the control without applied N, but higher doses of N than 20 kg $ha^{-1}$ reduced the activity. In tube culture studies of millet plants grown in unsterilized Alfisol and sand.FYM (93:3 w/w) mixture, nitrogenase activity was higher in tubes inoculated with a culture of some nitrogen-fixing bacteria than in noninoculated tubes.

## Mycorrhiza in Cereals
## (Mycorhizes chez les cereales)


### D.J. Bagyaraj

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The most common mycorrhizal association in crop plants is the vesicular-arbuscular mycorrhizal (VAM) type, which produces vesicles and arbuscules in the cortex region of the root. These associations are geographically ubiquitous and occur over a broad ecological range, from aquatic to desert environments. They are formed by nonseptate phycomycetous fungi belonging to the genera *Glomus*, *Gigaspora*, *Acaulospora*, and *Scekrocystis* in the family Endogonaceae. These fungi are obligate symbionts and have not been cultured on nutrient media. It is now well established that VAM improve plant growth, mainly through improved phosphorus nutrition. Other beneficial effects are a role in the biological control of root pathogens, enhancement of biological nitrogen fixation, hormone production, and greater ability of the host plant to withstand drought stress. In the last few years there has been a rapid increase in the number of scientists working and publishing on the biology of VAM. Reviewing the progress at this point one could visualize research in two main directions. First there is continued emphasis on the measurement and prediction of plant growth responses, inoculum production, and field inoculation. Second there has been great progress in our basic understanding of the VAM symbiosis, especially in the areas of anatomy, taxonomy, physiology, ecology, axenic culture, and biological interactions. The current status of VAM research with special emphasis on cereals is discussed.

## Vesicular-Arbuscular Mycorrhizal Symbiosis in Relation to Pearl Millet Phosphorus Nutrition
## (Symbiose vesiculaire-arbusculaire des mycorhizes liee a la nutrition en phosphore du mil)


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**and**

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Vesicular-arbuscular mycorrhizal (VAM) association with pearl millet is ubiquitous in the SAT regions of both India and West Africa. The extent of root colonization, the fungal species involved, and their densities differ with location. *Glomus* spp. predominate in Indian soils, but pearl millet in West Africa is predominantly colonized by *Gigaspora* spp.

A series of experiments in pots conducted in India and West Africa has shown that VAM inoculation increased growth and phosphorus uptake. The extent of increased phosphorus uptake varied with the available phosphate level in the soil and the inoculated fungus. Phosphorus absorption from rock phosphate was enhanced four-fold by V A M inoculation in comparison to noninoculated control.

Seven field trials at different locations in peninsular India have shown that V A M colonization is a plant genotype dependent trait, and other experiments have indicated that the extent of V A M colonization is heritable. Preliminary field inoculation studies have indicated that the possibility to screen and select genotypes for higher responsiveness to V A M inoculation exists. The techniques for more efficient screening and for identifying and enumerating V A M are also discussed.

## Interaction Between Associative Nitrogen Fixing Bacteria and Mycorrhiza in Cereals (Interaction entre les bacteries fixant I'azote par l'association racine-microbe mycorhizes chez les cereales)

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Inoculation experiments under field conditions clearly demonstrated the beneficial effect of *Azospirillum brasilense* in increasing the dry matter production of pearl millet. Response to inoculation differed between cultivars. Hybrid BJ 104 responded more to inoculation than the others. Inoculation increased the number of *Azospirillum* in the rhizosphere as well as root numbers. The effect was more pronounced in the roots than in the rhizosphere. Roots of inoculated plants harbored a substantial number of bacterial cells in the rhizosphere. Grain yield increased significantly following inoculation along with fertilizer N up to 60 kg $ha^{-1}$. Studies indicated an increase on nitrogen uptake of about 20 kg $ha^{-1}$ N is possible by using the *Azospirillum* inoculant.

Under field conditions, BJ 104 seed inoculated with *Azospirillum brasilense* planted in soil inoculated with *Glomus fasciculatum* (a vesicular-arbuscular mycorrhizal fungus), yielded increased dry matter and grain and a higher phosphorus uptake, over individual applications of *A. brasilense* or *G. fasciculatum.* However, the results were not statistically significant.

In pot trials, the shoot dry mass and leaf phosphorus content were significantly higher in plants grown in mycorrhizae-inoculated soil *(Glomus fasciculatum* or *G. epigaeus)* than in the noninoculated soil. The leaf starch content of leaves from plants grown in the inoculated soil was significantly lower, but the reverse was true with the reducing sugar content. However, there was no difference in the total soluble sugar content of leaves from plants grown in the inoculated and noninoculated soils.

## Discussion

A possible error in acetylene reduction assay during the preincubation period was discussed. Tauro said that the amount of $N_2$ fixed could range from 5-10 kg $ha^{-1}$ N. He also clarified that the data were statistically analyzed and tested, and emphasized that in millet-growing areas such as Rajasthan there is a great potential for inoculation with *Azospirillum* and other $N_2$-fixing bacteria. He suggested that selection should be for the best combination of host genotype and $N_2$-fixing bacterial strain.

In response to a question about the effects of soil bulk density on $N_2$ fixation, Wani said they have not yet been tested. He said enhanced nitrogenase activity at low levels of combined N may be because the low level of N could help multiplication of bacteria, and/ or could also increase the initial vigor during early plant growth. However, high levels of combined N decreased $N_2$ fixation.

Benefits from the use of combined or single strains was discussed, and it was suggested that mixed strains show higher nitrogenase activity and are therefore better inoculants. Relationships between leaf area and nitrogenase activity were also discussed, and Wani clarified that this can only be studied by using high and low $N_2$-fixing lines. They would study these factors soon. It was suggested that there is a need to conduct covariance analysis and to establish the energy requirement for $N_2$ fixation, and that the crop should be studied as a community of plants. Subba Rao said that in general, leaf area need not be considered for acetylene reduction assay.

Relationship between soil temperature and nitrogenase activity is important, but this may not determine the time of inoculation. The possibility of 33° C as optimum for $N_2$ fixation, may be indirect because the same temperature is also optimum for leaf expansion. It was suggested these factors should be studied further. It was also clarified that nitrogenase activity is maximum around flowering, and is likely to be affected by drought at this stage.

Quantification of nitrogen fixed by bacteria was discussed. Under field conditions, it could be 10 kg $ha^{-1}$ N, but some pot-culture studies using $^{15}N$ have indicated that 17% of total plant N at low N levels is derived from the atmosphere by nitrogen-fixing bacteria. Subba Rao said that besides fixing nitrogen, these bacteria could have other positive effects on plant growth.

Bagyaraj stressed the importance of mycorrhyza in agriculture. He said it is very important to develop methods of culturing mycorrhiza in the laboratory, and until such time, mycorrhiza research may be only of academic interest. Two areas that are not well understood are whether mycorrhiza needs recurring applications, and the residual effects of inoculation. Bagyaraj said that mycorrhiza-infected plants are resistant to parasitic fungi such as *Sclerotium,* possibly because mycorrhiza produce certain orthodihydroxy phenolic compounds.

Krishna presented the mycorrhiza work in progress at ICRISAT. During the discussions, it was pointed out that currently in Africa, acid treatment of rock phosphate is being tried, and it was suggested that the economics of acid treatment of rock phosphate, and the alternate method of rock phosphate and mycorrhizal fungi need to be established. To a question on the mode of action of mycorrhiza, Krishna said that mycorrhiza do not solubilize rock phosphate, but these fungi exploit more of the available P.

Questions were raised on the interaction of mycorrhiza and other plant pathogenic fungi. Krishna clarified that mycorrhiza colonization offers resistance only to root pathogens. He also defined susceptibility, which indicates infection by mycorrhiza, and responsiveness, which indicates plant response.

Doubts were raised about whether mycorrhiza produce phytoalexins, and thereby protect roots from root diseases. Subba Rao wondered if there is a genotype x strain interaction, but Krishna said that he is looking for horizontal susceptibility, as in the case of endemic diseases. He also explained that infected roots show greater affinity for P, and mycorrhiza increase the root surface area. Wani said that since one hybrid without mycorrhiza performed well, why not select such lines? Krishna clarified that the plant is required to produce less energy per unit surface area explored when inoculated with mycorrhiza, compared to the energy required for root production and nutrient exploration.

Tilak summarized the interaction of mycorrhiza and *Azospirillum,* and said that while inoculation with a mixture is advantageous, mycorrhizal inoculum production is a major constraint. The culture filtrate of *Azospirillum* enhances the spore germination of mycorrhiza, and it was suggested that this information may help to culture the VAM in the laboratory. Tilak clarified that he used 1500 kg $ha^{-1}$ inoculum, and the *Azospirillum* inoculation could contribute about 10 kg $ha^{-1}$ N, and that the remaining 10 kg $ha^{-1}$ N could be applied. At higher N levels, Azospirillium has no effect.

Subba Rao summarized the session: VAM could be seen inside the root, but cannot be cultured, while in contrast, *Azospirillum* can be cultured, but cannot be located inside the plant cell. Both microorganisms have immense potential to increase millet production, and in both Indian and African agriculture, inoculation with these microorganisms is very important, and research in this area should be strengthened. Methods to culture mycorrhiza need to be developed immediately.

# Pearl Millet Production in Drier Areas

## Characterizing Variability in Rainfall in Arid Zones (Caracterisation de la variabilite pluviometrique dans les zones arides)

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Pearl millet is extensively grown as a rainfed crop by subsistence farmers mostly in sandy and often shallow soils in areas with 200-800 mm annual rainfall. More than 95% of the world's pearl millet is grown in Africa and South Asia, principally in the Sahelian-Sudanian Zones of West Africa and to the east and southeast of the Thar desert in India. Mean annual rainfall, and the distribution, area, and production of pearl millet in these regions are shown. Inter- and intraseasonal variability in available soil moisture is the major hazard to pearl millet production. Rainfall is erratic as well as low, and the water-holding capacity of soils is typically low to moderate, limiting the possibilities of buffering rainfall fluctuations with stored soil moisture.

The latitudinal variation in the distribution of rainfall amounts for selected locations in West Africa is also illustrated. Variability in the long term pearl millet yield in the arid zones of Rajasthan has been related to the onset and withdrawal of the monsoon and the distribution of the seasonal rainfall. Probabilities of different lengths of the growing season are calculated for various locations in India with 200-800 mm annual rainfall. When the annual rainfall is about 300 mm, mean length of the growing season is 8 weeks. In Jodhpur, the probability of 300 mm rainfall is 70%. The mean length of the growing season increases to 12 weeks when the annual rainfall is about 425 mm, but the probability of this amount of rainfall is 40%. Long-term climatic data are analyzed for five selected locations in the arid zones of Rajasthan, and grain yield patterns in these locations are related to the occurrence of water deficits, calculated from the actual and potential evapotranspiration data in different growth stages.

# Improving Millet-Based Cropping Systems in the Sahelo-Sudanian Zone of Mali (Amelioration des systemes de culture axes sur le mil dans la zone sahelo-soudanaise au Mali)

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Agronomic experiments on pearl millet-based production systems conducted jointly by Institut d'economie rurale (IER) and ICRISAT are briefly reviewed. Cropping systems research approaches are described which consider both improvements to existing pearl millet-based systems, and also the design and evaluation of more productive alternative systems. The two major production systems studied are two intercrops, maize/ millet in the Sudanian Zone and millet/ cowpea in the Sahelian Zone. The traditional maize/ millet and millet/ cowpea systems as practiced by the subsistence farmers in Mali are briefly described. The effects of such key agronomic factors as crop variety, density, and geometry, dates of planting and harvest, and added fertility on the total productivity of these systems are synthesized to develop improved technology packages. The suggested technologies for millet/cowpea system include planting millet after the onset of rains at about 30 000 plants ha$^{-1}$ with about 25 000 plants ha$^{-1}$ of cowpea planted later when millet is in the 3-4 leaf stage in a 2-row millet: 1-row cowpea arrangement. The recommendation domains for improved maize/millet and millet/-cowpea systems are also indicated. The need to introduce management-responsive millet cultivars to develop more productive millet-based systems is emphasized.

Alternative production systems presently being studied are indicated with particular reference to millet/-groundnut systems. It is suggested that the future target systems should include cash crops that provide income to farmers and as a result stimulate the use of agricultural production inputs on the millet component of the intercrop.

# Cropping Systems of Pearl Millet in Arid Zones of Rajasthan (Systemes de culture du mil dans les zones arides du Rajasthan)

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Pearl Millet is one of the principal crops of the Indian arid zone being cultivated on more than 60% of the total cropped area, sharing 80% of the state acreage and 60% of the production. It forms the staple food of the people and its stover is used as livestock fodder. Pearl millet is one of the components in the traditional cropping systems, either grown pure or mixed with grain legumes or oilseeds, top feed tree *Prosopis cineraria* (lopped for fodder), or shrubs *Zizyphus nummularia* spp.

Among the single crop systems tried from 1975-80, pearl millet-fallow, though it showed high yield, fluctuations, proved the most productive (1720 kg ha$^{-1}$). High and extended rainfall years permit double cropping and in these conditions pearl millet followed by mustard proved the most productive and remunerative (3030 kg ha$^{-1}$). Long-term fertilizer use studies in green gram-pearl millet rotation revealed a saving of 20 kg ha$^{-1}$ N than continuous growing of pearl millet. Intercropping one row of pearl millet between two pairs of green gram/ cluster bean/ mothbean resulted in higher total productivity and WUE. Pearl millet, either grown pure or mixed with legumes, proved more productive than sorghum-based fodder systems and a pearl millet

with cowpea system was the most efficient. Studies to further improve the efficiency of pearl millet-grain legume cropping systems carried out during 1982-85, led to identification of efficient genotypes of cowpea (Charodi-1, S-8/G-1), green gram (FS-277), clusterbean (T-18/JMM-259), and mothbean. Suitable techniques and contingency plans for stabilizing the production of pearl millet in aberrant weather situations have also been developed and are discussed.

## Breeding Pearl Millet Varieties for Arid Zones
## (Selection des varietes de mil destinees aux zones arides)

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Pearl millet is an important cereal crop of arid zones of India. It's hardy nature, energy transfer efficiency (leaves to grain), and efficiency in the utilization of limited moisture has made it more adapted to arid conditions. However, the productivity in arid zones is low (250-280 kg $ha^{-1}$), due to low and erratic rainfall and low relative humidities, erosive winds, poor soil fertility and physical conditions such as high soil salinity, and soil crusting. These problems restrict the establishment, growth, and yield of the crop.

Local varieties of pearl millet cultivated in these areas better withstand atmospheric aridity and drought stress but they are poor yielders.

The right direction for the pearl millet program for arid zones is to breed varieties capable of producing stable yields in adverse conditions such as limited moisture (drought tolerant), and which mature within the period of moisture availability, have high yield potential, and are resistant to diseases and pests. Besides description of the factors that limit high production of pearl millet under arid conditions, the prospects of increasing yield through breeding better varieties are presented. The merits of hybrids, composites, and synthetics of pearl millet for arid zones are discussed.

## Breeding Pearl Millet for Drought in the Sudan
## (Selection des mils resistants a la secheresse au Soudan)

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Pearl millet is the preferred staple food for the majority of the 6 million inhabitants of Western Sudan (Kordofan and Darfur Regions). Among the cereals, it comes second to sorghum in area and total production in the country. The millet area planted annually ranges from 1 to 1.5 million ha, and 90% of this area is in western Sudan, mainly in the extensive sandy soils zone. The crop is raised under traditional, rainfed farming methods with most of the production being centered in drier marginal areas of less than 500 mm of annual rainfall. Yields are generally very low, the average being 275 kg $ha^{-1}$ during droughts of the 5-year period 1981-85. Low and unreliable rainfall is the single most important constraint to millet production, hence the need for breeding drought tolerant, early-maturing varieties. Other constraints include poor soil fertility and cultural practices, insect pests and diseases, and socioeconomic constraints.

Millet breeding work was started in 1974, and was strengthened in 1977 through cooperation with 1CR1SAT. The program is concentrating on producing high-yielding, drought-tolerant, early-maturing varieties with acceptable grain quality and resistance to prevailing pests and diseases. A number of approaches have been followed, including collection and screening of indigenous germplasm, introduction and evaluation of exotic material, hybridization, and population improvement by recurrent selection methods. In national trials conducted from 1977-1979, one cultivar, Serere Composite-2 (SC-2) from Uganda, outyielded the best local variety 'Kordofani'. SC-2 was released in January 1981 for general cultivation under the name of 'Ugandi'

A composite 'Bristled Population,' which was derived from bristled inbreds of Sudanese and exotic origin, and improved by both S, and full-sib methods of recurrent selection, is showing good promise under drought conditions and attack of birds in national and on-farm trials. An early-maturing variety, ISMV 8223 derived from the Inter Variety Population, has shown good promise due to its high tillering capacity. Work on hybrid breeding has started, but there is a lack of male-sterile lines for producing suitable hybrids for the drier areas of Sudan. Efforts are in progress to introduce and breed new male-sterile lines in cooperation with ICRISAT Center.

## Discussion

Five papers were presented in this session: two covered aspects of millet production in the drier areas of sub-Saharan Africa, two others discussed production aspects in the arid and semi-arid areas of India, and the last brought together the characteristics of the rainfall variability in the two subcontinents. Discussion centered on three aspects: the susceptibility of millet to temperature and drought stress, plant density in drier areas, and intercropping in these areas.

A comment was made that pearl millet in Botswana exhibits good tolerance to drought stress only when tempertures are moderate. When temperatures are higher, the performance is poorer. Researchers in India indicated that it was generally difficult to separate the effects of drought and temperature stresses. Nonetheless, as selection for drought tolerance is generally carried out when temperatures are higher, better performing materials under these conditions are likely to tolerate drought stress in association with higher temperatures.

Farmers in Africa generally plant millet in widely-spaced hills to mitigate risk. The practice of selecting breeding lines from row-spaced plants, or high-density hill plantings was questioned. The point was made that density * variety interactions normally occur under higher fertility at higher densities. This appears to account for the rather high densities used in the drier areas of Rajasthan, where reasonable fertilizer levels are used. During the subsequent discussion it was pointed out that final panicle numbers in the WASAT approached planting densities in India, so that the actual yield-determining density is not very different from those used in India.

Intercropping millet with other species is a common practice. Some participants felt that the advantage or success of intercropping should be measured by methods other than using land-equivalent ratio. Shetty emphasized that the intercropping research conducted in Mali had also calculated monetary benefits to assess the comparative worth of the different cropping systems. He said the program objective was to improve the existing cropping system and not to quantify the intercropping advantage.

# Pearl Millet Pathology

## Disease Incidence on Pearl Millet in Niger during 1981-1985. (Incidence des maladies chez les recoltes de mil au Niger entre 1981 et 1985)

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Pearl millet is by far the most important staple food in the Republic of Niger and is grown on approximately 3 million ha. Regular surveys in farmers' fields conducted during five growing seasons (1981 -1985) revealed that the incidence of downy mildew *(Sclerospora graminicola),* generally considered the most serious disease on pearl millet, steadily decreased in most observed areas from 1981 through 1984. However, in 1985, disease incidence increased. Significant correlations between humidity or rainfall and the percentage of infected plants could not be established. The most prevalent symptom was green head mostly on secondary tillers and often without any foliar symptoms. Plants whose heads consisted of leaf-like organs were stunted and always exhibited heavy downy mildew.

In all 5 years, smut (*Tolyposporium penicillariae)* was generally widespread but its severity was low and rarely exceeded 3%. Ergot *(Claviceps microcephala,* was almost nonexistent on local varieties and was observed on exotic varieties only. Zonate leaf spot, caused by *Gloeocercospora sorghi,* was an important disease during the last 5 years and is thought to reduce yield. During the last 2 years, a bacterial disease characterized by brown, necrotic streaks which occur even in an early growth stage and probably caused by *Xanthomonas campestris* pv. *hoecicola,* exceeded the importance of zonate leaf spot.

Minor diseases which were found only sporadically, include those caused by *Collectotrichum graminicola, Dactyliophora elongata, Phyllosticta penicillariae, Puccinia penniseti,* and *Pyricularia setariae.*

## Recherches sur la resistance varietale du mil aux maladies au Senegal (Research on Pearl Millet Varietal Disease Resistance in Senegal)

**D.F. Mbaye**

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Au Senegal, les trois principales maladies du mil sont : le mildiou *(Sclerospora graminicola),* le charbon *(Tolyposporium penicillariae)* et l'ergot *(Claviceps fusiformis).* Le programme sur la pathologic du mil de l'ISRA est oriente actuellement vers la creation ou l'amelioration des varietes resistantes aux maladies. Les etudes suivantes ont ete menees dans le cadre de ces recherches i) etudes sur la biologie et epidemiologic des pathogenes; ii) mise au point des techniques de criblage; iii) identification des sources de resistance.

Les etudes sur la biologie et l'epidemiologie des pathogenes nous ont permis de maftriser les techniques d'inoculation et de mettre au point des techniques de criblage au champ. Avec ces techniques de criblage on a pu identifier des sources de resistance. Les resultats suivants ont ete obtenus suite a trois ans d'essais utilisant ces techniques :

- milldiou : 612, 1981 et 894 entrees se sont montrees respectivement resistantes en 1983, 1984 et 1985.

- charbon : en 1983,192 entrees se sont bien comport6es; en 1984, 971 entrees ont eu une severite inferieure a 10% et en 1985, 805 entrees, soit 48% du materiel teste se sont revelees resistantes.

- ergot : en 1985, plusieurs entrees ont presente une severite inferieure a 1%.

Cependant, on ignore les mecanismes genetiques regissant la resistance et les facteurs de l'equilibre dynamique entre l'hote et le parasite. L'etude de ces problemes importants apportera sans nul doute une contribution non negligeable a la lutte genetique contre ces pathogenes.

## Research on Pearl Millet Varietal Disease Resistance in Senegal (Recherches sur la resistance varietale du mil aux maladies au Senegal)

**D.F. MBaye**

**Pathologist, ISRA-CNRA, Bambey, Senegal**

The three major diseases of pearl millet in Senegal are mildew *(ScJerospora graminicola),* smut *(Tolyposporium penicillariae),* and ergot *(Claviceps fusiformis).* The Institut Sen6galais de Recherche Agricole (ISRA) Pearl Millet Pathology Program is currently concentrating on the development or improvement of disease-resistant varieties. The aspects examined included biology and epidemiology of pathogens, screening techniques, and identification of sources of resistance.

Biological and epidemiological studies have enabled the development of field-screening techniques and the improvement of inoculation techniques. The improved screening techniques were used to identify sources of resistance and the following results were obtained after 3 years of trials:

- Mildew. 612 entries in 1983, 1981 entries in 1984, and 894 entries in 1985 showed resistance.

- Smut. In 1983, 192 entries performed well; in 1984, disease severity was less than 10% in 971 entries; and in 1985, 805 entries (48% of the test material) proved to be resistant.

- Ergot. In 1985 disease severity was less than 1% in several entries.

The genetic mechanisms of this resistance and the factors governing the dynamic host-parasite balance are not yet known. A study of these problems will be extremely useful in genetically controlling these pathogens.

## The Pathology of Pearl Millet in Nigeria (Pathologie du mil au Nigeria)

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Pearl millet is an important food crop in northern Nigeria, second in importance only to sorghum. In Nigeria three types of pearl millet are grown: "gero" millets which are early maturing and photoperiod insensitive, and "maiwa" and "dauro" millets which are photoperiod sensitive. A number of diseases infect these millet types but the three most important diseases at present are downy mildew *(Sclerospora graminicola),* smut (*Tolyposporium penicillariae),* and ergot *(Claviceps fusiformis).* Other diseases of minor or localized importance are *Phoma* leaf spot, *Dactyliophora* leaf spot, *Pyricularia* leaf spot, rust, yellow leaf blotch *(Pseudomonas* sp.), *Curvularia* leaf spot, pokkah boeng, and maize streak. *Striga hermonthica* seriously attacks millet in the drier Sudan and Sahel savannah but not in the Guinea savannah. The *Striga* strain attacking pearl millet also attacks sorghum and maize, but to a much lesser extent. The etilogy of two fungal and one bacterial foliage diseases hitherto undescribed are currently being studied in addition to an undescribed stalk rot. Research in Samaru, Nigeria, has provided evidence of pathogenic variation in *Sclerospora graminicola, Striga hermonthica*, and *Tolyposporium penicillariae*. Millet lines resistant to downy mildew, smut, and ergot have been identified in Nigeria. Many millet lines resistant to downy mildew elsewhere are highly susceptible to downy mildew in Nigeria, while those resistant in Nigeria tend to maintain their resistance elsewhere. This and the fact that most other diseases reported on pearl millet elsewhere are found in Nigeria make it an ideal location for international millet pathology research.

## Research on the Management of Pearl Millet Diseases in West Africa (Recherches sur la maitrise des maladies du mil en Afrique de l'Ouest)

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In West Africa downy mildew and smut cause appreciable yield loss in pearl millet. Ergot is potentially dangerous, but not economically important at present. Seedling establishment failures due to seed and soil-borne pathogens occur sporadically in all millet-growing areas.

The long-term management strategy to protect traditional millet production should be through a judicious integration of host-plant resistance, seed treatment, and crop management practices.

In Mali, locations where downy mildew is economically important have been identified by annual surveys. Experiments conducted in recent years show that good seedling establishment and control of downy mildew leading to a 12-16% increase in yield can be obtained by seed treatment with an experimental formulation containing 1.5 g metalaxyl + 0.625 g TMTD + 0.625 g Heptachlore a.i. $kg^{-1}$ of seed. This has been verified and demonstrated through a network of on-farm experiments, and the product is recommended for use in locations where downy mildew is important. But in locations where downy mildew is not important, an experimental formulation containing 0.5 g Benomyl + 0.625 g TMTD + 0.625 g Heptachlore a.i. $kg^{-1}$ seed favored good seedling establishment and increased the number of productive tillers leading to a 10-12% increase in yield. This product is superior to the currently used TMTD/Heptachlore.

Crop management research indicates that oospores play an important role in downy mildew epidemiology. Cultural practices that reduce oospore production, dissemination, and infection could help reduce downy mildew severity. Only limited success has been obtained in this area, and further studies are in progress. Sporangia may play only a limited, but complementary role in downy mildew epidemiology in certain humid locations in Mali. Sporangial infection can be reduced by frequent removal of all infected seedlings during the first 30 d after sowing.

## Preponderence of Downy Mildew of Pearl Millet in Delhi and Haryana (Preponderance du mildiou de mil a Delhi et au Haryana)

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Cultivation of pearl millet is economical in the semi-arid tracts of Haryana and Delhi. In recent years, a widely cultivated hybrid, BJ 104, which had displayed a fair degree of field resistance to downy mildew *(ScJerospora graminicola)* for several years, has shown signs of resistance breakdown, particularly in Haryana. This has been attributed to the appearance of a new pathotype. To determine differences in pathotypes of Haryana and Delhi, 14 selected genotypes drawn from important centers of India were evaluated for their reactions to downy mildew in the DM sick-plots at Delhi and Hisar for 5 years (1980-84). A comparative assessment of mean DM incidence of genotypes over years showed close similarities between results from the two regions, despite considerable differences in weather conditions. It is therefore apparent that the same pathotype of *S. graminicola* is in the two regions, and that the resistance breakdown of BJ 104 is not due to the appearance of a new pathotype.

## Sources of Resistance to Downy Mildew from Local Landraces of Pearl Millet (Sources de resistance au mildiou parmi les varietes locales du mil)

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Downy mildew of pearl millet, caused by *ScJerospora graminicola*, has been the major problem with this crop in India since the 1970-71 epidemic. The high-yielding hybrids succumbed to this disease lowering production substantially. Identification and utilization of host-plant resistance is, therefore, the surest and most feasible means of disease control. Pearl millet landraces provide a wide genetic variability for different traits. After collection from different parts of Maharashtra, 123 landraces of pearl millet were screened at Aurangabad. Entries were screened in a downy mildew sick-plot with infector rows. The screening was repeated in three seasons (1981-83). After scoring, 30 entries were resistant (0-5% severity) and 51 were moderately resistant (6-10% severity). Five selected entries were included in the of All India Coordinated Millets Improvement Project multilocational downy mildew nursery in the 1985 season. The results obtained from ICRISAT, Jamnagar, and Aurangabad indicate that these genotypes (Satara 4, UCV 2-4-1, Makhani, Jakharan and RSJ 3) have stable resistance in different agroclimatic zones across locations. These genotypes are relatively early and mature within 90-95 d.

# Stunt and Counter-Stunt Symptoms in Pearl Millet Downy Mildew (Symptomes de rabougrissement et de retablissement ulterieur dus au mildiou du mil)

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Stunting is a form of symptom expression exhibited by particular cultivars of pearl millet in response to infection by *Sclerospora graminicola.* Such cultivars are susceptible to infection by the fungus, but do not permit fungal sporulation and therefore limit disease spread, which gives the crop a considerable advantage over cultivars which allow normal sporulation. Previous evidence showed that stunting was a feature of host genotype, was unaffected by the pathogen genotypes, and was potentially a durable character. However, field reports from India suggest that the stunt character is breaking down. Experiments were conducted to investigate possible explanations for this phenomenon. When a pathogen collection from Zambia was included in tests on a stunt host, hybrid BJ 104, the proportion of stunted plants was repeatedly lower than with other pathogen collections. Consequently there could be elements in the pathogen genotype able to overcome the stunt reaction. Conversely, the incidence of stunting differed between seed stocks of BJ 104 collected from different multiplication sites. Occasionally it was also noted that plants that stunted early may recover. Epifluorescence microscopy was used to compare diseased tissue. Mycelium in stunted plants were deformed and restricted. Treatment with the fungicide metalaxyl produced similar effects on the fungus and treated plants recovered from the disease. The possibility that effects of stunting and metalaxyl on the fungus may be related is discussed.

# Studies on Pearl Millet Rust (Etudes sur la rouille du mil)

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Detailed studies were undertaken on five single-spore cultures of *Puccinia substriata* var. *indica,* incitant of pearl millet rust in Rajasthan. Preinoculation exposure of the host to high humidity did not influence infection and disease development while postinoculation exposure was found necessary. Incubation period decreased with increasing duration of exposure to high humidity. Maximum disease levels occurred at 22°C. Light was essential for the disease development. The incubation period increased with a decrease in light intensity. The urediniospores survived for 40 weeks in glass vials at 5-8°C, 5 weeks under open field conditions, and 6 weeks under tree shade. When buried in the soil they did not survive for more than 3 weeks. Teliospores remained viable for 9 mo at room temperature, 8 mo under tree shade, and 7 mo under open field conditions. In inoculation tests, *Pennisetum americanum* and *Solatium melongena* were found susceptible to the rust pathogen.

Loss in grain yield was directly correlated with an increase in the coefficient of disease index (CODEX). A fungicide, Baycor, caused 100% inhibition of urediniospores at 100 $\mu g\ ml^{-1}$ in vitro and provided maximum disease control (94.5%) under field conditions.

The effects of different factors, i.e., temperature, relative humidity, spore drying, spore washing, pH, and light on germination of urediniospores and teliospores were studied. The duration of incubation period influenced the percentage spore germination.

## The Pertinence of Gynoecial Structure and Pollination Dynamics to Ovary Infection of Pearl Millet by Ergot
## (Importance de la structure du gynecee et de la dynamique de pollinisation dans l'infection des ovaires de mil par l'ergot)

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Ergot of millet is a floral disease in which the pathogen invades the host ovary and replaces plant tissue with a mass of sphacelial hyphae. Fungal growth is supported by the endogenous gynoecial nutrient supply which under normal circumstances would support ovule fertilization and subsequent grain development.

Successful establishment of the fungus depends on compatible entry into the ovary tissue without causing a hypersensitive reaction by the host. The path of entry traced by invading hyphae is dictated by pistil morphology. Penetration appears to be controlled by physiological and biochemical parameters associated with pollination and fertilization. Hyphae penetrate and travel down the stylodia, closely following the path taken by millet pollen thus providing direct entry into the upper ovary wall.

As host tissue is replaced, hyphae can no longer obtain sufficient nutrients for sphacelial growth from adjacent islands of degenerating host cells, isolated from the main vascular supply. The fungus establishes a host-parasite interface at the base of the ovary in close proximity to the main ovarian vascular trace, thus allowing unrestricted nutrient flow into the fungal sink.

Damage to the stigmatic hairs, occupation of the pollen transmission tracts, and stylodial constriction insure that the pathogen successfully isolates itself from pollen. It is evident that the phenomenon of stigma constriction provides a basis for ergot resistance in selected lines of pearl millet.

It is known that fertilization imparts resistance in other ergot/host interactions, however elicitation of stigma constriction in pearl millet, either by compatible host pollen or by ergot hyphae, appears to be a unique phenomenon. Investigation of pollen and hyphal transmission down the stylodia of pearl millet provides a novel model to investigate stigma interactions in Gramineae.

## Screening Pearl Millet for Resistance to *Striga hermonthica* in West Africa
## (Criblage du mil pour la resistance a *Striga hermonthica* en Afrique de l'Ouest)

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**and**

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The importance of the root parasite *Striga hermonthica* as a major constraint to pearl millet production in West Africa and the need for the breeding of host-plant resistance are discussed. Preliminary re-sults of screening pearl millet for resistance in West Africa are included. Screening in pots led to the identification of promising sources of resistance: Serere 2A-9-2-27-9-8-1, Serere 2A-9-2-27-9-5-2, inbred 5258-1-19-4-5-2, inbred 5258-1-19-1, and 3/4 HK-2-2. Experience indicates that both field trials in *Striga-sick* plots and screening under controlled conditions in pots should be carried out. Progress in identification of resistance sources has been slow and future research considerations to solve the *Striga* problem should include collaborative basic studies on the biology of *Striga* and research in the field, involving scientists from several disciplines.

# Pearl Millet as a Crop for Intensive Agriculture

## Pearl Millet Cultivation in Tamil Nadu
## (Culture du mil au Tamil Nadu)


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Pearl millet cultivation is mostly confined to Chengalpattu, South Arcot, North Arcot, Thirunelveli, Madurai, Trichy, and the Pudukottai disticts of Tamil Nadu. In this state, the area under pearl millet cultivation has changed according to seasonal factors. However, there is a long-term decreasing trend. The human consumption pattern in the state is changing rapidly towards rice rather than coarse grain cereals such as pearl millet, and this is a contributory factor in the decline.

The area under pearl millet cultivation has decreased from 1970-71 to 1983-84, by over 38% in total area and 50% in irrigated area. Although, there was some improvement in the yield of the irrigated crop during the 1970s because of the introduction of hybrids, there is a decreasing trend in yield in the 1980s. Production also shows a decreasing trend over the years. Details of area, production and yield from 1970-71 to 1983-84 are presented.

The decreasing trend in area and production may be mainly attributed to the poor returns from the pearl millet cultivation compared to competing crops such as sorghum, groundnut, and gingelly. The cultivation of pearl millet is economical under irrigated conditions, but the risks, such as downy mildew attack have discouraged farmers.

The demand for human consumption of pearl millet is rapidly going down and alternative demand for pearl millet should be explored. At present, there is an increasing trend in utilization of pearl millet for cattle and poultry feed in Tamil Nadu. As yet there is no proper research or specific recommendations for pearl millet as cattle and poultry feed. Any innovations in utilization of the crop as animal feed will help increase local demand for pearl millet. The scope for exporting to neighboring States also needs to be explored.

The risks involved in cultivation from pests and diseases have to be overcome by the introduction of resistant cultivars. Composites and synthetic varieties bred by ICRISAT, such as WC-C75 and ICMS 7703 have, no doubt, sustained the cultivation of pearl millet in the state. However, their yields are lower than hybrids, which are, however, susceptible to attack by downy mildew. The release of downy mildew-resistant hybrids may brighten the prospects of the crop in Tamil Nadu.

# Potential and Prospects of Pearl Millet as a Crop for Intensive Agriculture in Gujarat (Potentiel et perspectives de la Culture intensive du mil au Gujarat)


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**and**

## D.D. Malavia

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Pearl millet is a very important food crop in Gujarat, occupying an area of 1.44 million ha and producing 1.61 million t of grain with an average yield of 1430 kg $ha^{-1}$ (1983-84). Pearl millet is one of the important summer season crops, occupying 0.13 million ha producing 0.23 million t with an average yield of 1800 kg $ha^{-1}$ (1983-84). Pearl millet-based farming systems are found in different agroclimatic zones of Gujarat e.g., north and south Saurashtra, middle Gujarat, north Gujarat and the northwest zone. The cropping intensities where pearl millet is included in intensive cultivation may vary from 200-300%. A 200% cropping intensity is found in middle and north Gujarat, north and south Saurashtra and the northwest zone. In north Gujarat, north and south Saurashtra and the northwest zone, 300% cropping intensities are employed. Pearl millet-wheat-fodder maize cropping sequence is profitable followed by groundnut-wheat-mung. The area under summer pearl millet has been decreasing over the last 3 years because of an increase in dry season groundnut.

# The Potential of Pearl Millet as a Grain Crop in the Central Great Plains of the USA (Potentiel du mil en tant que culture a grain dans les grandes plaines centrales des Etats-Unis)


## W.D. Stegmeier, B. Khaleeq, and T.L. Harvey

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The conversion of tropically adapted pearl millets to a dwarf grain crop adapted to mechanized farming in the Central Great Plains area of the USA started in 1969 at Kansas State University (KSU). We have shown that pearl millet has a grain yield potential that may equal grain sorghum on silt loam soils and may exceed sorghum yields on the sandy soil types in Kansas.

If grain-type pearl millet becomes a crop in the Great Plains it is anticipated that most of the production will be utilized as an ingrediant in feed rations by the cattle, swine and poultry industries. Several years may elapse before millet grain is accepted in the USA food market where wheat, maize, rice, and oats are the preferred cereals.

Livestock feeding trials conducted at the Fort Hays station indicate millet grain is at least 1% more efficient than sorghum grain for fattening beef animals and 10% better than sorghum in growing rations for calves. Swine feeding trials at the main station at KSU show millet may be substituted for maize on a unit for unit basis. However, trials with laying hens show a reduction in egg yield with high levels of millet grain in the ration. We expect to see increases in efficiency with additional experience in processing methods and ration formulations.

Progress is being made in breeding for improved stand establishment, low temperature tolerance, and lodging resistance. Measurements of over 200 inbred lines indicated that significant variation occurs in length of seedling mesocotyis and coleoptiles; the ranges were 52-167 mm for mesocotyl, 14-30 mm for coleoptile, and

69-188 mm for total seedling lengths. In the field, planting at a depth of 3.2 cm showed few differences due to mesocotyl length. However, emergence from a 6.4 cm depth was excellent for long mesocotyl lines and poor for short lines.

Materials are being identified that tolerate temperatures below 13.9° C, a threshold level at which disruption of meiosis occurs. However, our procedures and techniques require further modification for effective screening.

Stalk breakage and lodging is a severe constraint for mechanized harvest. Several causes have been identified and progress is being made to reduce the incidence and severity of lodging.

## Strategy to Raise Pearl Millet Productivity through Intensive Agriculture (Strategies pour augmenter la productivite du mil par la culture intensive)

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In India, pearl millet is usually cultivated in semi-arid and sub-humid regions on marginal lands and average yields are low. During the past decade, high-yielding hybrids and varieties became popular due to their high yield potential, and ability to respond to improved cultivation practices and to light irrigation under drought stress. Improved varieties are early maturing so they are adapted not only to irrigated areas but also to dry lands with moderate rainfall. Hence pearl millet is becoming a dominant crop in intensive agriculture in many parts of Maharashtra and other millet growing states. National policy with regard to crop planning needs to be reexamined in view of the water use economy and overall production and productivity of various food crops. Efficient use of land and water is essential in dry zone irrigation schemes. High priority needs to be given to increased cultivation of crops such as pearl millet which respond remarkably to a few light irrigations. Agroclimatologists should assist in the formation of research and development strategy by mapping zones where millets could be grown with assurance. Breeding objectives of millets need to be redefined. The purpose should be improved yield stability, resistance to major diseases, pests and drought conditions, and adaptability to specific agro-environments. Cultivation technology should also be developed to suit specific conditions, crop rotations and mixed cropping patterns.

Extension efforts need to be strengthened to make farmers aware that it pays to use seed of recommended improved varieties, and to adopt improved production technology to realize their yield potential.

## Agronomy for the Realization of Yield Potential of Pearl Millet—a Speculation (Methodes agronomiques pour la realisation du potentiel de rendement du mil—une conjecture)

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Modern cereal crops cultivars generally possess high yield potentials. The realization of these potentials requires improved agronomic management, most notably with the increased application of plant nutrients as fertilizers. This fact has been convincingly demonstrated in the success stories of the green revolution with rice and wheat. Experimental results indicate that there is scope for revolutionizing the production of sorghum and maize by using improved cultivars in combination with improved agronomic management. How about the potential for revolutionizing pearl millet production? Is there such scope? Pearl millet is a typical $C_4$ plant with a very high photosynthetic capacity and high dry matter accumulation rate; in principle, the possibility of a phenomenal yield increase does not appear to be remote. For example, if in a pearl millet crop the yield components are, grain mass 8 g $1000^{-1}$, 2500 grains $head^{-1}$, 3 heads $plant^{-1}$ (or hill), and 100 000 plants (or hills) $ha^{-1}$, the theoretical yield will be 6 t $ha^{-1}$. To achieve this, the agronomic managerial requirements would be adequate planting geometry (for instance 45 cm row spacing x 20 cm inter-plant spacing) for the individual plant (or hill) to have sufficient head-bearing tillers, adequate irrigation or supplemental irrigation to make available 440 mm water for evapotranspiration (at assumed water use efficiency of 15 kg grain $mm^{-1}$ plus 10% excess), and an adequate supply of plant nutrients, most importantly N, if such nutrients as P, K, and others are not limiting. Based on some experimental results, on a moderately fertile soil (which supplied 45 kg $ha^{-1}$ N to plant), the fertilizer N to be applied was calculated as 300 kg $ha^{-1}$ to achieve 6 t $ha^{-1}$ yield of pearl millet. Many questions remain unanswered. With this quantity of fertilizer will 6 t $ha^{-1}$ be possible? Is it possible to achieve this level of yield with less fertilizer? Will these practices be profitable?

## La culture du mil—face aux contraintes de l'agriculture intensive (Constraints to Intensive Cultivation of Pearl Millet)

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**et**

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L'optique d'agriculture intensive est un choix de type socio-economique qui implique des contraintes particulieres dont la disponibilite des varietes a haute productivite, de la mecanisation des operations culturales, de la preparation des terrains a la recolte, l'apport d'intrants (engrais mineraux et organiques) et la protection des cultures contre les insectes, les mauvaises herbes et les maladies.

Les premieres reflexions sur l'intensification de la culture du mil menee au Senegal avaient fait apparaitre la necessite de reduire la production de paille des varietes locales a l'instar des hybrides nains a epis relativement longs et gros cultives en Inde qui donnent des resultats tres interessants. Les consequences de cette transformation sur les mils africains etant mal connues, les travaux n'ont pas abouti aux resultats escomptes.

Le bilan des travaux menes de 1975 a 1983 sur le mil au Senegal ont fait ressortir les points suivants :

Les mils de 80 a 90 jours sont plus productifs que ceux de cycle inferieur a cause d'une meilleure valorisation de l'eau. Leur culture n'est cependant envisageable que dans les regions ou les conditions climatiques ne sont pas trop aleatoires.

La paille joue un role significatif dans l'elaboration du rendement. Parmi les composantes de la plante, le poids de chandelles et de 1000 grains sont les seules variables qui contribuent de facon permanente a la production de grains. L'influence de toutes autres composantes de l'architecture varient en fonction des sites. II conviendrait done d'eviter un profil architectural trop strict et de creer des varietes dont la diversite facilite leur adaptation a differents milieux.

Le probleme de l'amelioration du rapport grain/paille n'est pas tres elucide pour le moment mais il semblerait que les variations de celui-ci soient contr616es par les criteres poids de 1000 grains, nombre de chandelles et de talles par plante.

Une meilleure connaissance de l'evolution des populations naturelles de la mineuse de l'epi a permis de conseiller des cultivars a cycle moyen, capables d'echapper aux degats infliges par des insectes.

Malgre l'interet certain du labour sur la production, l'adoption de cette technique par les paysans se heurte a un certain nombre de contraintes d'ordre materiel, temporel et sociologique. Dans l'intensification de la culture du mil, l'effort doit etre porte sur l'affinement des techniques qui retardent la dessication pour permettre aux paysans de pouvoir trouver le temps et la force necessaire de proceder a un labour.

L'enfouissement des pailles permet d'accroitre la productivit6 azotee en sol sableux en ameliorant l'utilisation des engrais par la plante, cependant, il apparalt que la simple restitution des pailles en association avec une fumure NPK adaptee ne permet pas de conserver la fertilite azotee du sol.

Les tentatives d'application des resultats ont montre que la mecanisation dans ce domaine n'est envisageable que dans une perspective de rentabilisation de la culture du mil.

## Constraints to Intensive Cultivation of Pearl Millet (La culture du mil — face aux contraintes de l'agriculture intensive)


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Intensive cultivation of pearl millet crops is faced with certain constraints such as nonavailability of high-yielding varieties, lack of mechanization for cropping operations and postharvest soil cultivation, lack of mineral and organic fertilizers, and lack of protection against insect pests, weeds, and diseases.

Initial efforts at pearl millet crop intensification in Senegal indicated the need to reduce the straw production of local cultivars as has been done with excellent results in India in dwarf hybrids having relatively long and broad heads. However, this modification in African millets did not produce the deserved effect.

Results of the studies on pearl millet from 1975 to 1983 in Senegal have highlighted the following points.

- Due to their more efficient use of water, cultivars that mature in 80-90 d are more productive than shorter-duration material. But they can only be grown in regions where climatic conditions are not erratic.
- Straw plays a significant role in yield development. Head and 1000-grain mass are the only yield components with any stable effect on grain yield. The influence of other yield components varies with location. Therefore varietal diversity for these phenotypically plastic characteristics facilitates adaptation to different environments.
- Improvement of the grain/ straw ratio is not clearly understood; this characteristic is apparently controlled by 1000-grain mass and by the number of heads and tillers per plant.
- A better understanding of the population dynamics of spike worms has enabled the recommendation of medium-duration varieties that can avoid pest infestation.
- Tillage operations, in spite of their beneficial effect on yield, cannot be carried out by farmers who lack equipment and time, and sociological constraints. Crop intensification requires improved techniques that can delay soil dessication, thus allowing more time and effort for tillage operations.
- Plowing in the crop residue increases nitrogen productivity in sandy soils and improves fertilizer use by the plant. However, the incorporation of crop residue combined with NPK fertilizer cannot adequately maintain the nitrogen fertility of the soil.

Attempts to apply the research results show that mechanization can only be envisaged in case of commercial cropping.

# Plenary Session

# Priorities for Crop Protection Research in Pearl Millet

## Diseases

### Downy Mildew

- Intensify host-plant resistance work.
- Conduct basic research on resistance mechanisms.
- Explore possible downy mildew variability between Africa and Asia.
- Global pathogen variability studies should continue at the University of Reading.
- Establish an African multilocational network for disease resistance screening.
- The downy mildew nursery inoculation technique using sporangial and oospore inoculation with both infector and indicator rows seems to be effective, but there are aspects which should be improved individually according to regional requirements.
- There is a need to better understand the biology of the pathogen, including oospore germination and population dynamics.
- Studies of seed treatment using appropriate chemicals should be continued. Systemic fungicides should be used cautiously because the effectiveness of such fungicides could break down rapidly.

### Smut

- Continue research on host-plant resistance.
- There is no need to modify the boot inoculation technique. It should be continued. Materials with adequate resistance are available in breeding programs.
- Resistance mechanisms to smut should be studied.

### Ergot

- Continue breeding for ergot resistance.
- Exploit the possibility to select for ergot resistance based on flowering events, including shorter protogyny.
- Study the biology, genetics, and epidemiology of the ergot pathogen.

### *Striga*

- *Striga* research in West Africa needs to be intensified, including screening and evaluation techniques.

### Rust

- Intensify research on host-plant resistance.
- Clarify the taxonomy of the rust pathogen.
- More information is needed about the epidemiology of rust in Asia and southern Africa.
- Screening and evaluation techniques need to be standardized.

### Screening

- The relative importance of pearl millet diseases in southern and East Africa should be examined and catalogued. Research priorities are suggested for the Indian subcontinent and West Africa (Table 1).

### Management

- Integrated management approaches to control the various diseases of pearl millet, including *Striga*, should be explored.

Table 1. Rankings of research priorities for pearl millet diseases.

| Pathogen | Location | |
|---|---|---|
| | Indian subcontinent | West Africa |
| Downy milew | 1 | 1 |
| Smut | 3 | 3 |
| Ergot | 2 | 4 |
| *Striga* | 5 | 2 |
| Rust | 4 | 5 |

## Genetic Stocks

- Biotechniques to select and preserve disease-resistant materials should be developed and documented.

## Insects

### Data Collection

- Knowledge of pearl millet insect pests is incomplete. Pest surveys to determine the major insect pests and associated crop losses need to be conducted in the pearl millet growing areas of Asia and Africa. Economic thresholds for the major pests such as stem borers, head caterpillars, shootflies, and other locally or regionally important insect pests should be determined.

- Appropriate techniques to assess the extent of losses from major insect pests need to be developed.

- Population fluctuations of important insect pests should be studied in relation to environmental conditions, using appropriate population monitoring techniques (e.g., fishmeal-baited traps for shootfly, and light traps for stem borers, army worms, and head caterpillars.

### Control

- Because chemical and other insect pest control methods are limited, major emphasis should be placed on host-plant resistance. Techniques to screen for host-plant resistance to insect pests should be developed. To accomplish this task, artificial rearing of stem borers and head caterpillars should receive top priority. Mechanisms and inheritance of resistance should be an essential component of crop improvement programs.

- Biological control research to determine the most efficient natural enemies should be started. Efforts should be made to develop simple techniques for encouraging indigenous natural enemies, along with efforts to introduce and evaluate exotic natural enemies.

- An insect-resistance nursery should be assembled and made available to entomologists and breeders.

- Other control methods (e.g., cultural and chemical) may be studied and recommended locally and regionally.

## Birds

- Efforts should be made to develop simple techniques to avoid crop losses caused by birds.

## Support for Researchers

- A map showing the distribution of pearl millet pests (diseases, insects, and *Striga)* should be prepared.

- There is a need for an illustrated booklet detailing pearl millet pests.

- An international working group meeting on pearl millet pest problems should be held in 1989 to design an effective strategy for integrated pest management.

- Special training courses on pearl millet pest management should be available.

## Pearl Millet Breeding Research in Africa

This group first prioritized all production constraints by region and rainfall zone, and then divided them into two groups:

- those which could be alleviated by breeding, and

- those falling into other disciplines, e.g., soil and water management, where there was some possible interaction with variety improvement.

Finally, the group identified:

- cooperative needs, and

- operational constraints to research.

## General Constraints by Region and Broad Rainfall Zones

In both zones, "early" (gero, souna) varieties are grown, but in the drier zone, soil moisture and nutrient deficits become more dominant (Table 2).

### Major Constraints for Breeding Work

#### First Priority

- Stand establishment (emergence and seedling survival under low moisture and high temperature stresses).

- Insect resistance, according to dominant species *(Raghuva* and borers in West Africa, and borers in East and southern Africa).

- Grain production (efficiency of water and nutrient use) and production stability.

#### Second Priority

- Diseases, according to region (more severe in the higher rainfall zone; downy mildew and smut are the most common diseases).

- *Striga* (not important in some localities, very important in others).

#### Third Priority

- Grain quality (acceptability assumes that in the normal course of selection an approximation to local standards can be recovered).

## Breeding Objectives

- Good emergence and seeding survival.

- Maturity slightly earlier than existing local material (in both medium and lower rainfall zones, e.g., the Sahel, western Sudan, and Botswana).

- Yield increases (which generally reflect increased water-use efficiency and nutrient-use efficiency when these are in short supply).

- Yield stability (implies tolerance or adaptability to drought stress).

During breeding several other objectives are normally selected to an acceptable level, e.g., disease

Table 2. Breeders aggregate prioritizations of all on-farm constraints to pearl millet production in Africa.

| Region | Annual rainfall (mm)[2] | Priority[1] Soil moisture | Soil fertility | Diseases | Insects | *Striga* | Stand establish-ment | Weeds | Grain quality[5] |
|---|---|---|---|---|---|---|---|---|---|
| West Africa | 300-600 | 1 | 1 | 2 | 1 | *2* | 1 | 3 | 2 |
| | 600-900[3] | 3 | I | 1 | 1 | 1 | 1 | 2 | 2 |
| Central/East Africa | 300-600 | 1 | 2 | 2 | 2 | 3 | 1 | 2 | 2 |
| Southern Africa | 300-600 | 1 | 3 | 3 | 3 | 2[4] | 1 | I | 3 |
| | 600-900 | 2 | 2 | 2 | 2 | 3 | I | 1 | 3 |

1. 1 = high priority, 2 = medium priority, 3 = low priority.
2. Approximate classes. In some regions 500 mm is a more realistic dividing line between classes.
3. A third millet zone in West Africa with rainfall above 900 mm was recognized, where improvement to millet is subsidiary to sorghum or maize. Any work on millet in this area would be priority 3, and change of maturity type is not recommended.
4. *Striga* of no importance to millet in some areas.
5. In terms of consumer acceptability.

resistance and conformity to an established local grain type class. Other breeding objectives can be added when testing procedures, or criteria become better defined, e.g., *Striga* resistance.

Selection for grain quality should have a high priority, but not enough is known about physical and biochemical kernel characteristics and their relationship to food preparation and taste attributes, to define precise breeding objectives. Research is needed to establish criteria to improve grain quality for storage, dehulling (ease and low percentage of hulls in the grain), processing, and taste. New foods and alternative uses for pearl millet grain are also areas for research.

Long-term basic research should utilize traits from wild pearl millets and other Pennisetae.

## Production Constraints for Collaborative Research

### First Priority

- Soil and water management (includes traction research and weed control).

- Plant nutrition (includes mineral element fertilization, interaction with nutrient-efficient varieties, C/N relationships). Markets (access and stability).

- Technology transfer and extension (including seed production and distribution, and fertilizer availability).

- Bird control (avicides and research into other protection methods).

### Second Priority

- Credit to purchase inputs

- 22ocusts (continued monitoring and early control).

## Cooperative Needs

- Regular exchange of breeding stocks and accessions, especially with ICRISAT regional centers.

- Cooperative regional evaluation trials.

- Research information dissemination network (ICRISAT's Sorghum and Millets Information Center, SMIC).

## Operational Constraints

- Not enough trained staff (training by INTSORMIL and ICRISAT to continue).

- Insufficient operational supplies (selfing bags, staplers, insecticides, fungicides, etc. Possible assistance from ICRISAT).

- Need for more research equipment (threshers, balances, moisture meters, etc.).

- Inadequate seed storage facilities (short-term storage for breeding stocks).

## Pearl Millet Breeding Research in Asia

## Biological Constraints

### Hybrids versus Varieties

The primary breeding priority should be hybrids because they are higher yielding and there is now an opportunity to release hybrids which utilize a diverse range of male-sterile lines. Hybrids should span a range of maturity groups, with differing adaptations to specific agroecological zones.

The second breeding research priority should be open-pollinated varieties.

### Disease Resistance

For both hybrids and varieties, the priority for disease resistance breeding should be downy mildew, smut, ergot, and rust. This order recognizes both the economic importance of the diseases, as well as the difficulties involved in breeding cultivars resistant to them.

Rust should have a higher priority in male-sterile lines to avoid problems caused by this disease in seed production.

### Insect Pests

The major insect pests of pearl millet in Asia are polyphagous, therefore breeding for resistance is probably difficult and has a low priority.

### *Striga*

Breeding for resistance to *Striga* should have a low priority for two reasons: it is a limited problem on pearl millet in Asia, and breeding for resistance to *Striga* in Africa has been difficult.

## Grain Quality

To avoid the replacement of pearl millet by other cereals, priority needs to be given to improving grain quality. Consumer-preferred characters should have the highest priority: large and uniform grain size with a light color. Second priority is milling characteristics: corneous endosperm and reduced nutrient loss are the most important. Other priorities include nutritional quality, total digestibility, food quality, and storability of the grain and flour.

Alternative food uses need to be examined, including weaning foods and substitutes for wheat and rice in processed foods. Future priorities are breeding for higher protein and oil content.

## Abiotic Stresses

Two priorities were identified: breeding for tolerance to drought stress, and improved ability of the seedling to merge and establish.

## High Input Agriculture and Mixed Cropping

Breeders should pay attention to input-responsive genotypes for intensive agriculture, and to genotypes suitable for mixed cropping.

## Forage

The first priority for breeding forage-type pearl millet is profligacy in early-maturing varieties. The second priority is for the plant to stay green after grain filling. There is a need to use *P. purpureum* types, which the ICRISAT Genetic Resources Unit can provide to breeders in Asia. Finally, multiple species crossing should be investigated.

# Agronomic Research Needs in India

## Fertility Management

### Nonorganic Fertilization

Future research on nonorganic fertilization should be on need-based fertilization based on laboratory analysis of field soil samples. Fertilization research should focus on the entire cropping system rather than on single crops.

### Biological Fertilization

Recent encouraging work on biological fertilization should continue with both applied and basic work on nitrogen-fixing organisms, especially *Azospirillum,* and vesicular-arbuscular mycorrhizae. Applied work includes both prediction of and returns to response to innoculation and better methods of inoculum production. Basic work includes studies on the role of the host genotype and the possibility to modify the system this way, plus additional microbiological work on species, mode of action, etc.

## Soil Management

Further research on land management for more efficient rainfall use was recommended. This includes both large scale watershed management for water harvesting and erosion control, and field-scale land management to increase the available water. An additional suggestion was to do research on simple, low-cost agricultural implements to place seed and fertilizer and to manage the soil surface.

## Crop Management

The group felt that most of the necessary basic work on crop management (plant populations, row spacing, etc.) has been done in India.

## Systems Research

### Cropping Intensity

Another recommendation was for research to increase cropping intensity utilizing pearl millet, along with various market or industrial crops (e.g., cluster bean), and a broader range of pulse crops.

#### Agroforestry

The potential of more intensively managed agroforestry systems should be explored for both arid and semi-arid zones, including evaluation of a wider range of tree species.

## Research on Utilization/Quality

Research on additional uses of pearl millet, particularly on its processing and use as a poultry and ruminant feed was strongly recommended.

Research to improve the quality of pearl millet stover as an animal feed, possibly utilizing the non-scenescent trait as in sorghum, for areas where millet stover is by default an important feed stuff, was also recommended.

## Agronomic Research Needs in Africa

These recommendations were made by scientists from Burkina Faso, Mali, Niger, Sudan, and Malawi. They are not presented in order of priority.

## Fertility Management

### Phosphorus

Several studies on phosphorus requirements indicate that pearl millet yields improved markedly with relatively low levels of phosphorus added to the soil, but the question of why the technology has not been adopted by farmers is still unanswered. Lack of fertilizer supplies or inadequate infrastructure were two suggestions. How representative is phosphorus deficiency in the main millet growing areas of the Sahel?

#### Nitrogen

Although nitrogen fertilizer is strongly recommended in Malawi, the appropriate dosage and timing, especially in areas with erratic onset of rains, is still not well known. Previous studies were mainly based on fertilizer formulations for cotton and maize, which may be inappropriate for pearl millet.

### Mycorrhiza

The group felt that research on mycorrhizal-phosphorus relationships are still in the early stages and should be continued at ICRISAT Center.

## Soil Management

Research on tillage and land preparation by animal traction is already underway, and should continue in order to examine the long-term consequences. Draft power is still not popular in many regions, and appears to be more prevalent in the cultivation of cash crops. Implements are available but there is no adequate testing under farmer conditions. Lack of cattle or donkeys may be one reason for poor adoption rates.

## Soil Conservation

As pearl millet conservation is extended to more fragile ecologies, it is important to impose appropriate land-management practices, e.g., contour bunds to prevent further degradation, and to improve soil structure and fertility. Strip vegetation, terracing, and agroforestry are high priorities as soil conservation measures.

## Crop Management

Some work on plant populations and weed control, which are dependent on rainfall and soil fertility, is still required, especially in the SADCC region. This work can be done by the national systems, but international centers should take a major role in the work on *Striga* control.

## Systems Research

### Intercropping

Intercropping studies of cotton/ maize, maize/ millet, and millet/legumes have probably reached the stage where only fine-tuning trials are required, e.g., fitting improved cultivars to existing practices. However, the ecological limits of intercropping are not well defined. Introduction of new crops as stylosanthes and other forage crops into millet-based systems should receive greater attention.

## Agroforestry

Agroforestry research is receiving renewed interest and multilocational trials have started to define the ecological zone suitable for agroforestry. Major issues are suitable tree species and appropriate spacing.

## Livestock Interactions

Livestock interaction depends on an adequate supply of fodder during the dry season, which has serious implications for the adoption potential of draft power. ILCA should be the main center for such studies.

# Pearl Millet Production Survey

# Survey of Pearl Millet Production and Utilization

The following tables are a compilation of responses to questionnaires that were sent to selected invitees of the International Pearl Millet Workshop. They describe details of production and utilization of pearl millet in all countries for which information was received. Regretably, responses were not received from all, and as a result information on some major production areas is missing. However, in spite of such gaps, this exercise does represent a global effort by many workers (Table 1) to provide information on aspects of pearl millet production and utilization that may not be readily available.

Table 1. Country and state (in India) representatives who supplied information for the survey on pearl millet production and utilization.

| Country/ Indian state | Name | Country/ Indian state | Name |
|---|---|---|---|
| Botswana | Louis Mazhani | Kenya | L.R. M'Ragwa |
| C6te dTvoire | M.B. Beninga | Malawi | C.F.B. Chigwe |
| Gambia | Albert Cox | Niger | Botorou Ouendeba |
| Ghana | W. Schipprack and M.S. Abdulai | Senegal | AT. NDoye |
| India | | Sudan | R.P. Jain and El Hag H. Abu-el-gasim |
| Andhra Pradesh | D. Narayana and R.R. Subba Reddi | | |
| Gujarat | H.R. Dave | USA | G.W. Burton |
| Haryana | R.L. Kapoor and S.D. Chamola | Zambia | Bholanath and F. Muuka |
| Karnataka | M.S. Patil | Zimbabwe | F.R. Muza |
| Madhya Pradesh | G.S. Chauhan | | |
| Punjab | D.S. Virk | | |
| Tamil Nadu | V. Subrahmanian | | |
| Uttar Pradesh | U.S. Santoshi | | |

Table 2. Production area ('000 ha) and production (in t and kg $ha^{-1}$) of pearl millet grain, during 1983-85, in some countries of Africa and the USA.

| | Production area ('000 ha) | | | Production (t) | | | Production (kg $ha^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| Country | 1983 | 1984 | 1985 | 1983 | 1984 | 1985 | 1983 | 1984 | 1985 |
| Africa | | | | | | | | | |
| Botswana | 16.5 | 16.7 | - | 435 | 715 | - | 30 | 40 | - |
| Cote d'Ivoire | 54 | 63 | 63 | 26000 | 41 000 | 41000 | 481 | 651 | 651 |
| Gambia | 19.4[1] | 21.3 | - | 14 360[1] | 23004 | - | 740[1] | 1080 | - |
| | 12.3[2] | 11.6 | - | 18 450[2] | 13 920 | - | 1500[2] | 1200 | - |
| Ghana | 175 | - | - | 40000 | - | - | 229 | - | - |
| Kenya | 35 | 48 | - | 10 700 | 12421 | - | 310 | 260 | - |
| Malawi | 12.5 | 15 | 13 | 15000 | 15000 | 11 700 | 1200 | 1000 | 900 |
| Niger | 3000 | 3058 | 3153 | 1 269 000 | 785900 | 1444000 | 420 | 260 | 460 |
| Senegal | - | - | 1000 | 585000 | - | 700 000 | - | - | 700 |
| Sudan | 1000 | 1310 | 1580 | 248000 | 158510 | 474000 | 250 | 120 | 300 |
| Zambia | 10.0 | 9.7 | 11.4 | 6 350 | 6 752 | 9721 | 635 | 696 | 853 |
| Zimbabwe | 0.4 | - | - | 80 | - | - | 200 | - | - |
| USA | 500 | 500 | 500 | ------ Forage only ---- | | | | | |

1. Early millet.
2. Late millet.

Table 3. Distribution of pearl millet, and rainfall, by district, in some African countries and the USA.

| Country | Area ('000 ha) | Rainfall (mm) |
|---|---|---|
| Africa | | |
| Botswana | Mainly grown in the northeast | 400 |
| Cote d'Ivoire | Northcentral area | 1300 |
| | Northeast area | 1100 |
| | Northwest area | 1500 |
| Gambia | Grown in all areas except eastern and western ends | - |
| Ghana | Guinea savanna (late millet) | 1200 |
| | Sudan savanna (late and early millet) | 950 |
| Kenya | | |
| Kitui District | - | <300 (short rains) |
| Machakos District | - | 300 (short rains) |
| Meru and Embu Districts | | <300 (short rains) March-May rains not reliable for millet |
| Malawi | | |
| Lower Shire Valley | - | 700-900 |
| Luchenza Phalombe Plain | - | 800-900 |
| Symon and Neno | - | 1000 |
| Karonga and Chitipa | - | 900-1200 |
| Niger[1] | | |
| Niamey | 781 | 520 |
| Dosso | 646 | 580 |
| Maradi | 643 | 480 |
| Zinder | 589 | 480 |
| Tahoua | 439 | 480 |
| Senegal | | |
| North | - | >400 |
| North central | - | 400-600 |
| South central | - | 600-800 |
| Sudan | | |
| North Kordofan | - | 150-400 |
| South Darfur | - | 400-750 |
| North Darfur | - | 150-400 |
| South Kordofan | - | 400-600 |
| Zambia | Western province | - |
| | Southern province | - |
| Zimbabwe | | |
| Region III (south and southeast borders) | - | 650-800 |
| Region IV (west and south central) | - | 450-650 |
| USA | Major production areas are in Arizona and Texas | - |

1. 1985 data.

Table 4. Major constraints to production and general pearl millet production trends (1960-85) in some African countries and the USA.

| Country | Major constraints to production | General production trends (1960-85) |
|---|---|---|
| Africa | | |
| Botswana | Quelea birds, drought. | Production generally decreased, may be due to drought. |
| *Cote* d'Ivoire | Absence of improved varieties and fertilizer, and crop losses due to diseases and insects. | From 1960 to 1979 millet production remained static (45 000 t). In 1980-83 it fell to 30000 t, but since 1984 there has been an increase in production due to government policies that have favored millet production. |
| Gambia | Weeds, untimely availability of inputs, pests and diseases, low rainfall and fertility. | Increasing trend, but fluctuated during some drought years. |
| Ghana | Poor soil fertility, erratric rainfall, and downy mildew. | Production is generally decreasing because of constraints and competition with other cereal crops such as rice and maize. |
| Kenya | Severe drought, armyworms, birds, poor seed set in local cultivars, poor husbandry, and lack of improved seed production and distribution. | Production about 30000 ha annually, but yields low without improved seed and crop management. Kenya has no dryland seed multiplication agent. |
| Malawi | Lack of improved varieties, competition for land with sorghum, lack of recommendations on major cultural practices. | Millet production increased following drought because large areas are sown during years following maize failure. |
| Niger | Drought in the beginning and end of crop cycle, sandstorm in the beginning of the cropping season, highly eroded soils depleted of organic matter, damage by birds and pests *(Raghuva).* | Millet production varies considerably from year to year due to the unpredictability of the rainy season and fluctuations in the quantity and distribution of rainfall. Production dropped from 1 325000 t in 1983 to 769000 t in 1984 but rose in 1985 to 1 450 000 t. |
| Senegal | Low yield, low grain/straw ratio, drought, diseases, insects, *Striga.* | 475 000 to 750 000 t with an average of 665 160 t or 79.7% of the mean target. In the Seventh Plan, the production target is fixed at 650 000 t. The annual increase in production is 0.62%, lower than that of the population growth (2.8%). |
| Sudan | Low and erratic rainfall, low soil fertility, unimproved cultural practices, unimproved cultivars, insects and pests, socioeconomic constraints. | Area is increasing, but yield per hectare is decreasing, mainly due to drought, and low soil fertility due to continuous cultivation and low or no fertilizer use. |
| Zambia | Lack of improved varieties and agronomic practices. | - |
| Zimbabwe | Lack of fertilizers, no improved varieties for general release, no hybrids grown yet, not much use for pearl millet, although price is high. | General production decrease up to 1981 as maize production increased, but millet increased from 1980-85 because of drought. |
| USA | Temperature in the Texas panhandle. | Increase due to demand and new companies producing millet. |

Table 5. Name, designation, year of release, and release documentation of pearl millet cultivars in some countries of Africa and India.

| Country | Cultivar name | Designation | Release year | Release documentation |
|---|---|---|---|---|
| Africa | | | | |
| Botswana | Serere 6A | Composite | 1960 | |
| Gambia | | | - | - |
| Ghana | Naara | Variety | | |
| | Zaa | Variety | | |
| Kenya | KAT/PM-I | Composite | 1983 provisional release | |
| | KAT/PM-2 | Variety | 1985 provisional release | |
| Malawi | Tomali local | Variety | Early 1950s | Annual Report of Ngabu Research Station, 1978-79 |
| | Nigerian composite | Composite | 1979 | |
| Niger | T18L | Variety | 1984 | Catalogue des varietes recommandees de mil, sorgho, niebe'et autres cultures du Niger. INRAN 1985. |
| | DG-$P_1$ | Variety | 1984 | |
| | GR-$P_1$ | Variety | 1984 | |
| | CIVT | Variety | 1978 | |
| | HKP | Variety | 1976 | |
| | $P_3$ Kolo | Variety | 1966 | |
| | $HKP_3$ | Variety | 1983 | |
| Senegal | Souna III | Variety | 1972 | Etasse, C. 1965. Amelioration du mil Pennisetum Senegal. Agronomie Tropicale 20(10):976-980. |
| | IBV 8001 (ICMV 2) | Variety | 1982 | |
| | IBV 8004 (ICMV 3) | Variety | 1982 | Etasse, D. 1969. Amelioration du mil Pennisetum au CRA de Bambey, etat actuel des travaux et orientations. Communication a la Conference cereale de Zaria, Nigeria du 13 au 16 octobre:l-9. Gupta, S.C., NDoye, T. A., and Andrews, D.J. 1982. Pearl millet improvement in Senegal. 3e reunion FAO/SIDA Nairobi (Kenya) 6-24 juin. |
| Sudan | Ugandi | Composite | 1981 | |
| Zimbabwe | RMP-1 | Variety | 1986 | |
| USA | Tifleaf 1 | Hybrid | 1980 | Burton, Glenn W. 1980. Registration of pearl millet inbred Tift 383 and Tifleaf 1 pearl millet (Reg. PL8 and Reg. No. 60). Crop Science 20:292. |
| | Gahi 3 | Hybrid | 1977 | |
| | Goldkist 500 | Hybrid | Commercial | |
| | Goldkist 600 | Hybrid | Commercial | |
| | Milhy 90 | Hybrid | Commercial | Burton, Glenn W. 1977. Registration of Gahi 3 pearl millet (Reg. No. 40). Crop Science 17:345-346. |

Table 6. Extent of cultivation of released pearl millet cultivars in some African countries and the USA, and their ability to produce certified seed.

| Country | Extent of cultivation of released cultivars | Country's ability to produce certified seed |
|---|---|---|
| Africa | | |
| Botswana | Serere 6A widely used | Weak seed production program due to lack of trained staff. |
| Cote d'Ivoire | | At present no facilities for certified seed production. |
| Gambia | - | Seed multiplication unit within Department of Agriculture. |
| Ghana | - | The Ghana Seed Company is capable of producing certified seed. |
| Kenya | Farmers expected to plant these cultivars in the future | Kenya Seed Company and other private seed companies are supposed to multiply seed, but are not willing to take the risk. |
| Malawi | Nigerian composite has been preferred to Tomali Local. Estimated 60% planted to the released variety. Main problem is availability of seed. | The National Seed Company of Malawi has shown interest in producing certified seed. |
| Niger | < 10% | Niger has an excellent seed production structure: 1 seed farm, 5 seed multiplication centers, contract farmers. One drawback is the absence of seed law. |
| Senegal | 5% (500 ha) | Breeders' and foundation seed production is undertaken by research organizations. At present, foundation seed is produced by the national seed production service. |
| Sudan | < 5%. Shortage of released variety. | Able to produce certified seed provided seed propagation facilities are strengthened. |
| Zambia | - | Good prospects. Zambia Seed Company produces the required seed of all crops |
| Zimbabwe | Not yet released | Excellent |
| USA | 90% | Good |

Table 7. Government price support, price at harvest, and percentage of pearl millet grain production sold through government and private channels, in some African countries.

| African country | Govt. price support (US$ $kg^{-1}$) in 1985 | Price per kg at harvest (US$ kg-') in 1985 | Production (%) sold through: Government channels | Private channels |
|---|---|---|---|---|
| Cote d'Ivoire | - | 0.14 | 0 | 100 |
| Gambia | - | - | 10 | 90 |
| Ghana | - | 0.12 | 0 | 100 |
| Kenya | 0.06 | 0.75 | 5 | 45 |
| Malawi | | 0.05-0.06 | Nil | 10-15 |
| Niger | 0.20 | 0.12-0.14 | - | - |
| Senegal | 0.20-0.25 | 0.15-0.20 | - | 10 |
| Sudan | - | 0.25 | 0 | 100 |
| Zambia | 0.17 | 0.25 | 5 | 95 |
| Zimbabwe | 0.15 | 0.15 | 50 | 50 |

Table 8. Principal uses and percentage of pearl millet grain consumed on and off farms in some African countries and the USA.

| Country | Principal uses (rank order) | Grain consumed (%) | |
|---|---|---|---|
| | | On farm | Off farm |
| Africa | | | |
| Botswana | Grain (human food); Fodder (stover) | Almost all | |
| Cote d'Ivoire | Grain (human food); Building material; Grain (livestock feed) | 40 | 60 |
| Gambia | Grain (human food); Building material; Grain (livestock feed); Fodder (stover) | 90 | 10 |
| Ghana | Grain (human food); Building material; Fodder (stover); Grain (livestock feed) | 90 | 10 |
| Kenya | Grain (human food); Fodder (stover); Building material | 5 | 90 |
| Malawi | Grain (human food); Grain (livestock feed); Building material; Fodder (stover) | 85-95 | 5-15 |
| Niger | Grain (human food); Fodder (stover); Building material; Grain (livestock feed) | 90 | 10 |
| Senegal | Grain (human food); Grain (livestock feed); Fodder (stover) | 90 | 10 |
| Sudan | Grain (human food); Building material; Fodder (stover); Grain (livestock feed) | 60 | 40 |
| Zambia | Grain (human food); Grain (brewing); Building material | 99 | 1 |
| Zimbabwe | Grain (human food); Grain (livestock feed); Building material; Fodder (stover) | 80 | 20 |
| USA | Fodder | - | - |

Table 9. Government price support (Rs $kg^{-1}$)[1], price at harvest, and percentage of production sold through government and private channels in some Indian states.

| Indian state | Govt. price support (Rs $kg^{-1}$) in 1985 | Price (Rs) per kg at harvest in 1985 | Production (%) sold through | |
|---|---|---|---|---|
| | | | Government channels | Private channels |
| Andhra Pradesh | 1.30 | 1.00±0.10 | Nil | 100 |
| Gujarat | - | 2.25 | - | Majority |
| Haryana | 1.30 | 1.65 | Nil | 100 |
| Karnataka | - | 1.70 | 10 | 90 |
| Madhya Pradesh | 1.34 | 1.50 | Nil | 100 |
| Punjab | 1.35 | 1.54 | - | Majority |
| Tamil Nadu | - | 1.35 | Nil | 100 |
| Uttar Pradesh | 1.30 | 1.40 | Nil | 100 |

1. Rs. 12.00 = US$21.00

Table 10. Area planted to released varieties, principal uses, and percentage of pearl millet grain consumed on and off farms in some Indian states.

| Indian state | Area planted to released varieties (%) | Principal uses (rank order) | Grain consumed (%) | |
|---|---|---|---|---|
| | | | On farm | Off farm |
| Andhra Pradesh | 50-60 | Grain (human food)<br>Grain (livestock feed)<br>Building material<br>Fodder | 60 | 40 |
| Gujarat | 85-90 | Grain (human food)<br>Fodder<br>Grain (livestock feed) | - | - |
| Haryana | 60 | Grain (human food)<br>Grain (livestock feed)<br>Fodder | 50-80 | 20-50 |
| Karnataka | 80 | Grain (human food)<br>Grain (livestock feed)<br>Fodder | 20 | 80 |
| Madhya Pradesh | 72 | Grain (human food)<br>Fodder | 0 | 100 |
| Punjab | 60-70 | Fodder<br>Grain (human food)<br>Grain (livestock food) | 20 | 80 |
| Tamil Nadu | 88 | Grain (human food)<br>Grain (livestock food)<br>Fodder<br>Building material | 43 | 57 |
| Uttar Pradesh | 4 | Grain (human food)<br>Fodder<br>Grain (livestock feed)<br>Building material<br>Fuel | 0.5 | 99.5 |

Table 11. Major production constraints and general production trends (1960-85) of pearl millet in some Indian states.

| Indian state | Major production constraints | General production trends (1960-85) |
|---|---|---|
| Andhra Pradesh | Millet grown on poor and marginal soils. Resource-poor farmers. Erratic rainfall. Uncertain market trends. | Production was stable from 1960-70 at almost 300000 t grown on just under 600 000 ha, but increased to 336 000 t on 60 000 fewer hectares when high-yielding cultivars were introduced in 1980. In 1984 production dropped to just over 200000 t as farmers switched to other, higher value, crops. |
| Gujarat | Erratic and scanty rainfall, diseases, and allocation of marginal land to millet. | Average yield in 1960-61 was 334 kg $ha^{-1}$, which has increased yearly to a record of 1028 kg $ha^{-1}$ in 1981-82. Possible reasons include use of hybrid seed and recommended cultivation practices. |
| Haryana | Inadequate supply of reliable HYV seed at the required time. Poor plant populations and stand establishment. Lack of adoption of suggested agronomic practices such as proper spacing, thinning, filling gaps, weed control, rouging diseased plants, and fertilizer use. | Area remained almost stable, but production was low and fluctuated highly. Compound production growth rate of 1.5%. High-yielding varieties responsible for increased productivity. |
| Karnataka | Lack of irrigation, timely monsoon rains, improved seeds, and farmers' poor economic conditions. | Possible reasons for increasing production trend: varietal improvement (yield and disease resistance), increased irrigation, and adoption of improved technology. |
| | seed not available. High cost of fertilizer limits its use. Lack of proper technology to maintain adequate plant stand and control weeds. Varieties suitable for mixed cropping not available. | Production area is decreasing as irrigation is introduced in the tract, but production is increasing by use of improved varieties and technology. |
| Punjab | Downy mildew epidemic in 1984 and 1985, use of marginal land, quality seed not available, local varieties grown widely, ergot susceptibility. | Area decreasing. Productivity stable at about 500 kg $ha^{-1}$, from 1960-65, but doubled 500 kg $ha^{-1}$, from HB1 was released. Yields dropped as the hybrids became susceptible to downy mildew in 1971-75, but rose again in 1976-80 as new hybrids were introduced. Yields averaged 1143 kg $ha^{-1}$ during 1980-85 as more new hybrids and composites were introduced. |
| Tamil Nadu | Lack of suitable hybrids (BK 560 now susceptible to downy mildew). Stores poorly under ordinary storage conditions; traders dictate prices and buy low. No industries based on pearl millet as for maize and finger millet. Reduced demand due to urbanization and increased income of consumers. | Decreasing trend from 1962-63 to 1974-75, but increased until 1978-79, from which time the trend has been decreasing again, perhaps due to competition from other crops. Traders reluctant to purchase WC-C75 (replacing BK 560) because they believe it stores poorly. |
| Uttar Pradesh | Use of local and low-yielding cultivars, delayed sowing, totally rainfed cultivation, low plant populations, local cultural practices, fertilizer not used, plant protection measures not used, crop grown on marginal land. | Low yields in 1960-61 probably due to heavy rains. Production trend decreased until 1981-82, then increased. Changes apparently due to seasonal fluctuations. |

Table 12. Production area and production of pearl millet grain in tonnes and kg $ha^{-1}$ during 1983-85 in some Indian states.

| | Production area ('000 ha) | | | Production (t) | | | Production (kg $ha^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| Indian state | 1983 | 1984 | 1985 | 1983 | 1984 | 1985 | 1983 | 1984 | 1985 |
| Andhra Pradesh | 493 | 394 | | 293 828 | 205 274 | _ | 596 | 521 | - |
| Gujarat | 1395 | - | - | 1 178 000 | - | - | 845 | - | - |
| Haryana | 781 | 848 | 750 | 506088 | 556 288 | 479 250 | 648 | 656 | 639 |
| Karnataka | 582 | 589 | 456 | 221 000 | 319000 | 181 000 | 380 | 542 | 397 |
| Madhya Pradesh | 170.6 | 172.2 | 161.7 | 104 902 | 122613 | 125 635 | 615 | 712 | 777 |
| Punjab | 42 | 45 | 59 | 50 300 | 55 200 | 60 000 | 1198 | 1227 | 1019 |
| Tamil Nadu | 296 | 295.8 | 366.3 | 375 328 | 334 261 | 405 860 | 1268 | 1130 | 1108 |
| Uttar Pradesh | 954 | 1040 | 954 | 741 000 | 901 000 | 955000 | 777 | 866 | 1001 |

Table 13. Rainfall and production in major pearl millet growing regions, in some Indian states.

| State | Area ('000 ha) | Production ('000 t) | Rainfall (mm) | State | Area ('000 ha) | Production ('000 t) | Rainfall (mm) |
|---|---|---|---|---|---|---|---|
| Andhra Pradesh[1] | | | | Madhya Pradesh | | | |
| Nalgonda | 106 | 42 | 958 | Chambal | 97 | | 650 |
| Prakasam | 58 | 55 | 741 | Ujjain | 8 | | |
| Visakhapatnam | 55 | 49 | 1125 | Indore | 47 | | |
| Anantapur | 44 | 40 | 551 | Gwalior | 7 | | 800 |
| Mahbubnagar | 43 | 16 | 742 | | | | |
| | | | | Tamil Nadu[3] | | | |
| Haryana | | | | South Arcot | 99 | 145 | 1008 |
| Bhiwani | | | 324 | Tiruchirapalli | 78 | 84 | 622 |
| Mohindergarh | | | 420 | Tirunelveli | 57 | 67 | 599 |
| Hisar | | | 393 | Periyar | 22 | 24 | 664 |
| Rohtak | | | 597 | Salem | 19 | 23 | 710 |
| Jind | | | 269 | Madurai | 18 | 22 | 650 |
| Gurgaon | | | 620 | Ramnad | 26 | 12 | 796 |
| | | | | North Arcot | 21 | 17 | 820 |
| Karnataka[2] | | | | | | | |
| Bijapur | 166 | 92 | 680 | | | | |
| Gulbarga | 160 | 47 | 700 | | | | |
| Raichur | 101 | 88 | 673 | | | | |
| Belgaum | 75 | 19 | 900 | | | | |

1. 1983 data.
2. 1984 data on four districts that encompass 87% of the state's millet-growing area.
3. 1985 data.

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# Participants

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ISBN 92-9066-134-8

ICR 87-0050