SORGHUM
IN THE EIGHTIES

Volume 1

International Crops Research Institute for the Semi-Arid Tropics

Sorghum in the Eighties

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Foreword

In October 1971 in Hyderabad. India an international symposium on sorghum was held which examined and reviewed the then scientific, production, and nutritional knowledge of sorghum as a crop and as a human food.

Almost exactly 10 years later, ICRISAT hosted Sorghum in the Eighties—an international symposium sponsored by USAID Title XII Collaborative Research Support Program on Sorghum and Pearl Millet (INTSORMIL); the Indian Council of Agricultural Research (ICAR); and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

It was felt by the organizers that because so much knowledge and information had been attained in the intervening 10 years, scientists should meet again. Consequently, 245 scientists from 37 countries attended the Symposium from 2 to 7 November 1981 at ICRISAT Center near Hyderabad. They examined and evaluated the achievements made in the last decade, discussed the current problems, and made recommendations for future research and other activities.

The participants showed a critical awareness of sorghum's role as an important cereal for food, feed, construction material, and fuel in the developed and the developing countries. On a world production and utilization basis, sorghum ranks fifth after wheat, rice, maize and barley. About 90% of the total production and 90% of the harvested area are located in 12 countries in Asia, the Americas, Africa, and Oceania.

Sorghum is one of the main staple food grains of the world's poorest people, particularly in the semi-arid tropics (SAT). Over 55% of world sorghum production is in the SAT. Of the total SAT production, Asia and Africa contribute about 65%, of which 34% is harvested in India. Matters of considerable concern are that sorghum production is growing more slowly than population and that the food situation in parts of Africa is rapidly deteriorating.

Situations such as these clearly indicate that more socioeconomic factors will need to be taken into account to guide and influence the direction of future scientific research on sorghum. The deliberations and discussions during the Symposium on factors related to sorghum and its environment, including climate, insects, fungi, and birds; the genetic resources; breeding for improvement; production technology; food quality and utilization; and the socioeconomic issues showed that many studies will still have to be made to further unravel the potentialities of this cereal. Sharp notice has been taken of research fields where there has been little progress in the last 10 years.

A main value of the Symposium has been to determine work priorities for ICRISAT and the national programs in the SAT, and to emphasize the need for continued cooperation with other institutions. Sorghum in the Eighties has been a rewarding Symposium which has not lost sight of the basic objective to increase the yield and production of better sorghum to feed people.

I believe that the Proceedings of Sorghum in the Eighties will be a prominent benchmark for our future studies and perspectives on sorghum in the next decade.

L.D. Swindale
Director General

Inauguration

Chairman: J. C. Davies

Welcoming Address

J. C. Davies*

It gives me great pleasure this morning to welcome you to this Inaugural Session on behalf of ICAR. INTSORMIL, and ICRISAT. The dream of about 2 years ago has culminated in this excellent attendance here at ICRISAT.

The sponsors have been gratified by the great interest, enthusiasm and encouragement received over many months of planning. We trust that you all had pleasant journeys and are fully rested before tackling the full program which the committee has prepared for you. This gathering of sorghum scientists is the largest I can remember and we have been overwhelmed by the intense interest occasioned by the topic, "Sorghum in the Eighties".

I am particularly happy to see so many scientists from the developing world here—some of them are old friends as far as I am concerned and I am pleased to say that I knew them as up and coming students in their pregraduation days. There is a very useful blend of experience represented by workers from the developed world and scientists with a deep and detailed knowledge of the situations regarding sorghum in India and Africa.

I trust that this blend will spark a great deal of debate and discussion over the next 6 days and thereby greatly assist us in our aims in ensuring significant improvements in the sorghum crop, and in the use of the crop as a food in the coming decade. I believe we have the opportunity to make very definite progress towards setting guidelines for research in the next 10 years, in identifying priority problems and in making bold suggestions for alleviating some of the major food supply problems which are known to be looming in the early 1990s for much of Africa and the developing countries of the SAT.

In spite of your full schedule I hope that you will all have the opportunity to see something of the interesting and historic city of Hyderabad and to sample the warmth of its traditional hospitality.

I wish you all a pleasant stay and hope that you all participate to the full in the symposium and extracurricular interactions. If we can help in any way to make your stay more comfortable please ask. Welcome to you all.

• Director for International Cooperation, ICRISAT.

Inaugural Address

L. D. Swindale*

It is a pleasure to add my word of welcome to that of the Chairman and to wish you well in this International Symposium on Sorghum. It is my pleasant duty to send this symposium on its way.

All of you assembled here are experts in one aspect of sorghum improvement or another and many of you are fully aware of the needs and challenges that relate to this important food and feed crop. I do not intend to try in this address this morning to review all those needs and challenges. Others will do it much more knowledgeably and expertly than I could.

I would, however, like to illustrate the issues by talking about the situation here in India in the hope and belief that what I say will have some relation to the conditions and circumstances elsewhere in the world. In the latter portion of my address I will speak of the contribution of ICRISAT to the work that needs to be done.

You are aware I am sure of the agricultural miracle that has occurred in India in recent years. A recent article in the New York Times said that India, once written off as a hopeless case, has almost tripled its food production in the last 30 years and now has a comfortable reserve for future bad years. Recently I read an article by an American writer who predicted that India could become the world's number one producer of grain in the near future which is quite a change from a basket case to a bread basket in 30 years.

The success that has been achieved has brought with it an improved infrastructure, input supply, and an adequate market strategy even if it is not perfect. We can believe that a reasonable rate of progress will continue, that periodic droughts will be withstood, and that an agricultural base for the improvement of other sectors of the economy now exists. One clear illustration of the solidity of the established agricultural sector is the manner in which the country weathered the 1979/80 drought, described by many as the worst drought of the century. On several occasions I have amazed people by informing them that India sustained the worst drought of the century in that year. They did not know, had not heard about it, there was no starvation, no deaths, no catastrophe, and no massive food aid from foreign countries. The world press finding nothing bad to write about, wrote nothing, and the world remained unaware.

This is not to say, of course, that the worst drought of the century passed without trace. Many problems were caused—a draw down in food stocks, the loss of hydroelectric energy, reduced utilization of industrial capacity, and severe inflation. Further droughts in several areas of the country last year aggravated the problem and lengthened the recovery period. It will take a while for recovery to be complete but the prospects for this year's harvest seem very good and this should put 1979/80 into history. India, as the Prime Minister of India was quoted as saying at Cancun, Mexico, recently, is again poised for take-off for rapid development, and rapid reduction in poverty.

Agricultural progress must continue in this country indeed at a greater rate than ever before. Plans to ensure that this will be done *are* in hand and embodied in the chapters of India's Sixth Five Year Plan. A compound growth rate of 5.2% is projected for agricultural production for the Sixth Plan period, the same figure that is projected for growth in the economy as a whole. The plan reads very well, all the interlocking calculations have been done, the targets and projections seem to make sense, the general tone of the document is optimistic and confident, and yet it may not be enough.

FAO, in a recent document prepared for the Seventh Session of the World Food Council.

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estimates that world cereal production needs to increase at 4% per annum to meet consumption requirements or at a greater rate if stocks are to be replenished. The Indian Planning Commission projects only a 3.6% growth in cereal production over the Sixth Plan period. The difference of 0.4% is significant because India is such an important nation in the world grain picture. Nonetheless, the Indian figure itself must be considered somewhat optimistic. At no time in the last 30 years has the growth rate in cereal production for any five-year period reached 3.6%. Mostly it has been below 3%. Can India then do more? Can it reach its own targets? Can it exceed them? Can it reach a growth rate of not 4% but 4.6% instead of 3.6% and thus supply grain to other nations and contribute to the replenishment of world food stocks? If this is possible at all. it is most likely to occur in those areas where plan projections are equal to or below recent performance trends. This is the case for sorghum. The Sixth Plan projects a compound growth rate of 2% per year for sorghum production. Over the last 7 or 8 years, production has increased at nearly 7%—about 3 times the projected rate. More importantly perhaps, yields per hectare have increased at more than 3 times the above rate, more than 6%, meaning that production of sorghum could be increased to 3 or 4% per year even if the area of land used for the crop were reduced.

This is not true for rice or wheat, the two major cereal crops of the country. The rates of increase of yield per hectare for those two crops are currently less than the projected rate of production increase shown in the Plan. Thus greater production could only be obtained with these crops by increasing the area of land and that means increasing irrigated land with all the heavy costs involved.

To increase sorghum production in this country it will be necessary to bring about the spread of improved cultivars, particularly hybrids, along with fertilizers in the rainfed areas where sorghum is mainly grown.

The combination of genes for reduced plant height and susceptibility to lodging with genes for responsiveness to added nutrients which resulted in quantum jumps in the yields of wheat and rice in irrigated agriculture are also proving successful with sorghum in rainfed conditions. Improved varieties and hybrids significantly outyield local varieties in most years in most parts of the country. The cost of purchasing improved seeds is small for sorghum and the benefits are substantial. The ratio of benefit to added cost is often in excess of 10—by all standards sufficient to ensure widespread adoption. However, satisfactory grain quality and levels of disease and pest resistance are necessary in combination with the high yields to make the improved cultivars attractive to farmers. Although year-to-year variability in yield is higher for hybrids than for local varieties, the yield gains and other characteristics of good cultivars are sufficient to persuade farmers to take the higher risks involved.

There is also much evidence to show that fertilizer used alone on local cultivars is economic in the semi-arid regions of India. Several hundred experiments on cultivators' fields with sorghum, maize, and pearl millet in rainfed areas have given average gains of 14 kg grain per hectare per kg of nitrogen, and 7 kg grain per kg of P_2O_5. Benefit to cost ratios are 3 or better.

Soil type and particularly water-holding capacity of the soil have significant effects on the efficiency of fertilizer use. Crops grown on the same soil in the rainy season will usually have higher fertilizer-use efficiencies than crops grown in the dry season on receding soil moisture.

Although the above statements would suggest that seeds alone or fertilizer alone would be satisfactory lead practices for increasing production, the absolute yield gains from a single practice are not sufficient to achieve the growth rates required. And there are in the literature and in practice, sufficient examples where fertilizer alone added to local varieties, did not provide significant improvements or did not cover the additional cost involved. The negative results are sufficient to feed the farmers' fears and to deter government agencies from recommending the application of fertilizers to local cultivars particularly in the rainfed regions.

However, the combination of improved seeds and fertilizers does provide the level of additional yield required and gives positive results and beneficial results consistently at a benefit cost ratio of 3 or more. The practice can be and should be recommended with confidence.

There are some problems however. Firstly the seed; India acknowledges its inability to produce enough improved seed for the farmer. This is aggravated in sorghum because some of the cultivars that are preferred have seed production problems. In fact there are very few hybrids in sorghum available to the farmer, at least few that he is willing to use. There are perhaps three or four for the rainy season crop and one or two at the most for the winter season crop. All of them have scope for improvement, two of them, as I said, have seed production problems. I do not say this to belittle the work that has been done. As I have already shown, the improvement in sorghum yield and production over the last few years in this country has been quite spectacular, and the people who have contributed to this have every reason to be satisfied with and proud of their contribution. But there is plenty more work to be done and there is a lot of room for additional research. There should be now in India a wider array of varieties and hybrids for the farmer to choose from in different districts.

Fertilizer supply is even more of a problem. Demand far exceeds national production. Distribution tends to be only to those areas where the marketing networks already exist. Interior villages in the country do not have access to the input that they so desperately require. The Government has recently introduced a scheme to subsidize the transportation cost of fertilizer to every block headquarters in the country, that is, to 5500 primary distribution points from north to south and east to west. This should help greatly to improve the access of farmers to fertilizer.

Another problem, of course, is cost. Although benefits substantially exceed the additional costs, the added costs themselves are significant. They range from about Rs.400 per hectare to Rs.1000 per hectare, and this is a substantial deterrent to the small farmer or the marginal farmer. They must have access to credit if they are going to benefit from the technologies that are now available to them.

The lead practices of improved seeds and fertilizers, although being satisfactory beginning strategies throughout the rainfed areas, will have only limited success if they are not properly combined with the rest of the package, to take account of the basic climatological and soil characteristics area by area, district by district and region by region, to assure stability, ameliorate some of the effects of drought, and increase food production per unit of land and capital.

I now wish to talk about ICRISAT's probable contribution to improving sorghum in the eighties. What is it that we here are best able to do? Our mandate and objectives will be well known to nearly all of you. If you do not know them, please obtain a brochure about ICRISAT and learn about our work in general. We work to improve sorghum, pearl millet, pigeonpea, chickpea and groundnut, to develop farming systems for the seasonally dry semi-arid tropics, to identify socioeconomic constraints to agricultural development in this climatic zone and to assist national and regional research programs, to operate training programs and to assist extension activities.

That mandate statement covers a lot of ground. It includes everything that we are likely to do. Obviously at any one time we must focus and concentrate on a portion only of the broad mandate. For the next 10 years, during the eighties, our Governing Board has agreed that ICRISAT will focus particularly on the small farmer of limited means, farming his land with few inputs and basically in rainfed conditions.

In addition to serving the small farmer, however, we will also serve all the users of our five crops wherever they are located. We are, for example, working on one of the most serious diseases of sorghum, sorghum downy mildew, and to the extent that we are successful in our work, obviously we serve all the people who are troubled by this disease.

Although the growers and producers of sorghum are then our target group, you, the scientists, who are interested and working on sorghum production, are our immediate clients, the direct users of our outputs and to a lesser extent, we also serve your extension and action agency counterparts.

Much of our research must be designed to serve your needs. ICRISAT, for example, as a general policy, does not release named cultivars. We release much breeding material for scientists to use. We involve you in our planning and we plan our work to complement your work. We try through example and cooperation to improve the quality and effectiveness of research, particularly in the developing world and we also try to strengthen and improve institutions.

We have established cooperative agreements with five universities in this country and with several research institutes in other countries.

Our objectively verifiable indicators of output —to borrow a term from USAID—are seeds, new technologies, reports of new concepts and methods, and graduated trainees. Initially our outputs are scientific and technical inputs to the client group. In time they will appear as outputs to the target groups themselves but through your channels rather than ours.

I have mentioned that we do release some finished cultivars in various countries; particularly in Africa, more so than in Asia. The countries below the Sahara do not yet have enough trained personnel to have extensive networks of research of their own, although I am pleased to say that this position is changing almost every day.

Several of our scientists are employed on special projects in those countries to assist the national programs and to help the national program people develop regional programs. We are sometimes involved in making varieties and selections available to the extension agencies.

We are also conducting many international multilocational trials and through that system you help us and we help you. For those who cooperate with us, it provides a golden opportunity to see what ICRISAT material is like and to make use of it. In India every year we have a field day for each crop to which we invite the national scientists to come and see what our crop looks like, and we always choose the right time when the crop is expressing its characteristic as best as it can. We invite the scientists to choose material that they will find valuable and that they think will be valuable in their programs. Obviously we do not have enough money to invite scientists from all over the world to these annual field days, but through the multilocational trial network the same opportunities exist—perhaps in a more limited sense—for people in other countries to benefit from ICRISAT material by taking it from us and using it in their own programs. We do not ask scientists how they use this material, but we would like to know, and I put in an appeal right now, whether you found the material useful or not, to let us know. It is helpful to us in talking to our donors and Governing Board to know that the material that was taken has proved to be useful.

We also are, of course, much involved in collecting germplasm. We have recently obtained some extremely interesting looking material from southwestern Ethiopia and this will be available in due course for distribution to all who are interested in using it.

In sorghum particularly, we have been very concerned in recent years in trying to find new methods of screening for important characteristics, and this work will continue. It is an important contribution that we can make. Sometimes, because of the large area that we are able to cover with a crop at any one time, we can make faster progress on developing new methods than others can and we are happy to contribute this work.

Most of ICRISAT's reports of our work are found in our own published reports, and I hope, that, if not all of you are on our mailing list now, that you will be on our mailing list before you leave. It is important that you let us know the subjects in which you are interested, give us your name and address, and we will do our best to keep you regularly supplied with ICRISAT's reports. The same is true of our Annual Report. We produce a glossy covered report annually on Research Highlights which is meant for our donors, and for the informed public but we also produce an annual report that is a scientific document and does contain brief but scientifically accurate information. We produce this because we believe that this is a good way for people, particularly in developing countries, with problems of hard currency, to get to know about our work, even if they cannot obtain access to the regular published journals. This is an important document and I hope that most of you will be able to have a copy of our scientific annual report.

We are also involved in organizing conferences and symposia such as this. These are ways in which we can tell you what we are doing, you can tell us, we can together plan an integrated or coordinated program throughout the world and you can tell us what ICRISAT ought to do.

During last week, we had a unique conference here on sorghum grain quality. Those who attended found it extremely interesting because we collected together some very interesting information about the use of sorghum in various preparations and the quality standards that go with those preparations. I do not think anybody else in the world has done this before. I am sure that the proceedings of that conference, when they come out, will prove to be extremely valuable and interesting and should be a foundation for future progress in this very interesting field.

Finally, we contribute by providing training courses. We have a variety of programs under the general heading of training, some of which, of course, are not really training—but are joint scientific investigations between ICRISAT staff and Visiting Scientists. We would like to develop more of these opportunities for such Scientists, although obviously there are limits to the numbers that we can handle at any one time.

We have Research Fellows, people with recent Ph.D's and Master's degrees who come to spend time with us for one to two years; Research

Scholars, who are people doing their graduate studies and come here to undertake the research portion; and Inservice Trainees who are scientists and technicians who come for a cropping season to learn the details and the routine of scientific work in sorghum improvement.

Our facilities for training are becoming somewhat strained but we would like to encourage more Fellows and Scholars from developing countries, other than India. At the moment, most of our Fellows and Scholars from developing countries come from India itself We do not want to shut that off, but we would like to see more people coming from the other countries where sorghum is an important food crop

ICRISAT is a global center for sorghum improvement but it is not *the* global center. The scientific manpower resources available to us to do our global work are less than those that are available for sorghum improvement in India. I would not be surprised if they were less than those available in the State of Texas

So, there are limits to what we can do. We can fulfill our responsibilities only in cooperation with others, with you and your colleagues and counterparts throughout the world.

A major goal of this Symposium must be to consider how to cooperate best to make effective use of each other's time, abilities and knowledge, to strengthen this network of science through the bonds of friendship and common interest.

I hope that the Symposium on Sorghum will be a great success. I have no doubt that during it you will be busy planning a symposium for Sorghum in the Nineties! It is my pleasure to inaugurate this symposium and to wish it well.

Objectives of the Symposium

L. R. House*

This symposium, Sorghum in the Eighties, occurs almost to the day, 10 years after the symposium. Sorghum in the Seventies. Hopefully it will become a 10-year event enabling us as a group of scientists interested in sorghum to take account of what has happened and to better identify what are likely to be our priorities in the future.

The overall objective that we have, as agricultural scientists, is to increase human welfare. An effort has been made in organizing the symposium to include major areas of research, training, and development relevant to this basic objective. There is consideration of varietal and hybrid development, factors that limit production, institutional requirements, quality and nutrition, and socioeconomic considerations. In all of these, there are applied and more basic aspects of importance and for which long-term funding is essential.

An objective of the symposium is to outline the state of the art at the end of the seventies and from this experience identify priorities for the eighties. This is important to what we do and how we work together to do it. An effort has been made to bring together at this meeting scientists from many countries and many disciplines so that from their varied backgrounds there will be a useful interaction and the development and strengthening of relationships.

The Need

The problems of population growth and increase in food production will be detailed in this symposium. That the rate of population growth exceeds that of production (IADS 1980) is of concern. The projections of required increased food production by 1990, the 10-year period that we are considering, make us realize the seriousness of the problem that we as sorghum scientists have to face (Ryan 1981). An objective of this symposium is to help us to better respond to this urgent need.

The Clientele to Whom Our Objectives Must be Relevant

Our basic objective is to make improvements in sorghum production. A major thrust is to the poorest of farmers working in harsh environments with little or no resource base; another thrust is in areas where the environment is good but a technical, more productive agriculture, is yet to develop; yet another thrust is in areas where agriculture is already highly technical and a community of necessary goods and services exists. We should recognize that the farmer, in each instance, is an important end point and as scientists we cannot say that our job is finished when the technology is developed. We must help ensure that our findings assist in solving the production problem in the farmers' field. The important concept is change—we need the imagination to see beyond what is; we must be careful not to lock the farmer into his tradition being ourselves convinced that he has no base for change; we must be prepared to exploit opportunities that begin to make a change and not over-generalize feelings that we must meet all needs simultaneously. One change will bring another. Our community of developments, experiences, and capabilities are mutually supporting and an objective of this symposium is for us to better see how they can be made more relevant to the farmer.

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Cooperation

Most of the problems that we face are complex and can be most effectively solved by cross discipline and cross institutional cooperation. Some institutions have the capability to resolve the more basic issues on which the applied is generated. Others can adapt technology to local needs and identify problems requiring a more basic understanding. Communication is a problem to which we should give consideration. There is a need to develop priorities; and to share ideas, materials, resources, and recognition. This symposium provides an opportunity to evaluate and improve these interactions.

I have long maintained that our germplasm belongs to everyone. Some collect and preserve it, but for the good of all. Every nation interested in sorghum improvement has received seeds from outside and benefited—it is for the common good that our germplasm flows easily. This symposium should endorse attitudes and practices that encourage seed exchange and the continuous need to monitor quarantine requirements to be effective, but not unnecessarily restrictive.

It is not for us just to give priority to our research but to give thought to the speed of accomplishment. Time is important if we are to meet the challenge, and consideration of the rate of accomplishment should figure in our objectives. With limited resources we must balance them across research, development, training, and infrastructure requirements. These are not static needs, and the balance between them will change with time and differ with location. A function of this symposium can be to help gain a perspective among these aspects.

International and National Program Relationships

I have long felt that the development of a variety or hybrid and a package of management practices is relatively an easier part of our task. Midge followed the introduction of an early maturing hybrid and damaged later locals in northern Maharashtra. Fifteen years ago one could rarely find charcoal rot in India—now it is a problem. *Striga* is increasing in severity where the new hybrids are sown, and the entomologists are raising concern about the seriousness of armyworm in India in the eighties. The change in variety and its management brings on an array of problems requiring a fairly sophisticated research capability to solve.

Ultimately an objective is for each sorghum growing country in the world to have its own research capability. Today, some do and many do not. International agencies can assist by generating useful materials and techniques and by placing scientists with the necessary range of skills in strategic locations to adapt and generate new materials and techniques for different environments. Training of different kinds is imperative to success. There is no substitute for a country having adequate research capability—the function of international agencies is to hasten the day when this exists. Countries must look carefully at the deployment of their scientists and develop conditions encouraging their creative capability. This interrelationship is an important issue and will continue to be into the eighties and deserves our consideration.

Technology is not a cure-all. It must be applied if it is to be meaningful. Government policies can encourage or discourage new technology; and expertise within international agencies can be relevant to the development of national policies. Improvement in sorghum production is no exception. I hope that we hear more about this during the coming week.

This symposium is diverse in structure in an attempt to allow us to respond to many relevant facets. An attempt has been made to bring people together from different backgrounds and experiences. We hope that you will all contribute effectively to the objectives of this symposium.

References

IADS 1980. Agricultural development indicators—a statistical handbook. Washington, D C, USA: IADS

RYAN, J. G 1981 Demand projections for 10 year plan. ICRISAT. Aug 3 1981, Inter Office Memorandum

Session 1

Setting the Scene

Chairman: J. S. Kanwar

Co-Chairman: A. E. Kambal

Rapporteurs: Bhola Nath

R. K. Maiti

A Look Back at the 70s

H. Doggett*

My mandate is to look back at the sorghum research situation, and the next speaker will be dealing with production. Let me preface my remarks in this hall by congratulating farmers and scientists in the Indian National Program on the sorghum yield increase of 50% from 484 to 734 kg/ha over 16 million hectares which has been achieved since the "Sorghum in the Seventies" Symposium held here 10 years ago. Improved varieties and hybrids have contributed a lot towards this yield increase.

Two events gave a great impetus to the development of sorghum research during the seventies. The establishment of ICRISAT resulted in a big increase in the number of scientists working in the developing world, as well as greatly increased international support for such research. The implementation of the Title XII legislation in the USA is more recent, but is already resulting in valuable cooperation in breeding, disease, and grain quality work. All areas of sorghum research under study in the U.S. universities will be linked through this program to the developing world, in due course.

We may look forward to an increasing cooperative research program, with the increasing inputs from scientists in Europe, for example, from Britain, France, Germany and The Netherlands which have continued steadily through the seventies, fitting into one coordinated attack on the problems of sorghum and sorghum growing which require research.

The main need, which has been increasingly realized during the seventies, is for strong national agricultural research programs. Only the national programs can do the final research and development appropriate for its own farmers; only the national programs can involve the farmers in that research, and help them to implement the improved farming patterns and to adopt the improved cultivars. The establishment of The International Service for National Agricultural Research (ISNAR). as a channel to help strengthen those national programs, is therefore, one of the achievements of the seventies, as important for sorghum as for general tropical farming and all other tropical crops.

Strong international programs and weak national programs can only result in the international programs becoming involved in what should be the sphere of the national program, because the work needs to be done. This in turn can result in the weakening of the national programs, to the detriment of all concerned. We must look forward to greatly strengthened national agricultural research services, so that international research can recede into the background, to its proper role of providing unobtrusively backup and support for the national agricultural research programs.

The "Sorghum in the Seventies" Symposium started by considering world germplasm resources, and I shall follow much the same order here.

Genetic Resources

During the past 10 years, more of the entries in the original IS world collection have been obtained by ICRISAT. Fresh collecting has been done in neglected areas of India, in the eastern Sudan, Western Ethiopia, Tanzania, Kenya, Somalia, Niger, Senegambia, Mali, Malawi, Zambia, and Botswana. Additional material has been obtained from Nigeria, the Sudan, and the USA. The greatest number of accessions has come from Ethiopia. Nineteen descriptors have been selected, and the collection evaluated and put on tapes. An introgression program to make use of

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outstanding germplasm entries by backcrosses to elite adapted cultivars is in progress. Many thousands of seed samples have been distributed to workers overseas and within India.

Ethiopia used an effective collection procedure which might be useful in other countries. Brhane Gebrekidan arranged for the Ethiopian Sorghum Improvement Project (ESIP) to employ collectors, who familiarized themselves with the sorghums being grown in their area. They obtained details about them beforehand from the farmers, and went through at harvest time collecting the samples. In this way, province by province over several years, a fairly thorough sampling of sorghums in Ethiopia was made. ESIP may be able to train collectors from other countries in the procedures used, in conjunction with ICRISAT.

Looking to the future, subsamples from the collection ought to be maintained in ecological zones closer to their original habitats than is Hyderabad. Desirable locations would be in areas such as Northern Nigeria, highland Ethiopia, Tanzania, and the Sudan. There are practical problems, but this should be the objective.

Population geneticists should be involved in planning the utilization of the collection. A set of climatic zones might be defined, and a random mating population made up for each zone containing the main resistances and the grain and plant characters likely to be of value in that zone. Plant breeders would find such composite populations easy to use and of great value.

World collection nurseries would be very desirable to test some of the better entries across locations on a world scale. This would help to identify those with the best stability of performance. This type of nursery put out by R.C. Pickett from Purdue under a USAID supported program was of value in identifying outstanding types, one of which, SC 108, is proving very successful in conventional sorghum improvement programs.

Classification

Harlan and de Wet's system of classification presented at the "Sorghum in the Seventies" Symposium has proved to be a simplification of very practical use. The situation within populations may be likened to a relief map, a series of adaptive peaks of varying altitudes separated by saddles and valleys. Botanists have defined the major peaks, using a large number of characters, and have sometimes tried to define the foot hills and the lower peaks also. Snowden (1936) provided a good example of this. However, sorghum is a rolling countryside as well as a mountainous one, and the precise positions and altitudes of many of the hills are difficult to define. Harlan and de Wet cut across these difficulties by defining the major peaks on simple grain and glume relationships, and some association with panicle type, the major factors for which people have selected. Cultivated sorghums can now be allocated to five main groups, or to ten intermediates between these five groups. This tells us little about the origins of the intermediates, whether they are steps along the road to the peak, or products of hybridization between the races.

Race bicolor is least homogeneous in this system, often because people have been selecting for characters other than grain, which may be needed only as seed.

To obtain a deeper understanding of the history of the crop, it would be necessary to use more plant characters, some being subject to direct human selection, others not. and to analyze them by numerical taxonomic procedures. De Wet and Huckabay (1967) have made an illuminating study, based on material available to Snowden (1936). Now that the world sorghum populations have been sampled so much more thoroughly, data could be collected on known indigenous materials from a wide range of geographical and special ecological zones, and analyzed by a suitable numerical taxonomic method.

This would add to the evidence available on the history of the crop. It would also be useful to have additional studies, followed through several generations, of hybrids between the main races, and between them and the wild races and ecotypes. Some of the work already in progress at ICRISAT on wild x cultivated crosses will contribute towards this. Further analyses of the geographic distribution of neutral alleles, such as fertility restoration to the milo-kafir cytoplasmic male sterility, are also desirable.

The Sorghum Conversion Program

The lines extracted from the sorghum conversion program have made a big contribution to the hybrid programs in the USA. They provide perhaps the main reason for the steady progress in yields. This approach has a big potential still, relatively little material has been handled in this way. Population breeding programs could contribute towards making much more photoperiod sensitive tropical material available as photoperiod insensitive stocks in a range of plant heights.

Sorghum Improvement

Table 1 sets out what has been happening to sorghum since the last meeting through 1979. Argentina and India show the best percent yield increases, 55% and 52% respectively, and much of this will have been due to the use of hybrid sorghum. In Africa and Asia, only China exceeds 1.0 t/ha but Ethiopia approaches it, and both Ethiopia and Upper Volta have made useful yield increases, without the use of hybrids as yet. The figures in the table underline the contrast between the larger farmer with good hybrids, able to afford inputs: and the small farmer, operating near the subsistence level, the difference between 2.9-3.6 t/ha, and 0.5-1.0 t/ha. I hope that somebody is going to tell us more about the situation in China, which grows 16.5% of the world's total crop, second in area only to India, but with 80% more yield.

The situation in Developing Africa causes concern. It will be seen from Table 2 that the total area under all three cereals increased by 8%. while the mean yield declined by 1.5% and the human population increased by 29%. Unless this trend can be reversed, there is real trouble ahead.

In the New World, there is a wealth of expertise on sorghum in North America, which is evidently transferable to the situation in parts of Latin America, where sorghum is a new crop, still free from some of the Old World pests. We should

Table 1. Comparative areas (1000 ha) and yields (kg/ha) of sorghum, 1969/71 to 1977/79 (FAO Yearbook 1979).

	1969/71		1977/79		Percent change		Percent of
Country or region	Area	Yield	Area	Yield	Area	Yield	area
Nigeria	5 572	652	6 000	628	+8	-4	11.6
Sudan	1 828	834	2 854	767	+56	-8	5.5
Upper Volta	1 054	501	1 033	591	-2	+ 18	20
Ethiopia	950	870	745	958	-22	+ 10	1.4
Niger	589	445	780	450	+32	+ 1	1.5
Africa	12 844	704	14 353	714	+ 12	+ 1	27.7
USA	5 820	3318	5 477	3 647	-6	+ 10	106
Mexico	934	2 766	1 422	2912	+52	+ 5	2.7
N.C. America	7 248	3 094	7 390	3 339	+ 2	+ 8	14.2
Argentina	1 979	1 932	2 253	2 987	+ 38	+ 55	4.3
S. America	2 097	1 933	2 866	2 788	+ 37	+44	5.5
India	17 585	484	15 981	734	-9	+ 52	30.8
China	8 571	1 090	8 570	1 304	0	+20	16.5
Yemen	1 235	711	886	730	-28	+3	1.7
Pakistan	518	594	489	558	-6	-9	0.9
Asia	28 293	689	26 473	899	-6	+30	51.0
Australia	374	2 031	465	2 006	+ 24	-1	0.9
USSR	43	1 423	86	1 288	+ 100	-10	0.2
World	51 043	1 103	51 835	1 320	+ 1.6	+20	100.0

Table 2. **Comparative areas (1000 ha) and yields (kg/ha) of cereal grains, 1969/71 and 1977/79; populations (1000), in Developing Africa.**

	1969/71		1977/79		Percent change	
	Area	Yield	Area	Yield	Area	Yield
Sorghum	10 657	671	11 136	683	+4	+2
Maize	12 349	1 012	14 108	971	+ 14	- 4
Millet	14 401	587	15 072	576	+5	- 2
Total Cereals	37 407	(752)*	40 316	(741)*	+8	-1.5
Population	282 734(1970)		365 738(1979)		+29	

* Mean for total cereals is average of the three yields, and not recalculated from original area and production figures

note that the improved genotypes in the USA preceded improved crop management, because only then was this profitable. Mean grain yields in the USA were around 1.2 t/ha before the release of hybrids, lower than the present figure for China over a similar area. Thus the importance of both plant breeding and of the economic system are underlined. The latter can defeat all the efforts of plant breeders and agronomists. The less developed countries have to pay for the infrastructure of civil service, health service, transport, education, defence, etc., but collecting taxes is difficult. Urban populations are politically aware: the rural populations labor on uncomplaining. It is easy to raise the money for infrastructure by paying low prices to the producer for his crops. Unless the farmer can market his harvest easily and profitably, there will be no increases in either yield, or in area under the crop, nor any improvements in farming standards.

The success of the traditional plant breeding methodologies has never been in doubt. Population methods only supplement and provide backup for these traditional methods.

Perhaps the most useful advance over the past 10 years has been in methodologies for screening against pests, diseases, *Striga,* and drought, which are important for all plant breeding procedures.

One premise on which the breeding programs have to be based for much of the developing world is that the advantages of hybrids will take some time to be adopted. Reliable seed production and distribution, and education on the need to purchase fresh seed for each planting, will take time to develop fully. Many small farmers will continue to save their own seed for some years yet. Good varieties will be needed for a long time, but since good hybrids come from good varieties, there is no conflict, and this forms one program.

Traditional Breeding Procedures

Good progress has been made in many countries through using traditional breeding methods. Looking only at India, we find average trial yields during the *kharif,* over four seasons, of 2.0-3.6 t/ha for the variety CSV-4, and 3.1 - 5.0 t/ha for the hybrid CSH-9. In the 1980 advanced *kharif* variety trials, we find SPV 350 from ICRISAT and SPV 346 from Udaipur only 400 kg/ha below the 3.8 t/ha yield of the hybrid CSH-5 (Anon. 1981).

In the advanced *rabi* hybrid trials, SPH 200 through SPH 204 from Parbhani, and SPH 210 and SPH 212 from Dharwar, all outyielded the hybrids CSH-8R and MSH-41, the latter from the Mahyco Seed Company.

Apomixis

Various attempts are being made to retain some of the benefits of heterosis which do not require such a highly developed seed industry as do conventional hybrids. Work on apomixis has now reached the stage when facultative apomicts, and "Vybrids" from crosses between them, are likely to be developed for farmer use. These will exploit and retain some of the heterosis available in crosses.

Genetic Vulnerability

Farmers in the SAT have learnt down the years to grow a range of cultivars, and landraces. This gives a better spread of defences against pests, diseases, and parasites. A reasonable level of resistance to the locally important pests and pathogens has been accumulated by selection in the locally adapted germplasm. When the local types are replaced by high yielding varieties (HYVs) or hybrids, a broad, adapted germplasm base is replaced by a single narrow genotype. This may become vulnerable to a local problem which was being kept under control by the local types and so passed unnoticed. This was evident with downy mildew on the earlier Indian millet hybrids. I obtained the first record of charcoal rot in East Africa by growing a USA double dwarf, shallu, at Ukiriguru in 1950. Some of the new HYVs and hybrids are showing similar vulnerability to this disease. *Striga* is being built up by some of the hybrids released in India in Telangana and Gadwal, Andhra Pradesh (API. to which parasite the local type PJ8K is very tolerant.

The development of new cytoplasmic male-sterile systems in the seventies will result in reduced genetic vulnerability

Population Breeding Methods

The biggest advance made in the 1970s has been in population improvement through recurrent selection. Initiated by Orrin Webster in the USA in 1960, population improvement was taken up by C. O. Gardner, P. T. Nordquist, W. M. Ross, and D. L. Oswalt. At the "Sorghum in the Seventies" Symposium, H. Doggett and A. B. Maunder gave some preliminary information on practices and results. 0. J. Webster commented thereon and C. 0. Gardner and S. A. Eberhart gave papers on population building and handling.

This work has continued in the USA during the past decade, especially in Nebraska, and for disease resistance and pest resistances in Texas, Oklahoma, and Kansas. I understand that only Funk Seeds International are using population breeding in their hybrid program.

In the developing world, the ICRISAT breeding program contains an important component of population improvement, but only as one component of a complete program. Population improvement is also being continued by A. Tunde Obilana in Northern Nigeria, building on the foundation laid by D. J. Andrews, and also by Brhane Gebrekidan in Ethiopia.

Why Population Improvement?

1. Classical plant breeding systems, especially in crops which are handled as self-pollinating crops, work on a steadily narrowing genetic base. Their elite lines stem back to a small number of original stocks. There is a wealth of variability available in sorghum. Population improvement by recurrent selection makes effective use of this.
2. There is a large number of characters requiring improvement, and the classical system takes these individually. If they are polygenic, as are yield, certain resistances and quality factors, they are difficult to handle by traditional means. With recurrent selection in populations, the genes controlling these characters become steadily more concentrated in the population, cycle by cycle, and the chances of selecting plants possessing many of the desired combinations steadily increase.

The Use of Population Improvement

1. Population improvement is one component of the ICRISAT program; the other components are breeding by conventional means for quality, and for pest, disease, *Striga* and drought resistances; for better seedling establishment, and other desirable traits. Promising elite lines from these programs are fed into the populations at the recombination stage, as we shall be hearing later. Provided that the populations are subjected to the right kind of selection pressures, the resistance and quality levels will be maintained and improved, and the chances of selecting the stable, high-yielding genotypes with the desired phenotypic expression will be steadily increased.
2. Populations are being developed, selected, and tested across environments. Experience indicates that each major ecological zone will require its own population, but there need not be many such zones. Plant breeders would withdraw lines from these populations, inbreed, and test them in trials, just as they do now with segregating F2 or F3 generations. These would be tested in yield trials, and an aliquot of seed from the best would be returned to the population to begin the next selection cycle. But in all other respects, the material would be handled along completely conventional lines, from that point on, with

selfing, reselecting and testing across environments in the usual way.

The need for international support for the population and initial evaluation trials arises because these must operate across national boundaries, and because only a low proportion (20 -30%) of the entries in the S2 evaluation trials is useful material. We may expect to see more of the population side of the work taken over by the national programs as they become stronger and the populations themselves are further improved. As this happens, ICRISAT will be able to recede more into the background. Developing countries with 80% of their people involved in agriculture must have strong indigenous national agricultural research and development programs. ISNAR will be helping in this. The sooner that foreigners can retreat to the place of providing back-up services to the national programs the better. We should look forward to the stage being reached again that existed in the early 1960s, when international scientists could be posted back-to-back with national programs at national research centers strategically located to meet many of the needs of the ecological zone concerned.

The Achievements of Population Breeding

I hope that we shall be hearing something from A. Tunde Obilana of his experience in Nigeria, and that someone from Funk Seeds International will be telling us a little of their success in developing hybrid parents by population breeding in the USA. Bhola Nath will be telling us of his work at ICRISAT. In the 1980-81 *rabi* advanced variety trials in India, SPV 422 and SPV 424 from Bhola Nath's program came first and second for both grain and fodder yield, beating hybrid CSH-9, 3.7 t/ha, by a small margin on the grain yield, and the best variety SPV 427 (from Dharwar) by 1.9 t/ha and 0.6 t/ha respectively on the fodder yields. The following points should be underlined.

1. The S2 testing system has been developed over the four seasons available in every 2 years. This involves selection and S1 testing in year 1, and S2 testing and recombination in year 2. If selection and S2 testing are done in the major season, S1 testing falls in the minor season. Any selection in that generation is thus largely for evident agronomic characters, or resistances, or quality, but not for grain yield, for which selection and testing must be done during the season of the year in which the crop is grown commercially.

Testing must be conducted across locations, using different seasons as one or two "locations" (e.g., *rabi* season for *kharif* material) may help to increase breadth of adaptation.

We need to be clear about our breeding objectives. Table 1 brought out the contrasts. In the developing world, we should not be shooting for 8 t/ha at the present time—that will come later. The immediate need is for improved stability of yield, combined with better yield. Average yields of only 1.5 t/ha would double production in Africa and India.

Yield stability depends upon resistances to pests, diseases, and *Striga;* upon the good establishment of seedlings under difficult moisture regimes; upon the ability to endure drought; and upon the ability to endure excessive rain and still produce a grain of acceptable quality. Also another factor in Africa outside the disciplines of plant breeding or agronomy, except for possibilities of some avoidance, is the *Quelea* bird problem; the birds descend upon the small grains of Africa in hundreds of millions and devastate them like locusts. They need to be controlled like locusts.

Testing across locations is the mechanism for achieving improved yield stability "Locations" in the broadest sense include disease and pest nurseries, seedling establishment screening, and drought testing. There is sometimes confusion over the fact that populations need to be designed to serve certain ecological zones, but need to be *tested* beyond the range of those zones This is essentially a partial substitute for testing across seasons. The ecological zone for which the population is designed will sometimes have wetter years, sometimes drier years, sometimes longer rainy seasons and sometimes shorter rainy seasons. Locating a few of the testing sites in wetter and drier zones in the same year helps to develop the season-to-season stability needed.

2. I would draw special attention to the system which Bhola Nath has developed for incorporating fresh characters, such as resistances, into the populations. Originally, we had planned a "side-car" system, essentially by backcrossing the character into the population. Bhola Nath has been selecting elite lines, and merging them directly into the population, which is a far simpler system.

3. I would emphasize the value to hybrid prog-

rams of recurrent selection in populations. By operating separate "R" (restorer) and "B" (maintainer) populations, potential hybrid parents are being improved separately. This is of special value for the development of female parents (A lines). A range of excellent new potential female parents has already been produced at ICRISAT, and this in itself is a "breakthrough". Hybrid seed production programs are hindered by having to use female parents which are relatively low yielding, often lacking in important resistances, and which may not flower at the same time as the pollinator.

4. We have stressed S2 testing. When more resources become available, other possibilities can be examined. I look askance at the S1 testing system with one cycle per year. Growing three generations in the same year is a mad scramble, and impossible if seed has to be sent to other locations for trial, and results received back. It is better to be content with two generations each year, and to adopt the S2 system. Not only can selection and S2 yield testing both be done in the corresponding season, but much more seed is available for testing across locations. The full potential of mass selection has not yet been explored and this could be particularly valuable over a range of testing locations.

5. To sum up the sorghum population improvement situation:

(a) The system allows a broader germplasm base to be used.

(b) It is an excellent source of selections for traditional progeny-row breeding programs.

(c) It is an excellent source of steadily improving hybrid parents.

(d) It allows a wider range of desired characters, such as resistances or quality characters, to be maintained and improved simultaneously.

(e) It offers an effective vehicle for the development of greater yield stability in both varieties and hybrids.

(f) The development of multiline and synthetic type varieties is a spin-off which will occur one day. These will provide greater yield stability, will utilize some of the available heterosis, and will greatly reduce the risks of genetic vulnerability.

Resistances

These will be fully reported upon by later speakers. I shall select only a few examples, without any disrespect to those remaining unmentioned.

Entomology

Very good progress has been made in identifying shootfly resistance. Some countries feel that they do not need this. In fact, wherever shorter-term sorghums are to be grown in the tropics late in the season to permit more intensive land use, with the grain still ripening in the dry weather, shoot fly resistance is a "must". Better sources of *Chilo* stem borer resistance are urgently needed. Mass selection in population under Hissar conditions should be tried. The discovery of good resistance levels to earhead bugs is an unexpected bonus.

Good advances have been made in the USA, in conjunction with work in South America, in obtaining midge resistance. The sorghum conversion program contributed some good resistant genotypes, and these are being used in breeding programs at several centers, including ICRISAT.

The distribution of pest resistance nurseries from ICRISAT has contributed to the solution of breeding problems during the past decade.

Plant Pathology

Very satisfactory progress has been made in the development of the methodology for screening for grain mold resistance, and good advances in obtaining better levels have been made. The charcoal rot resistance program is becoming increasingly important in the developing world, as much superior high-yielding material is proving susceptible to this disease, overlooked because indigenous cultivars were resistant, or selection was done where the disease was unimportant. Again, workers in the developing world have had the advantage of the research carried out on this disease in the USA.

Progress has also been made with downy mildew resistance sources.

The cooperation between Texas A&M and ICRISAT in sending out a series of international nurseries containing sources of various disease resistances has been of great value during the seventies.

Plant Physiology

Good progress has been made in plant physiology research during the past decade. This has included genetic differences in responses to temperature levels, mineral deficiencies, and drought. Much work has been done on drought, and this is without doubt the most important physiological problem in the developing world.

Two important sources of low yield are poor stands in the field—usually due to poor seedling establishment—and the effects of drought. At ICRISAT these are major areas for research. Differences in seedling vigor, inability to push through a soil crust, and inability to survive drought stress have been identified. These now need to be translated into practical results in the breeding program, and deserve high priority.

Drought tolerance has proved to be a difficult problem for plant breeders to handle. How does one select individual drought-resistant plants from a segregating population? The answer is that one probably does not, because one cannot. In the past, it has been very difficult to screen short rows; a satisfactory procedure for this would permit the use of S1 testing. However, under drought conditions, soil irregularities are so magnified that comparisons are very difficult, and too many replications are required to identify apparent differences. This problem has been tackled in several ways. One has been an attempt to analyze the main plant hormones, which govern the response of the plant to drought. The balance between these hormones under stress conditions may make possible the identification of drought resistant genotypes. A team at the University of Saskatchewan, Saskatoon, has made excellent progress in analytical methods allowing the estimation of very low levels of the main hormones, and this shows promise of being of practical use.

The main advance, however, has come from the use of the line-source technique. In this, a pipe delivers a spray which can be regulated to provide full irrigation close to the pipe and then declining evenly over a distance of several meters to the point where there is no irrigation. Sorghum rows are planted at right angles to the pipeline, and the plants in those rows receive decreasing amounts of water the further they are from the pipe. Drought tolerant types can therefore be identified. These conclusions are then confirmed in replicated field trials in which a known amount of water can be given, i.e., there must be no rainfall. This is practicable in the Hyderabad summer season, and impressive progress has been made in identifying drought tolerant lines. That does not yet solve the problem of breeding for drought resistance, i.e., making crosses and selecting drought resistant progeny, although it goes a long way towards doing this. It is likely that a few cycles of mass selection in a random mating population planted in a "line-source" plot, with the best plants harvested from the dry strips furthest from the line, would tell us a good deal about the practical potential of drought resistance breeding. The need for a close season at ICRISAT Center to restrict the build-up of pests presents real problems to those who must work on drought resistance in the off-season.

Striga

This was the subject of a workshop in October 1981 in West Africa. The seriousness of this problem in Africa needs constant emphasis: Dr. B. S. Rana has just returned from 2 years in Kenya on a UNDP project. His figures indicate that the grain yield loss there for a susceptible variety was 59%.

The problems of breeding for *Striga* resistance present similar difficulties to those of drought resistance. In both cases, identifying resistant plants out of segregating populations, and the technology for field screening, are complex issues. Natural field distributions of *Striga* are very uneven. It looks as though screening seedlings for low stimulant production is a practicable technique for reducing the number of susceptibles in the population to be screened—i.e., the population of low stimulant producing lines contains a higher proportion of *Striga* resistant types than does the unscreened population. Field screening then becomes practicable. In fact, many of the resistant types identified show mechanical resistance, but having this coupled with low stimulant production is likely to be helpful in reducing the number of *Striga* plants which grow and set seed. Evidence has been accumulating on the existence of several strains of both *S. hermonthica* and S. *asiatica.* There can be little doubt that the same will prove to be true in the majority of *Striga* species.

An interesting advance towards the control of *Striga* has been made through the development at Sussex University of synthetic analogues of strigol, the stimulant which causes *Striga* seed to germinate (Johnson et al. 1976). There are indications that these could be very effective in reducing the reservoir of *Striga* seed in the soil, but sheer lack of agronomists in Africa has frustrated proper field testing of these compounds. They show promise in the USA (Eplee in press; Norris and Eplee in press).

The most neglected problem of the seventies was the control of *Striga.* This parasite is one of the two major causes of crop loss in cereals in the tropics of the Old World, comparable in importance to birds. There has been progress in resistance breeding, but the development of good farming systems, including crop rotations, herbicide, and improvement of soil fertility, which lie within the reach of the small grower.have been almost totally neglected.

Grain Quality

This item has been left until last, because it has just been the subject of a workshop of its own.

A real achievement of the 70s has been the awakening of interest in, and the work done on, evident quality characters and their relationship to food preparation for people. Much progress has been made, and breeding for grain quality is becoming a regular feature in breeding programs, because we now have a better understanding of what grain quality is.

During this last decade, the foundations have been laid for cooperative work on quality between ICRISAT, the developing world, USA universities, and Canadian universities, and the Prairie Regional Laboratory through IDRC. This last organization has supported innovative work in machinery and methods for pearling and milling sorghum, now being compared with equipment developed in FAO projects. The International Symposium on Sorghum Grain Quality held at ICRISAT in October 1981 has recorded the main progress in grain quality.

For those obliged by bird damage to live off bitter, tannin-loaded grains, progress in studying the methods of reducing the tannins and enhancing the nutritive value of these grains is also heartening.

Progress in pearling and milling machinery at the village level is particularly to be welcomed. This is likely to be much extended during the next decade, easing the burden for many housewives.

One of the disappointments of the 70s was the failure of the attempt to improve the nutritive value of sorghum protein. The development of high-lysine grain sorghums has not yet made much practical progress. We need to be on the lookout for a high-lysine character which is more readily transferable to good grain types than have been those tried so far. This has nothing to do with protein gaps or mixed diets. Ten percent of the yield is protein anyway; we should endeavor to see that it is usable protein. An unusually large proportion of sorghum protein is not.

Socioeconomics

It is good to see that these disciplines are represented at this Symposium. The main problem in the 1980s will be how to use the results from surveys in a way that is of real practical benefit in applying new technology to improving the farmers' lot. The South-East Asian cropping systems methodology operated through IRRI has lessons in approaching this problem which may be applicable to other areas also.

References

ANONYMOUS. 1981 Progress report of the All India Coordinated Sorghum Improvement Project, 1980/81. ICAR and cooperating agencies

DE WET, J. M. J , and HUCKABAY, J P. 1967 The origin of *Sorghum bicolor* II Distribution and domestication. Evolution 21 : 787-802.

EPLEE, R E (In press) Progress for control of *Striga asiatica* in the United States

FAO (Food and Agriculture Organization) 1980 FAO production yearbook 1979 Rome, Italy: FAO.

ICRISAT 1982 Proceedings. International Symposium on Sorghum Grain Quality, 28-31 Oct 1981. ICRISAT. Patancheru, A.P. India: ICRISAT

JOHNSON. A W.. ROSEBERY, G . and PARKER. C 1976. A novel approach to *Striga* and *Orobanche* control using synthetic germination stimulants Weed Research 16 : 223-227

NORRIS, R S . and EPLEE. R. E (In press) Effects of stimulant plus herbicide on *Striga* germination

SNOWDEN. J. D 1936. The cultivated races of sorghum London, UK: Adlard.

Status of Sorghum Production as Compared to Other Cereals

Earl R. Leng*

Improvement in the production of two important cereal crops—wheat and rice—has resulted in sharply increased food grain supplies in many areas. The much-heralded "Green Revolution" in the late 1960s and early 1970s, based on this improvement, has been described by many and has been well documented by Dalyrimple {1978, 1980). No similar documentation has been published concerning the status of the two other major cereals—maize and sorghum, but many development workers appear to believe that similar improvement has occurred with these crops as well.

In planning the present symposium, it appeared desirable in "setting the scene" that the current status of sorghum production be evaluated, and particularly that it be compared with the production status of other major cereals. This is the task undertaken in the present paper.

Bases of Comparison

After due consideration, it appeared that the most useful comparison would simply be to evaluate progress and current status in *per unit area production,* on the most general basis possible. Accordingly, the excellent production reports issued annually by FAO were utilized, with the "kilograms per hectare" data being the major information employed (FAO 1961, 1966. 1975, 1980).

The four major cereal species of the world —wheat, rice, maize, and sorghum—were studied. Data used in the comparisons, as will be explained in more detail below, were for the United States, Mexico, Western Europe, India, the "developing countries" of Africa and Asia, and for rice only, China and Brazil. The time framework used was to take the four post-World-War-II years of 1948-49 and 1952-53 as the "base," and then chart the 3-year average yield levels for the periods 1963-65, 1969-71, 1973-75, and 1978 -80. No attempt was made to adjust for "unfavorable years" or any other cause.

Major Cereals—Trends

Wheat

It is clear from the data (Fig. 1)that wheat yields have improved significantly in all areas of the world where this cereal is a major crop. Mexico and Western Europe are the most spectacular examples, with Mexico showing over a fourfold increase between the base period and the 1978 -80 span (880 kg/ha to 3645 kg/ha as a national average). Gains in the Near East and wheat-growing countries of Asia do not appear so spectacular from examination of the charts, but in fact yields in Asia have doubled and those in the Near East have risen by over 50%. Moreover, the rates of improvement in recent years (since 1970) have been particularly striking in these areas.

While yield levels in the United States have approximately doubled in the period under consideration, closer examination reveals that nearly all this improvement took place between the base period and 1970. From a base of 1120 kg/ha, yields rose to an average of 2144 kg/ha in the 1969-71 period, and only to 2200 in 1978-80. As Dalyrimple (1980) has pointed out, the adoption of "modern" semidwarf types has been quite variable regionally in the U.S. It has been quite low in

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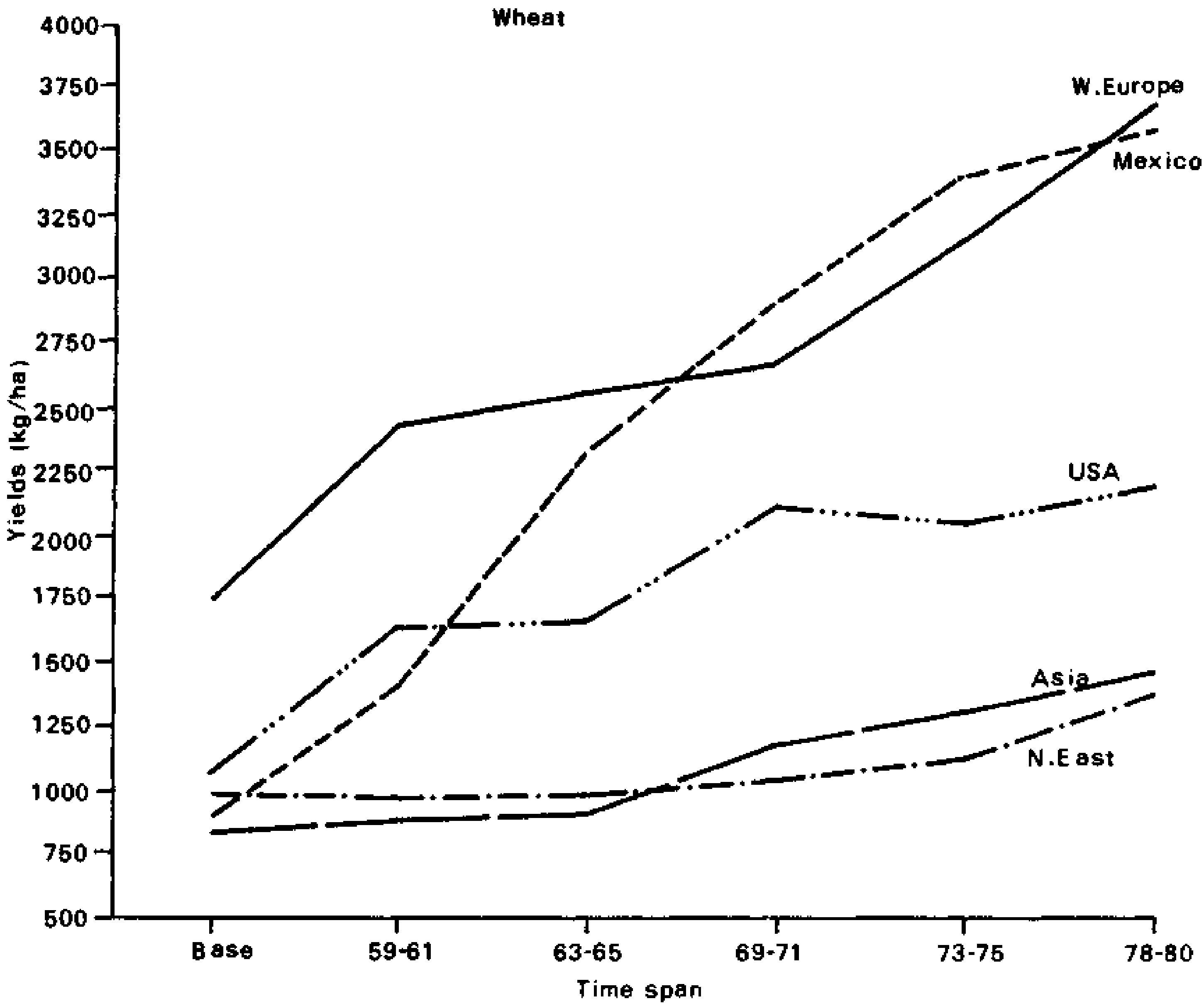

Figure 1. Progress in wheat yield improvement, 1948-1980. "Base" is 1948-49/1952-53 averages; other "time span" dates are averages of 3-year periods

large areas of major production, especially in the hard red winter belt. Thus, we see the interesting situation that, in the past 10 to 15 years, the United States is in a sense the laggard in world wheat production improvement.

Rice

Significant gains in rice yields have occurred in the U.S., mainland China, and the major rice producing areas of Southeast Asia (Fig. 2). Although rice yield improvement received the initial attention as evidence of the "Green Revolution," the effects on cereal grain supply have not been as marked as those of wheat improvement. In the U.S., which has led the world in rice production levels throughout the time span, there is again (as in wheat) evidence that little progress has been made since 1970.

In contrast to the situation described above, rice production levels in Africa (not including Egypt) have shown very little improvement. In Brazil, there has been none at all. Clearly, the major effects of the "Green Revolution" in rice have not reached these areas. Why, and what can be done about it, should be of considerable concern to African and Brazilian rice workers.

Maize

Although not a food grain in many areas in the same sense as wheat or rice, maize is the staple cereal for tens of millions in Latin America, Africa, parts of Asia, and even a few areas in Europe.

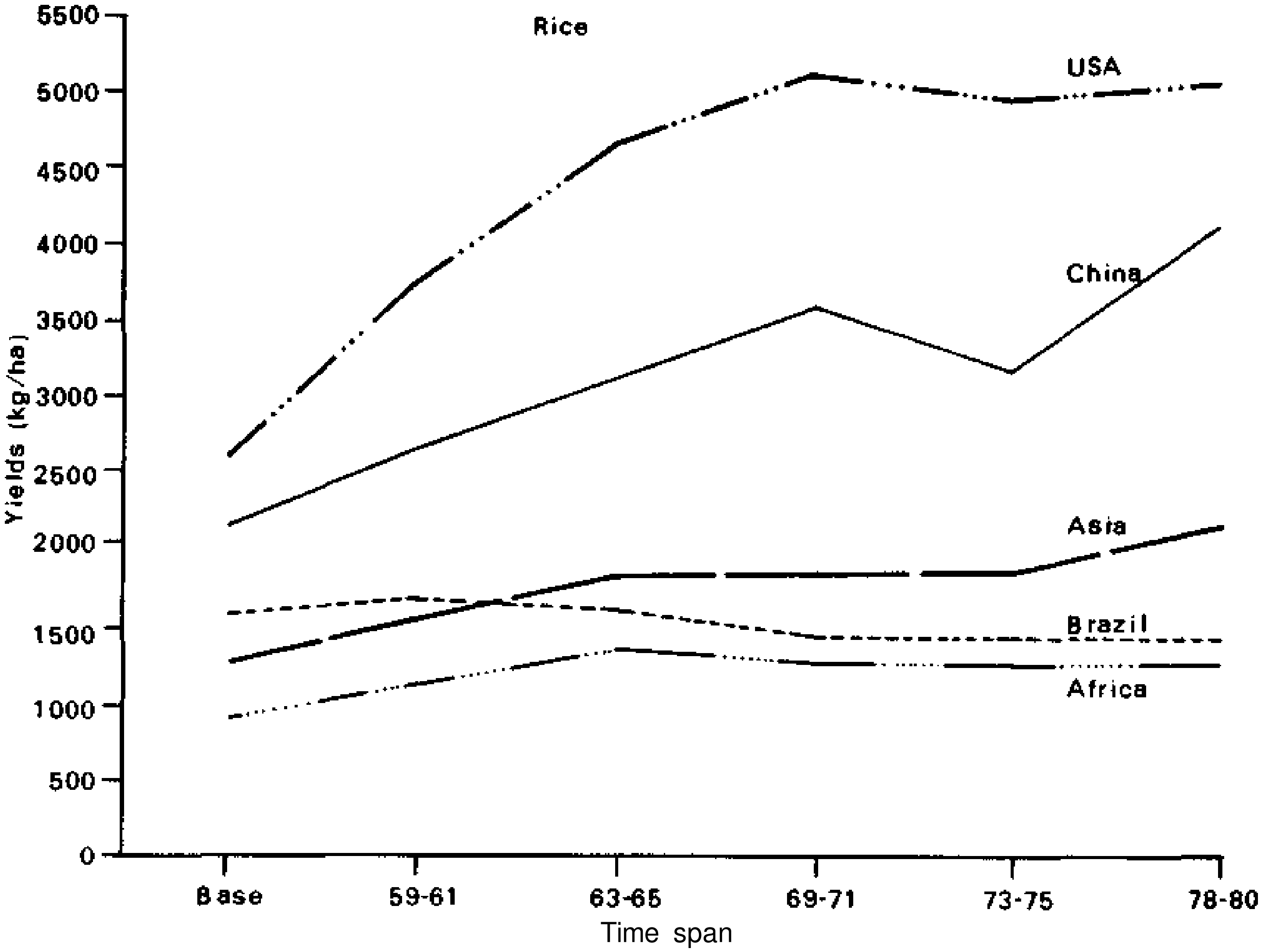

Figure 2. Progress in rice yield improvement. 1948-1980. "Base" and "time span" as in Figure 1 (this applies to all subsequent figures)

Spectacular increases in production levels were achieved in the United States even before World War II, as a result of the introduction of hybrid maize (Aldrich et al. 1975, p. 20). The rate of these increases continued through the base period and has been maintained up to the present time (Fig. 3). Unit-area average yields of maize exceed those of all other cereals in the U.S.

Transplanted to Europe after World War II, the same technology has greatly increased maize production in Eastern Europe and Italy, where the crop was already well established, and has revolutionized the agriculture of Western Europe, particularly in France but also in Switzerland, Austria, and West Germany. Yields have increased fourfold during the period (1240 to 4891 kg/ha), and area has increased explosively (2.472 million hectares to 6.255 million). Yield trends, as in the U.S., continue upward at an unabated pace.

In contrast, maize yields in Mexico, and developing countries in Asia and Africa have improved little, if at all. There is some slight evidence of a recent improvement in Mexico, but between 1963 and 1975 there was no gain at all. In developing countries of Africa, and in most countries of Asia, the evidence points to a *decline* in yield levels since the mid-1960s.

It is not the province of this paper to attempt to explain the drastic differences in maize yield improvement in the various areas of the world. Suffice it to say that technological improvement obviously is continuing at a sustained rate in the U.S. and Europe, while virtually no application of a truly improved technology appears to be occurring in Mexico or the developing Asian and African countries.

Sorghum

Sorghum is the cereal with which this paper is chiefly concerned. Maunder (1972) pointed out

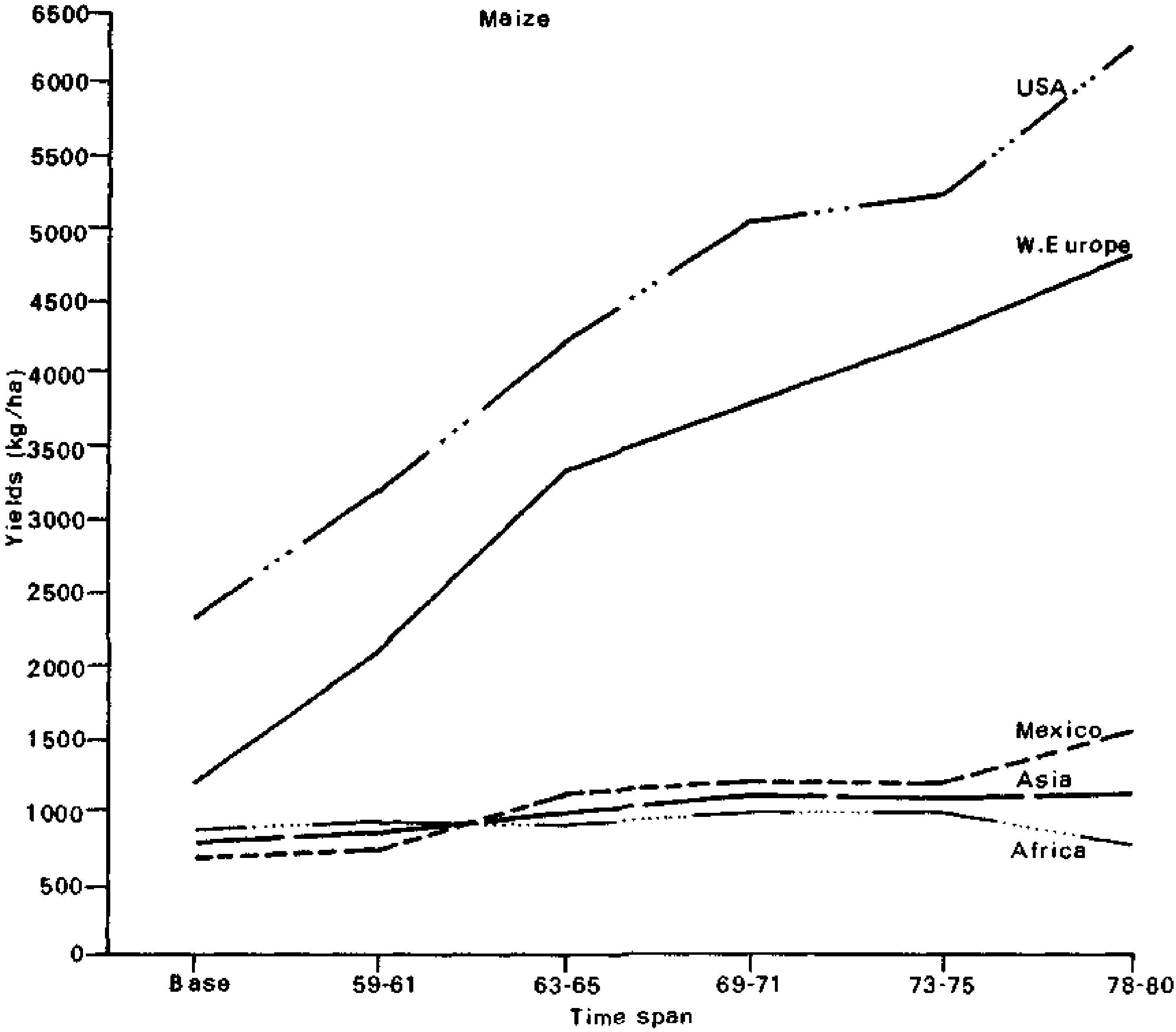

Figure 3. Progress in maize yield improvement, 1948- 1980.

that in the United States improvement in sorghum yield levels had, up to that time, outstripped that in the other major cereals. Figure 4 confirms this, but also suggests that an abrupt plateauing in the gain rate occurred about 1970. Yield levels in the 1978-80 period are virtually the same as for the 1969-71 period (3392 as against 3318 kg/ha), and the 1973-75 level was lower (3201 kg/ha). This is an interesting observation, which perhaps other speakers in the symposium will care to examine in more detail. The situation in Mexico is even more interesting, and I believe, highly significant for development-oriented persons. I have already noted the great gains in wheat production levels and the contrasting insignificant improvement in maize yields. It might be expected that sorghum trends would resemble those in maize, but the opposite is true. The crop was almost unknown in Mexico in the 1948-1953 period, so that the area was not reported by FAO. By 1969-71, the area under sorghum had risen to 930 000 hectares, and in 1978-80. it was 1 457 000. Apparently, sorghum is replacing the traditional staple cereal, maize, on a significant hectarage. Why? The answer is clear; sorghum yields in Mexico now are almost double those of maize (sorghum 2924 kg/ha; maize 1508). Clearly, a modern technology is being effectively applied for sorghum but not for maize.

In the developing countries of Asia and Africa, the picture is clear but discouraging. Yields have improved little in Asia (with perhaps a few exceptions) and not at all in Africa. Clearly, ICRISAT, INTSORMIL, SAFGRAD. and sorghum workers in general still have an enormous task before them.

Country Comparisons

United States

Summarizing cereal yield trends in the U.S. (Fig. 5), we note the interesting situation that only maize is continuing to show a steady rate of gain in yield levels. The other three cereals do not appear to have increased much in yield during the past 10 years. Whether this reflects actual plateaus in technology, or is the result of other factors, is not clear. Maize yields are about double those of sorghum and more than three times those of wheat, with rice following maize at about 1000 kg/ha less.

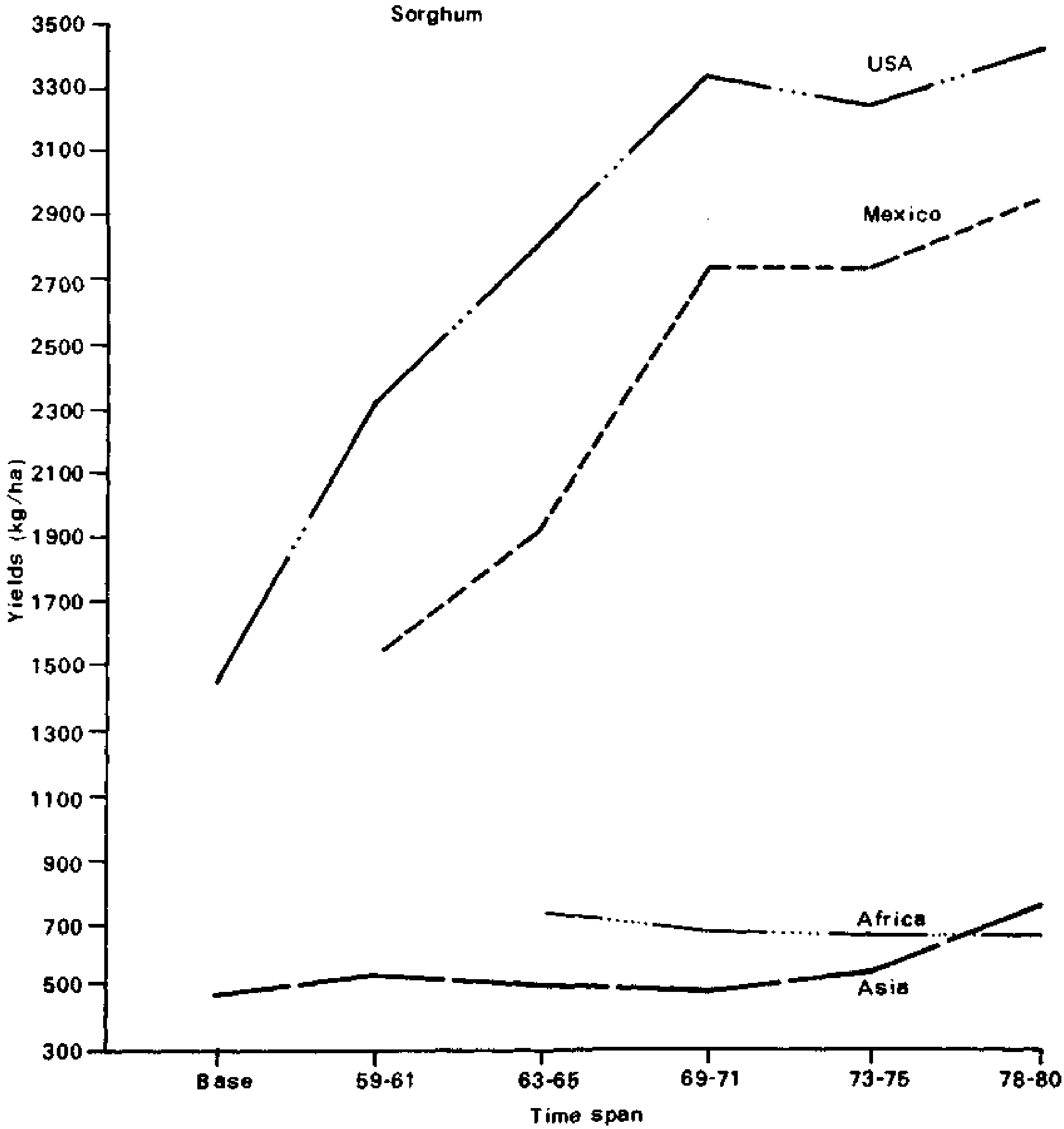

Figure 4. Progress in sorghum yield improvement 1948-1980.

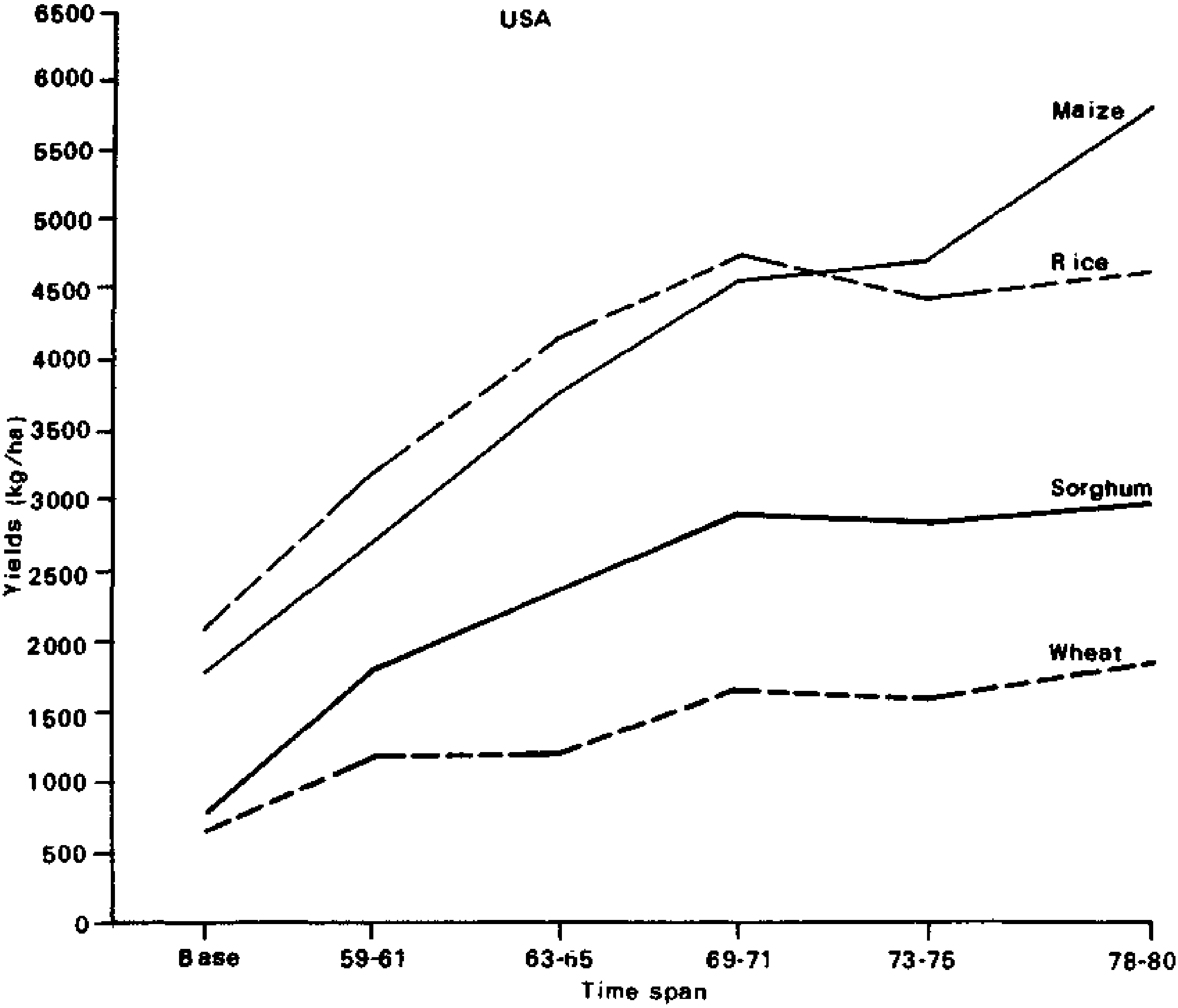

Figure 5. Changes in yield levels of four major cereals, United States, 1948- 1980.

Mexico/Brazil

The following comments apply to Mexico except for rice, where Brazil has been used as a comparison standard since Mexico grows little rice. Astonishing progress has been made in production levels of both wheat and sorghum (Fig. 6). Maize, the traditional staple grain, is lagging badly in yield levels, though perhaps some improvement has occurred in the past 5 years. But in contrast to the U.S., where maize yields are double those of sorghum, Mexico has a sorghum yield average double that of maize. Rice (in Brazil) has shown no progress at all. Clearly, improved technology for wheat and sorghum production is available and being widely applied at the farm level in Mexico.

India

Fifteen years ago production levels of three major cereals (wheat, maize, and sorghum) appeared to be stagnated at very low levels in India. Significant gains in rice production had occurred between the base years and 1965, but there followed a period when rice yields did not improve. Now (Fig. 7) there is clear evidence of major gains in wheat and rice production. There is some evidence that sorghum yields are improving, but yields are still very low. Maize, for which much was hoped in the 1960s, is showing little or no progress at all.

Summary and Conclusions

Examination of yield trends in the four major

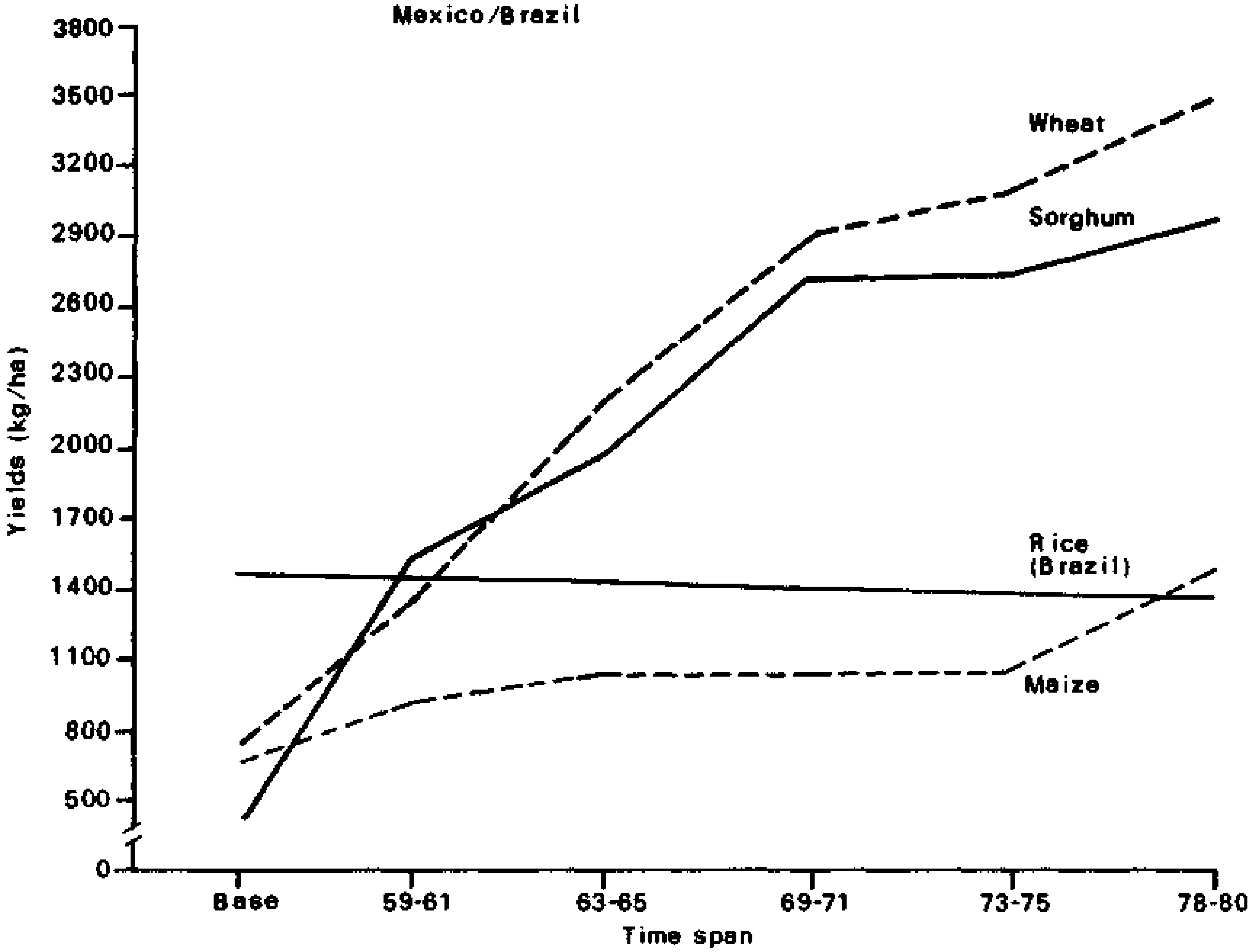

Figure 6. Changes in yield levels of tour major cereals. Mexico and Brazil, 1948-1980 (wheat, sorghum, and maize are in Mexico; rice is in Brazil).

cereals—wheat, rice, maize and sorghum—shows several interesting features of significance for development and world food production. Wheat generally, and rice in developed countries and the Asian production areas, have shown significant—even spectacular—yield increases. Clearly, improved technologies for producing these crops have been developed and are widely available at the farm level. More needs to be done, of course, but progress in these crops is quite encouraging. Maize, in contrast, presents strange anomalies. Yield increases have been highly significant and continuing in the U.S. and in European countries. In the developing world and in Mexico, the home of maize, very little progress has been made. Either no technologies suitable for increasing yields are yet available, or there is a major gap in bringing suitable technology to the farm level. It is not my role in this paper to analyze the situation in detail, but it is very troublesome to those concerned with maize improvement.

Turning in conclusion to our crop, sorghum, we find encouragement, difficulties, and above all. challenge. Sorghum yields in the Western Hemisphere are generally quite high. Spectacular progress in yield levels and total production have recently been achieved in Mexico, where maize yields remain low. It is clear that recent technological advances have been made available to Mexican farmers. In India, there is some evidence of recent progress but there is a long way to go since sorghum average yields are still very low. There seems to be good reason to believe that improved technologies are now available or about to become so; the next challenge is to get these adopted widely at the farm level. In most other developing countries, and particularly the "sorghum belt" of Africa, so little progress has been

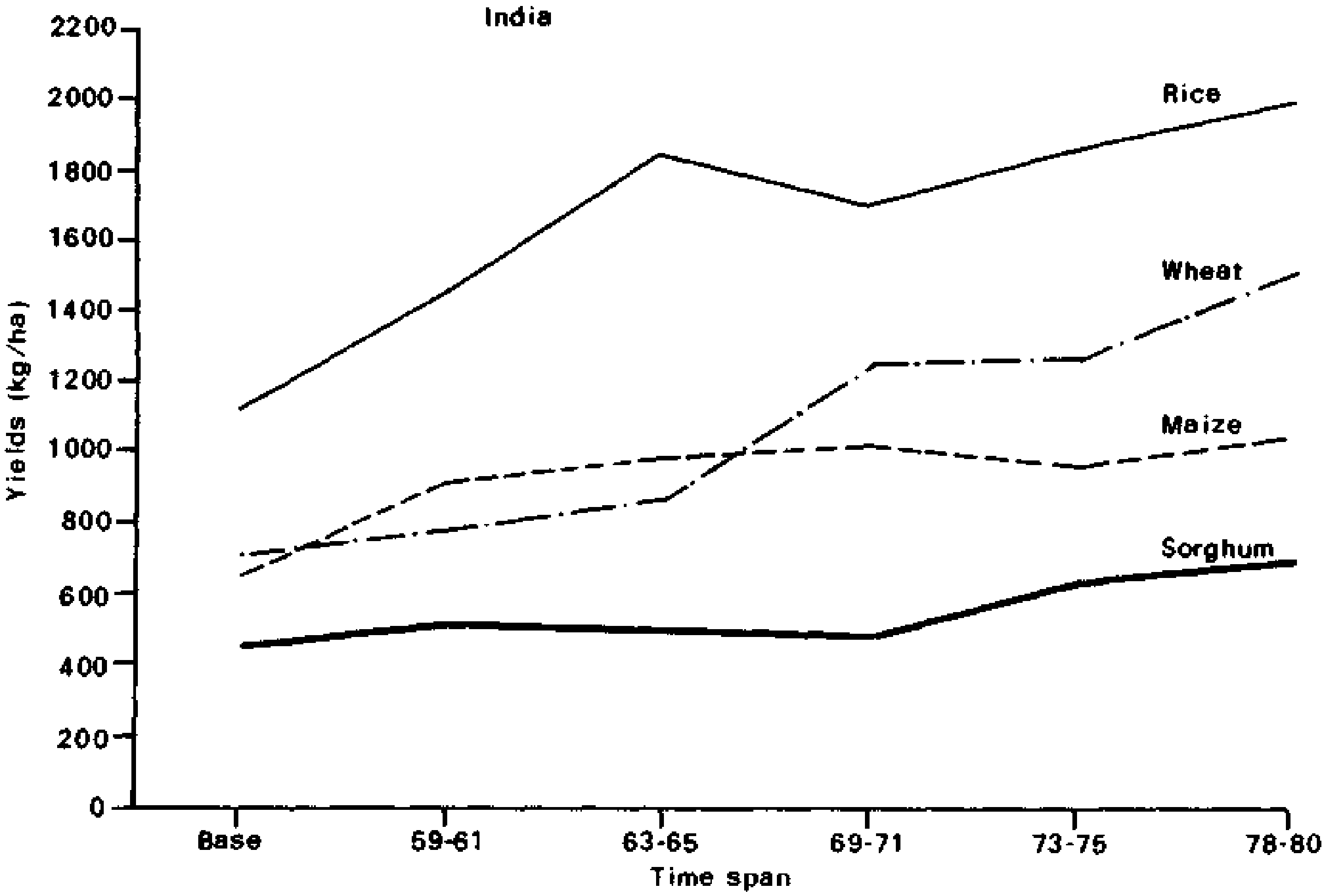

Figure 7. Changes in yield levels of four major cereals, India, 1948–1980.

made in yields that there is serious question if *adaptable* improved technology actually is available. If it is, the farmers have not yet adopted it at all. All of us therefore have a triple challenge — *first to* find out what the real limitations on yield are, *second* to overcome these limitations in a practical fashion, and *third* to facilitate the adoption of improved technology by farmers on a broad scale.

"Sorghum in the Eighties" will have achieved its objective if we can give major answers to the first challenge and suggest practical means of conquering the second and third.

References

AIDRICH, S. R., SCOTT, W. O., and LENG, E. R. 1975. Modern corn production. Champaign, Illinois, USA: A and L Publications.

DALYRIMPLE, D. G. 1978. Development and spread of high yielding varieties of wheat and rice in the less developed nations, USDA/OICD, FAER 95.

DALYRIMPLE, D. G. 1980. Development and spread of semi-dwarf varieties of wheat and rice in the United States. USDA/OICD. FAER 455.

FAO. 1961, 1966. 1975, 1980 FAO production yearbook vol. 15, 20, 29, 34, respectively. Rome, Italy: FAO.

MAUNDER, A. B. 1972. Objectives and approaches to grain and forage sorghum improvement in the Americas. Page 60-100 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co.

Institutional Considerations as Related to Sorghum Improvement in the 80s

R. W. Cummings*

The Symposium on "Sorghum in Seventies" held in Hyderabad almost exactly 10 years ago, addressed the major topics related to sorghum improvement. The nine major divisions and forty-six chapters of the report on that meeting provide a very appropriate reference point for the deliberations of the current symposium. Major topics covered by that meeting included biometric classification of sorghums, genetic resources; varietal improvement, including breeding methods and approaches; physiology; production technology; seed production; pests and diseases; utilization and nutritional aspects and world outlook.

The present symposium will address most of these same topics and wilt also be giving limited attention to socioeconomic considerations including marketing. Marketing and government price policy are subjects, which would seem to merit more attention in the future, particularly in the less developed regions in which sorghum grain is used primarily as a human food.

On a world basis, sorghum ranks fifth among the cereal grains in extent of production (after wheat, rice, maize and barley). Current FAO statistics indicate a world production of approximately 70 million metric tons of sorghum grain on more than 51 million hectares of land. Some additional production may perhaps be included in the reported statistics on millet production. In the USA and South America, sorghum is grown principally as a grain for animal feed, while in Africa and Asia, the grain is grown primarily for use in human food, either directly or after brewing. In these latter regions, the production and use of stover (stubble) for animal feed, building material, and fuel assume relatively greater importance than in the former.

In the African and Asian continents, sorghum has been a crop principally of the small cultivator, and has been consumed largely at or near the areas in which it is produced. It has not generally been a major item of commerce in urban areas and has not had attention by governments in terms of stockpiling, purchase, price support, research, or policy considerations comparable to that given to some other basic food commodities. In fact, rural migrants to cities, as urbanization has increased, have not carried with them a proportionate demand for sorghum grain, but have tended to shift their demand in the direction of rice and wheat.

Sorghum is a crop which can be grown with relative advantage in many areas in which the amount and dependability of rainfall make maize growing a high risk or unsuccessful in too high a proportion of years. In meeting world food needs, sorghum will continue to have a very important place. It will be crucial to a very substantial segment of population across central and western Africa south of the Sahara, parts of East Africa, Southern Africa, and of India. It will fill a very significant place in helping to meet the human food and animal feed budgets in many other areas, including South and East Asia, China. Latin America, and the USA.

This crop has not, at least until recent years, received the attention in the scientific community, by governments, and institutionally which it deserves. Its limited place in the commercial urban markets, the fact that it is classed as a coarse grain, and the fact that so much of its production for direct use as human food is done by small producers and consumed at home may account in part for this situation. Increasing pressures of population growth on food supplies will necessitate our giving increasing attention toward realiz-

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ing more fully the potential of this crop which fills a unique and highly significant place. In many ecological, social, and climatic situations, it may be the only, or at least the principal, viable alternative for providing the basic staple food for the local diet.

I shall make no attempt to be exhaustive in my treatment of institutional considerations with respect to "Sorghum in the Eighties"; I shall begin by listing a few institutions or classes of institutions which now have, have had, or are destined to have a very significant role in this report, such as:

The commercial seed industry (individually and collectively)
ICRISAT (The International Crops Research Institute for the Semi-Arid Tropics)
USDA (The United States Department of Agriculture)
The Land Grant Colleges and Experiment Stations of the USA, especially Nebraska. Texas, and Indiana and BIFAD (The Board for International Food and Agricultural Development) through its cooperative Research Support Project on Sorghum
The Indian national sorghum research programs, notably PIRRCOM (Project for Intensification of Regional Research on Cotton, Oilseeds, and Millets) and AICSIP (All India Coordinated Sorghum Improvement Project).
National Research Institutions in Africa, notably the Sudan, Ethiopia, Tanzania, Uganda, Nigeria, Upper Volta. and the Senegal
FAO/UNDP (Food and Agriculture Organization of the U.N. and the United Nations Development Programme)
The Rockefeller Foundation

ORSTOM	- Organizacion de Recherche Scientifique et Technique Outre Mar	France
IRAT	- Institut de Recherche Agronomique Tropicales et des Cultures Vivrieres	France
EMBRAPA	- Empresa Brasileira de Pesquisa Agropecuar ia	
IBPGR	- International Board for Plant Genetic Resources	
ICIPE	- International Centre of Insect Physiology and Ecology	
TPI	- Tropical Products Institute	UK
COPR	- Centre for Overseas Pest Research	UK
WRO	- Weed Research Organization	UK
ODM	- Overseas Development Ministry	UK
USAID	- U.S. Agency for International Development	
SAFGRAD	- Semi-Arid Food Grains Research and Development Project	
OCLALAV	- An International Program in Africa for study of grain eating birds	

All of the above, and many others, can and should be complementary to one another and do not need to be competitive, nor does there need to be unnecessary duplication of effort. For each to reinforce the impact of others, a very good level of intercommunication, sharing of information, and joint planning will be needed. Not one of these organizational entities needs to feel threatened by the existence or accomplishments of another, but each can draw on the contributions of the others to help accelerate the progress it is able to achieve.

The gene pool residing in the various genetic entities embracing the total worldwide diversity of the genus is a central element. Several institutions contribute to the collection, preservation, description, maintenance and utilization of this basic resource. The International Board for Plant Genetic Resources (IBPGR), with its Standing Committee on Sorghums and Millets, can continue to fulfill a key coordinating role in efforts toward making the most of this basic resource. This committee has contributed toward developing an appropriate list of descriptors for characterization and recording information on the entries in the collections. The USDA, through its Division of Plant Exploration and Introduction, the Rockefeller Foundation, the Indian national sorghum improvement program, ORSTOM, IRAT, and ICRISAT have all been instrumental in collecting and assembling the basic germplasm collections presently on hand consisting of more than 17 000 entries. Ethiopia and nearby areas, considered as the center of origin for this crop, have provided a rich range of genetic diversity. Collections from other parts of Africa and the Indian subcontinent to which the crop had spread have made valuable and extensive additions.

The Sorghum and Millet committee has indicated that the present collection, rich as it may be, is still deficient in its completeness in sampling the genetic diversity which may exist in sorghum growing areas not yet covered, in more remote and less accessible areas in the countries already covered, and is especially short in its coverage of the diversity in related wild species in the genus. The same agencies will need to make up these deficiencies.

The maintenance and preservation of genetic collections in a viable condition, the evaluation and description of the various entries, the identification of genes carrying specific qualitative and quantitative characters, and ultimately their utilization through incorporation into superior varieties and hybrids must involve a wide range of institutional participation. ICRISAT has developed good medium term seed storage facilities and is currently developing facilities for long term storage. ICRISAT has been designated as a primary center for maintenance of the sorghum germplasm collection. Duplicates will be maintained in long term storage in the USDA center at Fort Collins. Colorado. Turrialba, Costa Rica; Addis Ababa. Ethiopia; Bari, Italy; and Brasilia, Brazil are among the locations which will supplement the primary centers in maintaining portions of the collection.

It is not always possible directly to utilize, in breeding and varietal improvement programs, many of the valuable characters of varieties or entries taken from one type of environment for the improvement of varieties suitable to another and different ecological situation. One program aimed at overcoming a part of this problem is the conversion program of the USDA in which the characteristics of some of the taller growing photoperiod sensitive varieties from the tropics are transferred into semidwarf nonphotoperiod sensitive varieties which can be grown in more temperate environments. These converted entities then become a part of the resources which can be drawn on in both tropical and temperate programs.

The characterization of entries in the world collections must be a continuing process carried out in a wide range of locations which expose the entries to a range of ecological conditions and stresses. The development of standard descriptors and their progressive refinement provides a basis on which the observations from various locations can be taken for analysis and collation. The ultimate institutional arrangement for a comprehensive collation, computer recording, and management of such information is still to be developed.

The ultimate value of genetic collections lies in the preservation of the total genetic diversity of the genus and its availability for use in developing genetic combinations which are productive and are able to meet and overcome the stresses to which they may be subjected in the wide variety of environments in which they may be needed around the world, including stresses produced by new diseases, insect pests, or other hazards.

A comparison of different breeding methods and approaches is beyond the scope of this paper. Institutionally, however, one might make some distinction in the roles being performed or which seem likely as between private commercial firms, individually or collectively, and those in which public agencies may be needed.

The Texas Agricultural Experiment Station, with cooperation of the USDA, deserves special mention for its pioneering leadership in demonstrating the potential for sorghum as a feed grain and for introducing and developing the varieties and plant types necessary for its major expansion and production in the plains area of the USA. Other state experiment stations including Kansas, Nebraska, and Indiana have also made important contributions in recent years.

In the aggregate, private commercial seed companies can be expected to concentrate their attention to those segments of sorghum production in which a substantial volume of market sales of seed can be anticipated and therefore, a profitable commercial seed operation can be anticipated. The most obvious segment for this type of operation is the relatively large-scale production of sorghum as a feed grain. As indicated previously, this has developed to date in the middle west and plains area of the USA. Argentina, Brazil, and parts of Mexico. Grain type does not have to play as large a part therein as is the case in which human taste preferences and processing and cooking qualities become more significant. The grain does need to be reasonably bold, its digestibility and nutritive value good, and yield relatively high and dependable. Obviously, components which might affect its digestibility or utilization of its nutritional components should be avoided. Generally speaking, varieties or hybrids with relatively short stature, which are weakly or nonphotoperiod sensitive, quite uniform in maturity, with a narrow grain to stover (stubble) ratio, and suitable for mechanical harvesting would be preferred. For this segment of sorghum production, the private commercial seed industry has done an excellent job in building on the pioneering work referred to above in developing suitable hybrids and varieties and providing sources and supplies of planting seed. Public agencies perform a vital role in providing access to the necessary range of genetic characteristics, in developing principles and techniques for genetic improvement, and in evaluating progress. The plant breeding and seed production for this sector can be handled well by private commercial seed companies.

The development of sorghum varieties needed for providing the basic subsistence food needs, with their desired grain qualities, taste characteristics, and adaptation to the various environmental conditions and specific situations encountered by small farmers of the tropics cannot be expected to be a high priority for the private seed companies and remains, to a large degree, a need to be filled by public agencies. Even in the more advanced and larger research systems of the developing world, this has not in the past been a high priority activity. It has usually been relegated to a secondary position and often combined with other responsibilities and commodities in a miscellaneous category. This is still a neglected area, but one which will, no doubt, receive more prominent attention in the future in nations throughout the semi-arid tropics. The task is ultimately one of the primary concerns of the individual nations in which sorghum is a significant basic staple food. But there are many common elements and problems which cut across national boundaries. And even within small nations, the range of climatic patterns, rainfall duration and distribution, and soil characteristics may provide several different varietal and cultural adaptation zones. Such nations often do not and cannot have a research organization in the near future adequate to cope fully with their needs. And even if they did, it would be wasteful and inefficient for them to do so individually since several nations in the same region have similar needs.

ICRISAT can fulfill a vital and indispensable role in such situations in providing the range of genetic materials, put together in combinations which provide the range of characters needed, and out of which varieties can be selected and developed, tested, and proven for their dependability in the various ecological situations encountered. By promoting and organizing testing within and across several nations in locations in which the environmental conditions are monitored, the range of transferability of information from one location to another can be predicted. ICRISAT's work on climatic modelling as a basis for predicting the adaptability of crops and varieties to the characteristics of their environments should enable it to select materials and elements of production technology most likely to fit specific situations and thus achieve substantial economies in experimentation by eliminating in advance those materials and practices which could not be expected to be successful and concentrating attention on those with greater probability of success. The individual national programs would be cooperating partners in such international development, adaptation, testing, and verification of materials and technology. Regional organizations and programs such as those provided by IRAT and SAFGRAD can and should be partners in such activities.

ICRISAT will no doubt continue its search for ways to improve its service to the programs of the many nations of Africa, Asia, and Latin America which are seeking to develop the full potential of this crop. Because of sorghum's central importance to the food budget and economies of a large number of nations in West Africa, and the substantial divergence in ecological and pest conditions from those prevailing in ICRISAT, and the need for close contact with production and marketing problems in that region, ICRISAT has established a subcenter for sorghum work in West Africa, linked to its headquarters, but oriented especially to problems peculiar to the region. It is anticipated that this will improve ICRISAT's ability to provide service to national programs throughout the region, in several of which ICRISAT personnel have been posted on special projects, and with the regional Semi-Arid food Grains Research and Development (SAFGRAD) program.

ICRISAT also recognizes the need for attention to sorghums suitable for higher altitudes and cooler climates on several continents, as well as for other situations in Latin America with high potential for sorghum production. The cooperative project presently hosted by CIMMYT is helping to fill these needs. Other approaches for providing a two-way liaison to Southern and Eastern Africa, Southeast Asia, and South America, especially Brazil, while less intensive at present, will require continued study and attention.

The UNDP has been very helpful and imaginative in helping to provide the financial resources for extending ICRISAT's program, especially to important areas on continents other than its headquarters location. The support and assistance of the UNDP/FAO field staffs in these regions have contributed substantially to program effectiveness.

The French organizations, IRAT and ORSTOM have a long history of work on sorghum improvement and development work in the Francophone countries of West Africa. ORSTOM, in cooperation with the IBPGR, has taken the lead in recent years in organizing sorghum and millet collection missions in Africa and has thus made important additions to the germplasm collections. IRAT continues to provide support to cooperative applied research on sorghum improvement in those nations, including the provision of key personnel in ICRISAT cooperative regional programs in Africa.

Likewise, the UK has had a long historic association with agricultural research and improvement programs in the Anglophone countries. This has been particularly significant in countries such as Nigeria, Ghana, Kenya, Uganda and the Sudan. Institutions in the UK concerned with tropical agriculture such as the Weed Research Organization, the Tropical Products Institute, the Centre for Overseas Pest Research, and Reading University are among those institutions whose input has proved valuable in studies on *Striga* control, pheromones, grain quality, pest management and control, and crop physiology.

The International Centre of Insect Physiology and Ecology (ICIPE) has been cooperating with ICRISAT in the study of certain problems related to the biology and behavior of the sorghum shoot fly and to a lesser extent on other insect pests. This cooperation will no doubt be further cultivated and extended.

The Rockefeller Foundation and the Indian national sorghum improvement projects supported by the Indian Council of Agricultural Research deserve special mention in an institutional context, for their contributions to advances in attention to sorghum improvement during the past 25 years. First under the combined Project for Intensification of Regional Research on Cotton, Oilseeds, and Millets (PIRRCOM), systematic collections and evaluation of sorghum germplasm were made throughout India, supplemented by importations from other areas. In cooperation with the USDA, the Rockefeller Foundation supported collection missions in Ethiopia.

India later separated out sorghum for special attention under its All India Sorghum Improvement Project (AICSIP). The use of male-sterile lines in production of hybrids received early attention but presently both first generation hybrids and varieties are included. The Rockefeller Foundation personnel promoted exchange of genetic material and studies on production technology not only in cooperative programs in India but in other countries and continents as well. These studies have helped in identifying and calling attention to many complex problems which must be faced if sorghum is to fulfill its potential in contributing to the world's food and nutrition budget.

The Symposium on "Sorghum in Seventies" held just prior to the establishment of ICRISAT, was a landmark as, I am sure, the current symposium on "Sorghum in the Eighties" will become.

We all know of the susceptibility of sorghum to depredation by birds and in particular to the hordes of *Quelea* on the African Continent. An African regional program (OCLALAV) has devoted considerable effort to the study of the population dynamics, migration patterns and behavior of these birds. Some effort has been devoted to the genetic factors and grain qualities of sorghum varieties which favor or diminish bird preferences. Unfortunately, grain characteristics which appear to be less attractive to birds have frequently been associated with chemical components that seem to reduce the nutritive value or digestive utilization of the grain. Bird damage remains a serious problem, especially in Africa, and justifies continued attention.

Since this paper is concerned with institutional considerations, the listing of individuals who provided the leadership to programs has been avoided. It should be remembered, however, that the imaginative, dedicated, and sustained leadership of outstanding individual scientists has been, and will continue to be the factor that makes institutions effective.

My treatment on institutional considerations has not been, and cannot be, exhaustive. The orchestration of the cooperative and complementary efforts of able and dedicated people working through the large range of organizations concerned will largely determine the contribution this crop can and will make to the future welfare of mankind.

Transforming Traditional Sorghums in India

N.G.P. Rao*

Viewed against the background of the agricultural history of India, changes that influenced Indian agriculture during the 1960s and 1970s are perhaps the most significant. The rapid impact of these changes and the potential created do give us confidence that India could successfully meet its current and future needs of the most needed agricultural commodities. We have certainly been fortunate to be participants and witnesses to this great transformation.

Mixed cropping, crop rotations, cultural practices, organic manures, chemical fertilizers and plant protection chemicals no doubt influenced traditional agriculture, but it is the major genotypic changes brought about during the 1960s that triggered cultivar-input-management-interactions; resulted in quantum jumps in productivity; imparted stability to production and enabled practice of new cropping systems leading towards more efficient land and water use.

The transformation that began with irrigated wheat and rice soon pervaded dryland food crops like sorghum and pearl millet, commercial crops, fruits and vegetables. Changes leading towards the transformation of sorghum in India is the subject of my presentation.

Agricultural Systems of Semi-Arid Tropics: Improvement or Transformation?

Agricultural systems of the semi-arid tropics (SAT) by and large, continue to be subsistence systems and reflect the highest degree of crop diversification. Analyzing the role of risk in dryland agriculture in India, Binswanger et al. (1980) concluded that income risk, measured as the variance of income over time, is high. Variability in production is the major source of this income risk rather than price variability. For risk averse farmers they contend that such income variability leads to underinvestment. This is true of all subsistence agricultural production systems. Consequently, mixed or intercropping became an important feature of traditional agriculture and its superiority in terms of insurance from risk, higher returns and better labor use has been well documented (Abalu and D'Silva 1980, Jodha 1980).

It may, then be pertinent to examine the essential components of traditional agricultural systems. There is a striking parallelism in the evolution of tropical cultivars across continents. They are tall; late maturing, the growing period being considerably longer than the length of the rainy season; generally photosensitive; and characterized by localized adaptation and low harvest indices. Such tropical cultivars are generally adapted to low population levels and generally exhibit lower rates of fertilizer response. Under adequate moisture and low populations they do produce large earheads reflecting their individual superiority, but their community performance is poor even when there is no stress. Since flowering generally takes place after the cessation of the rainy season, rainfall fluctuations render them highly vulnerable, and crop losses approach total failure in years of low and erratic rains. Depending on the components of the cropping systems, the degree of damage may vary and one of them might provide some insurance. Yet, sole and mixed crops in traditional systems are low yielding and climate-vulnerable. This is generally so with sorghum and applicable with some modifications to other dryland crops and cropping systems.

This being the case, a pertinent question is whether research efforts should be directed to improve existing systems or should they be directed towards transformation of existing sys-

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terns. All researches in India till the 1960s and in most African countries till today have been directed towards improvement of existing agricultural systems. They generally involved crosses between related varieties for cultivar improvement, fertilizer and population studies, practices aimed at better soil and water management and modifications to existing cropping systems. These efforts were based on local or improved local cultivars and did reflect increased yields under experiment station conditions. The recommendations that emerged from such researches were aimed at marginal increases and frequently involved change of cultivars, but similar in plant architecture to locals, use of organic manures, low levels of fertilizer and low plant populations and with some soil and water conservation measures such as mulching, contour bunding, etc. The recommendations that emerged from the dry farming research stations of the Deccan *rabi* furnish examples in this direction. They were somewhat "survival-oriented" rather than "productivity-oriented" and did contribute to some yield advances but could do little to cross the environmental barrier or the yield barrier.

Analyzing crop yields in relation to rainfall fluctuations, Rao et al. (1975) emphasized the need for transgressing environmental limits and aiming at quantum jumps in yield levels to enhance the productivity of rainfed crops. A breakthrough in rainfed agriculture can, therefore, be expected by planning for large quantum jumps rather than for slow and graded increases which are within the limits of environmental fluctuations. Illustrating from data on sorghum obtained during 1972/73, which was one of the most difficult years encountered with respect to rainfall, we (Rao et al. 1975) preferred the transformational approach to that of an improvement approach. It is this approach that has yielded results in the Indian context. I consider it meaningful to the rest of the SAT.

Considering the policy implications of their risk analysis in SAT India, Binswanger et al. (1980) concluded that there is no need for advocating development of risk graded technologies so that small farmers may adopt the low yield low risk ones and the large farmers the high yield high risk ones. I fully agree with them and the transformational approach cutting across environmental limitations is the answer and I therefore, propose to further deliberate and elaborate on this.

Genotype Alteration: Performance, Adaptation, and Stability

The attributes of tropical cultivars have been listed: tallness, lateness, photosensitivity, low harvest indices, poor community performance, etc. In traditional agriculture, the timing of the main stages in the reproductive cycles of plants is optimized in relation to seasonal conditions through control mechanisms that are extremely sensitive to daylength and temperature (Evans 1980). If this is so in traditional agriculture, the design and development of productive and stable agriculture requires re-optimization of the cycles of growth and reproduction in such a way that the emphasis is on the economic product rather than on total dry matter and that the more critical phases of growth coincide with favorable periods of climate.

Water use efficiency refers to the yield of dry matter produced per unit of water consumed and drought resistance is the ability to survive, endure and compensate for or escape damage from wilting (Reitz 1974). Sorghum is no doubt efficient in water use requiring about 322g of water per g of dry matter (Briggs and Shantz 1914), but if the production of total dry matter of the plant extends beyond a limit, it will then limit water use efficiency. Severe stress during seedling, flower primordial and grain filling stages is generally critical and it is desirable that the probability of these stages coinciding with assured periods of rainfall or profile moisture be maximized.

Most traditional *kharif* sorghums of the Deccan and the central Indian plateau require 140 days or more to mature, while the duration of a normal rainy season is from the beginning of July to mid or late September. August usually represents the peak rainfall month. Such sorghums usually remain in the vegetative stage till the second week of October, and if rains cease earlier, yield losses are heavy. The total dry matter produced in normal circumstances may be as high as 450 g per plant, and nearly 70% of this is accumulated in the stalk (Rao and Venkateswarlu 1971). They are characterized by a single peak for the rates of growth coinciding with flowering. The behavior of several African sorghums is similar (Goldsworthy 1970). The temperate sorghums on the other hand produce less dry matter per plant, exhibit two peaks for growth rates coinciding with preflowering and grain-fitling stages resulting in a 50 : 50 dry matter distribution (Anantharaman et al. 1978). This is illustrated in Figure 1.

Superior sorghum hybrids and varieties developed from temperate-tropical crosses have reduced maturity duration (100-110 days) and consistently yield well (Table 1). The critical stages of growth—seedling, flower primordia, and grain filling—coincide with periods of assured rainfall or satisfactory profile moisture status. Thus, in breeding for efficient water use for grain production such corrections for duration, dry matter production and differentiation at optimal times of the season are essential and should constitute the first steps in modifying traditional tropical sorghums.

Yet arguments are still advanced that in heavy rainfall areas the duration of the traditional sorghums still represents the optimum and that improved cultivars should match the duration of locals. Efforts in Africa (Andrews 1975) to develop long-season dwarfs are yet to yield useful results. Earlier studies by Rao et al. (1973) reveal that highest yields are obtained at intermediate heights and maturities and that an "intermediate optimum" satisfies several requirements including grain, stover, input responses etc., in tropical countries. If there is an extended season, it is better to capitalize on it through practice of suitable cropping systems rather than through

Table 1. All India performance of sorghum hybrids and varieties (*kharif*).

Hybrid/ Variety	Grain yield (kg/ha) 1978	1979	1980	Av,	%CSH-1
			Hybrids		
CSH-1	3582	3522	3034	3379	100
CSH-5	4307	3808	3437	3851	114
CSH-6	4265	3648	3480	3798	112
CSH-9	5036	4353	3836	4408	130
			Varieties		
SPV-221	3198	3303	3160	3220	95
SPV-245	3868	3564	3237	3556	105

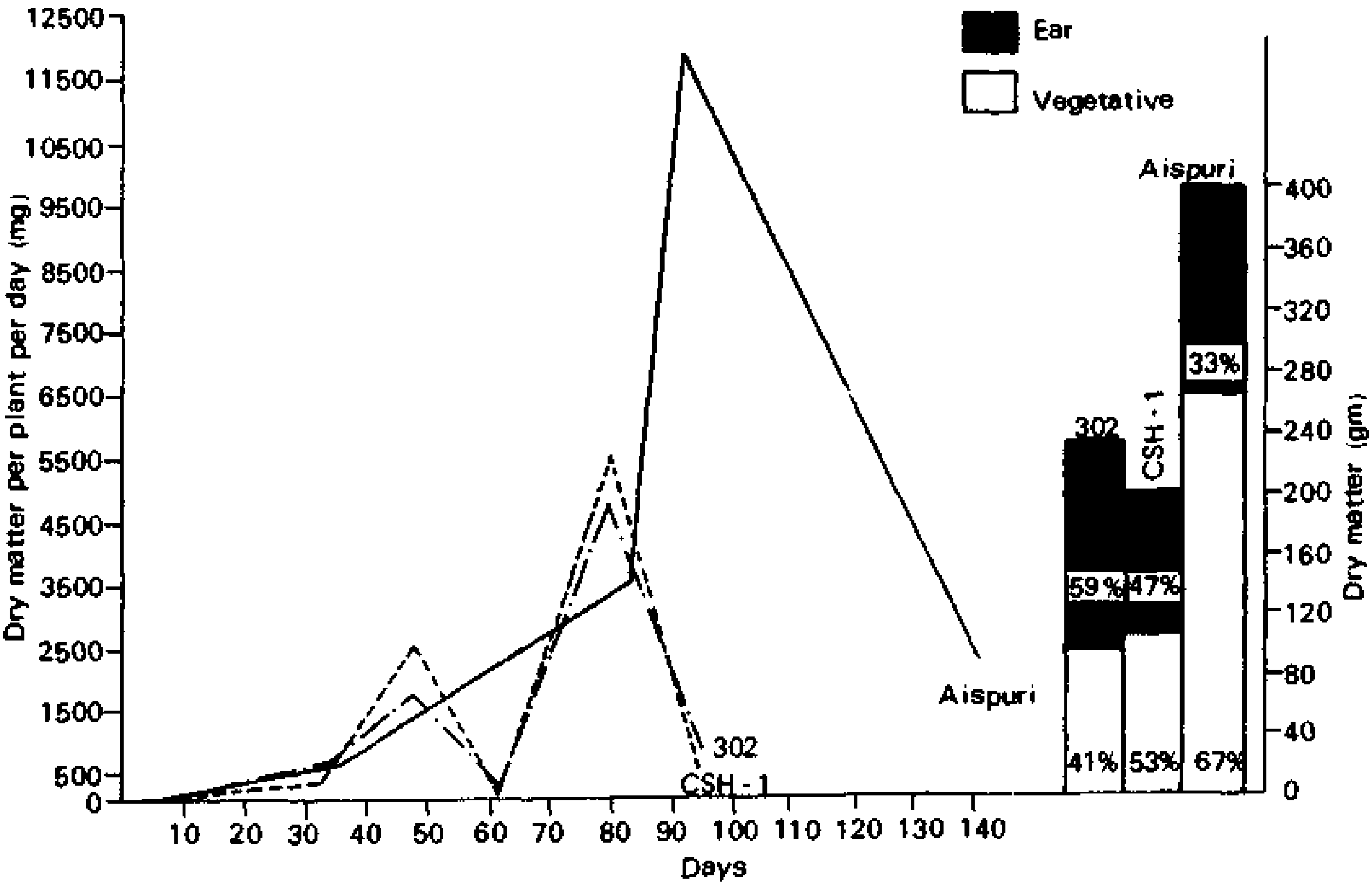


Figure 1. Rates of growth and dry-matter distribution of tropical and temperate sorghums.

growing very late cultivars. Extremely late varieties have no yield advantage.

Once, the major corrections for duration and dry matter in relation to rainfall probabilities are accomplished, we could capitalize on incorporating attributes like varietal differences for photosynthesis under moisture stress, root systems and various attributes associated with drought resistance. We have discussed these aspects earlier (Rao et al.1979) and I shall not go into them presently since other speakers may be considering them at length.

While the impact of altered genotypes of sorghum has been spectacular in some parts of India during *kharif,* attempts of altering *rabi* sorghums have met with partial success. The planting of *rabi* sorghums grown under residual moisture in black soil areas generally starts towards late September and may extend up to late October. Mid-October plantings are common. By November the temperatures begin to drop. Depending on the moisture status of the profile. the black soils begin to develop deep cracks either at flowering time or later. This results not only in moisture stress during the postflowering period, but it causes heavy lodging.

The variety M35-1 predominates in the *rabi* belt and we (Rao and Murty 1963) analyzed the reasons for its wider adaptation. Compared with compact headed types, it is earlier in maturity, has a better root system, and had optimum dry matter production. It is also the most drought resistant variety (Sullivan 1972).

The problems of varietal improvement during *rabi* are somewhat different. In years of stress, extreme earliness as exhibited by photosensitive hybrid CSH-2 enables it to escape drought effects and produce yield, but the yields are low and not comparable with M35-1 in normal years. In fact, we considered the use of such hybrids in extremely drought prone areas. The late *kharif* sorghums are also highly sensitive and become extremely dwarf, early, and low yielding during *rabi.*

The total dry matter produced by traditional winter types like M35-1 is not high like *kharif* sorghums and they do exhibit two peaks for rates of growth and a favorable dry matter distribution pattern. Efforts to further influence harvest index in favor of grain rendered types like R16 more susceptible to charcoal rot. This means, unlike *kharif.* the options for influencing duration and dry matter are limited during *rabi.*

Yet some progress has been made and hybrids like CSH-7R and CSH-8R and an improved variety SPV-86 did exhibit constant yield superiority over M35-1, even though the margin of increases were not as high as those obtained during *kharif* (Table 2). But, when the new hybrids were grown under a new set of agronomic conditions, i.e. advanced dates of plantings, fertilizer use, and optimal populations, yield differences over M35 -1 were substantial (Fig. 2). But as plantings became delayed, the yield advantage over M35-1 declined, and after a point in November they were inferior to M35-1. The parents of the hybrids had more *kharif* parentage in them, and as the plantings were delayed, apart from moisture stress, temperature sensitivity came into operation. The variety M35-1 is also less sensitive to low temperature. Therefore, I feel that development of temperature-insensitive males and females with *rabi* adaptation could lead to the development of superior *rabi* hybrids.

The *rabi* situation is difficult but is more predictable, since very little rain is received during crop growth. I believe that the limits of the moisture status and its progressive decline in *rabi* soil profiles under extreme stress, optimal, and suboptimal conditions have been quantified. It is then possible to decide on the limits of dry matter that such profiles could sustain to maturity. If these limits are known and with the present understanding of drought resistance and temperature sensitivity of genotypes, it should be possible to develop more efficient genotypes for the future.

That tropical cultivars are highly photosensitive and local in their adaptation has been well recognized. The virtues of photosensitivity in tropical situations have also been frequently overemphasized. While photosensitive varieties do tend to flower about the same time when plantings are scattered within a season, the yield

Table 2. All India average performance of *rabi* hybrids and varieties.

Hybrid/Variety	Grain yield (kg/ha)
CSH-8R (Hybrid)	3313
CSV-8R (SPV 86) (Imp. Variety)	3299
M 35-1 (Local)	2881

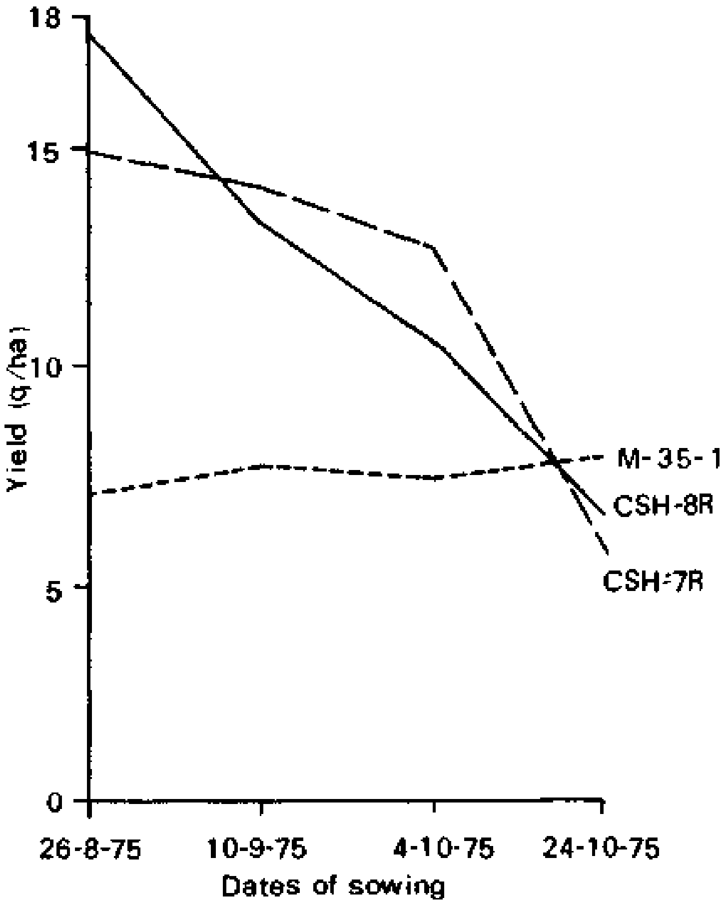


Figure 2. Yield of sorghum as affected by different dates of sowing during rabi *season (Sholapur).*

reduction on late plantings is drastic. Such cultivars, which by themselves are low-yielding and subject to climatic fluctuations in their own environments, could not be expected to adapt and perform in an altered environment.

Wide adaptation, therefore, involves genotype alterations to suit growing conditions, superiority in performance per se, and less sensitivity to daylength and temperature in some situations. Once these changes have been incorporated in altered genotypes, the entire *kharif* sorghum belt of India could be treated as one zone (Fig. 3) in place of the several small agroclimatic regions towards which breeding efforts were directed in the past (Rao 1970). This is a major conceptual change that furthered sorghum improvement efforts in the country.

The statement of Evans (1980) that high-yielding crops are neither more nor less susceptible to annual variation must be viewed with caution since the precise purpose of genotype alteration for dryland agriculture is to minimize such variation. An analysis based on over 300 experiments over several years (Rao and Rana 1980) furnished data on changes brought forth in improved cultivars developed early in the project with respect to average yield levels and coefficients of variability (Fig. 4). This is a very significant change that reflected on sorghum production over vast areas in Maharashtra and Karnataka States.

Our studies to date have also established that, compared with improved varieties, hybrids do exhibit homeostatic advantages particularly under moisture stress (Rao and Harinarayana 1968; Singhania and Rao 1976). A more recent analysis of 3 years data from All India experiments by Rao et al. (1982) further established that the hybrids CSH-9, CSH-6, CSH-5, and CSH-1 were the highest yielders in the *kharif* tracts of the entire country and were the most widely adapted. The improved varieties were no doubt superior to locals in yield and adaptability but were not comparable with hybrids. The locals were characterized by low means and high coefficients of variability We are now examining the possibilities for raising the yield of improved varieties to the level of hybrids (Balaramireddy and Rao 1981).

Further efforts to use risk aversion in plant breeding (Barah et al. 1981) point out that yield and risk preference based rankings are closely related. Also correlated are adaptability and stability lending support to our past breeding efforts towards genotype alteration and multilocational testing in the pursuit of low risk and high yields (Fig. 5).

We are now concerned with the task of incorporating greater levels of resistance to insect pests (Rao et al. 1977) and diseases (Rao et al. 1980) against the altered genetic background so as to confer greater levels of stability in performance besides reducing or even eliminating use of pesticides. Our emphasis now is on understanding and incorporating resistance to several of the insect pests and diseases together in altered genotypes (Rao 1981).

Adaptation to Soil and Climate

Soil, water (rainfall) and solar energy constitute the natural resources of semi-arid crop production systems with a well established relationship of subsistence adaptation. It has been the past experience that resource management by itself did not yield perceptible results until a relationship of productive adaptation has been established.

The SAT regions have an arid season of 5-10 months when potential evapotranspiration (PET) exceeds precipitation. Since PET is dependent on rainfall, temperature, and crop cover, crop adaptation to soil and climatological factors is of primary concern. We will now consider genotype adaptation to soil and climatic factors.

Agriculture in the tropics is said to have first developed in areas where the soils are of high base status—Vertisols, Alfisols, Mollisols, and certain Entisols and Inceptisols—which are also the centers of population density. The impact of the green revolution has also been largely con-

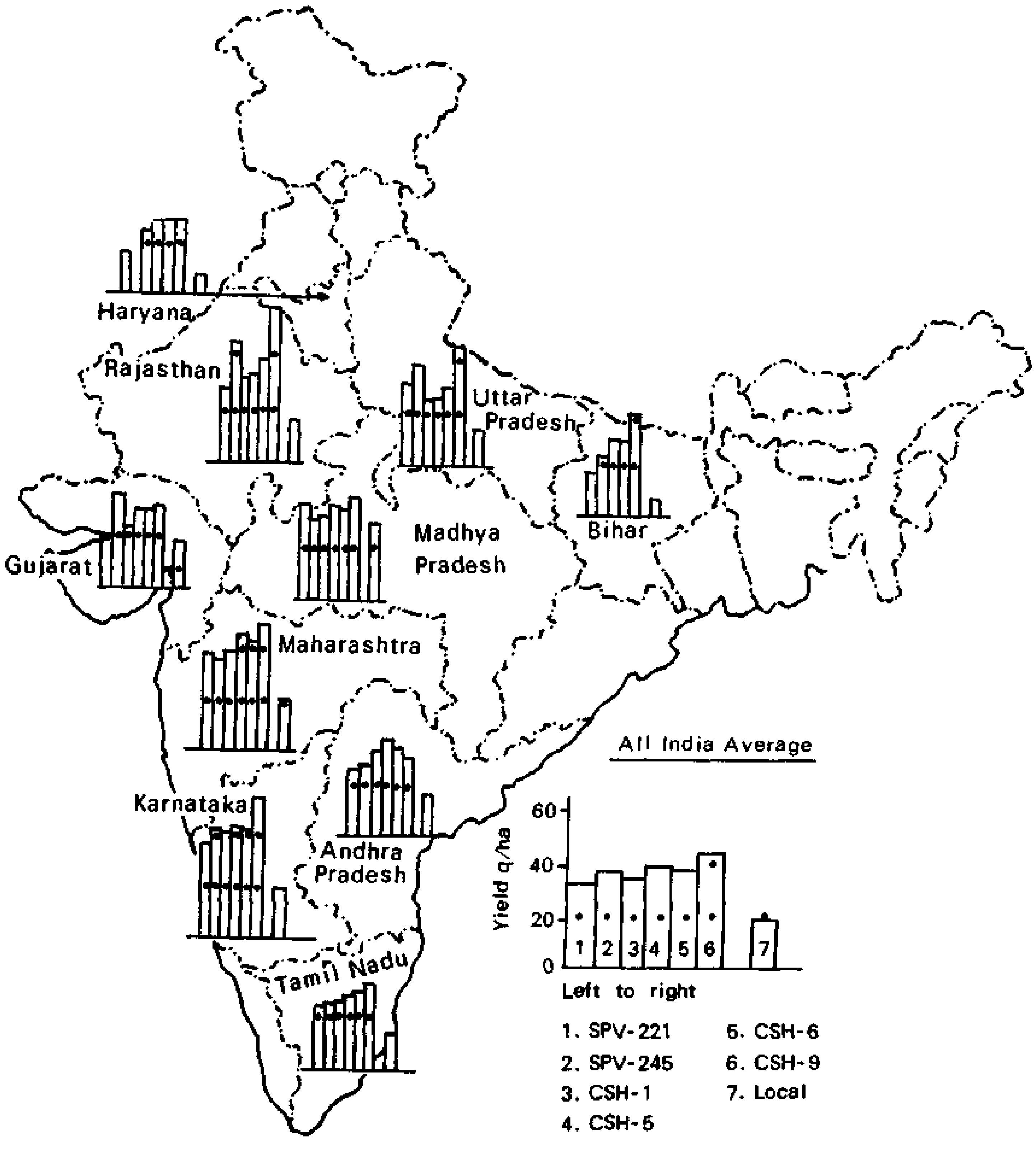


Figure 3. Hybrid and varietal performance in India (1978-80 kharif).

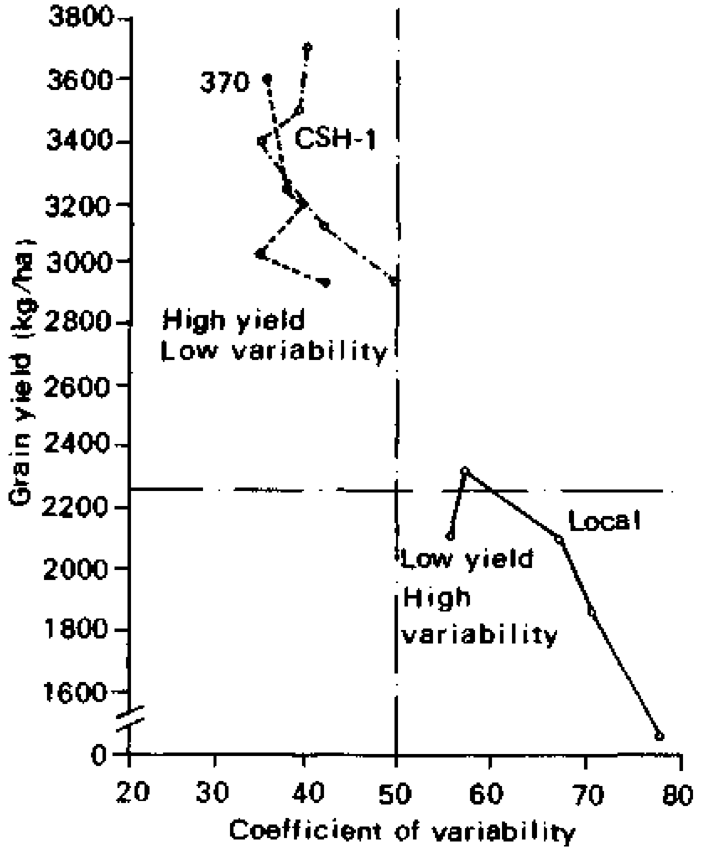


Figure 4. Adaptability of tropical and temperate sorghums.

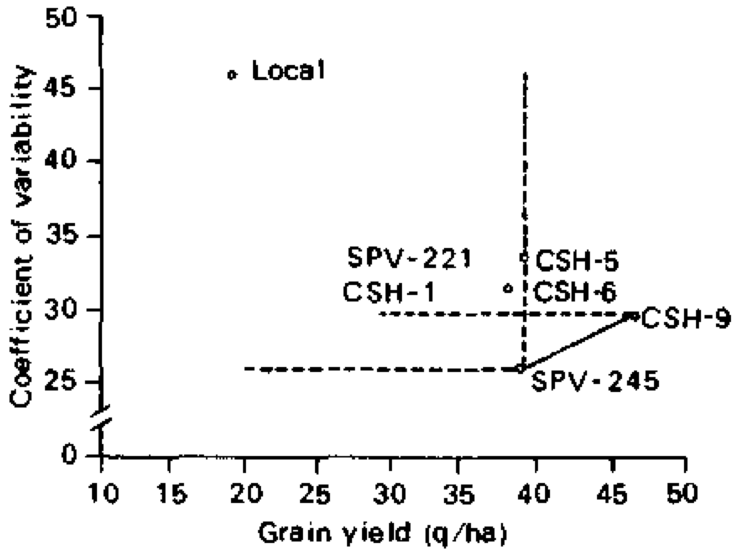


Figure 5. Adaptability efficiency of some selected hybrids and varieties (1978, 1979, 1980).

fined to areas of high base status (Sanchez and Buol 1975).

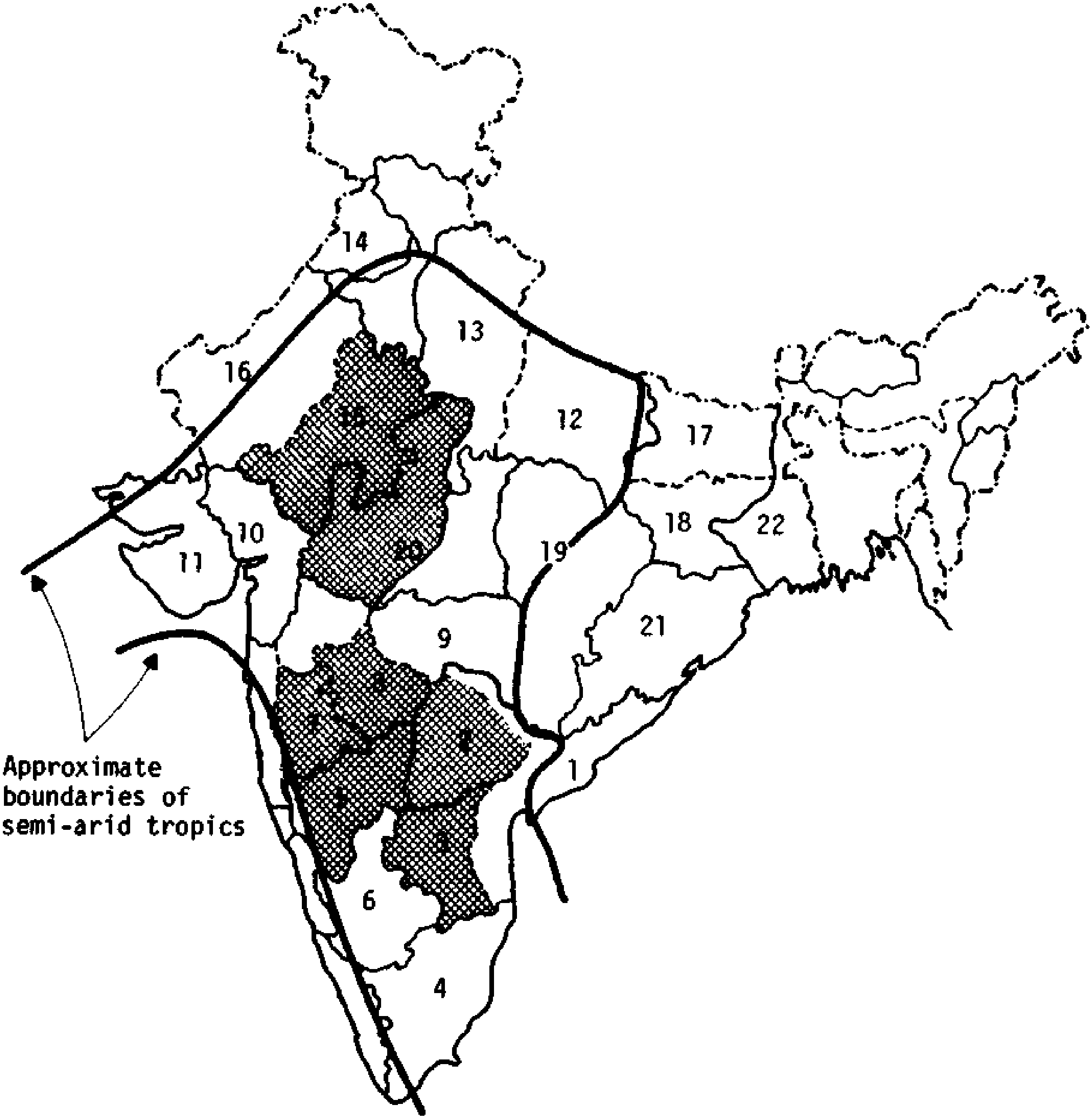
Sorghums in India are predominantly cultivated in Vertisols and to a limited extent in Alfisols and both have not posed any serious problems. The major point of concern is the ability of the soil profile to store water for crop use. Depending on the soil type, this may vary from less than 100 mm to over 250 mm. The storage ability partially mitigates the effects of irregular rainfall. Encrustation problems may be encountered, more particularly in the red soil areas, if heavy rains after sowings are followed by a hot and dry spell, but this problem has not been serious.

If water does not limit vegetative growth, total dry matter production is related to solar radiation and can be predicted. But frequently water stress does limit the rate of dry matter production. Fluctuations in rainfall, which are changes repeated over time, are a rule rather than an exception. Predictions of the amount and distribution of rainfall are difficult. Based on early rainfall in a season, some predictions of the behavior of rains may be possible. Studies by the Indian Meteorological Department estimated that climatic variations resulting in droughts, floods, etc., may account for more than half the variation in crop yields.

In recent years there has been growing interest in climate changes.and climate-food output relationships. It is believed that good or bad weather in one part of the world may have a similar influence in other parts (USDA 1975). Unfavorable weather conditions during 1964-66 and 1972-74 were responsible for a decline in global food production. Weather variability is considered to be a much more important consideration than a global cooling or warming trend (Thompson 1975). Averages of the preceding 30 years are stated to provide better guidelines for development of strategies compatible with the laws of nature to mitigate effects of climatic fluctuations on production.

The SAT region of India, excluding the coastal areas of Andhra Pradesh and Tamil Nadu, parts of southern Karnataka, eastern Uttar Pradesh, eastern Madhya Pradesh, northeastern Rajasthan, Haryana, and Punjab represents the major grain sorghum belt. Even these excluded areas grow forage sorghums. The areas prone to moderate and severe drought are depicted in Fig. 6. Of the 16-18 million hectares grown under sorghum, approximately 2/3 of the area is cultivated during the rainy season (*kharif)* and 1 /3 during winter *(rabi)* primarily in the Deccan Plateau covering near continuous areas in Maharashtra, Karnataka. and Andhra Pradesh.

The limits of the rainy season in most regions



1. Coastal Andhra Pradesh
2. Telangana
3. Rayalaseema
4. Tamil Nadu
5. Interior Karnataka North
6. Interior Karnataka South
7. Central Maharashtra
8. Marathwada
9. Vidarbha
10. Gujarat
11. Saurashtra & Kutch
12. Uttar Pradesh East
13. Uttar Pradesh West
14. Punjab & Haryana
15. Rajasthan East
16. Rajasthan West
17. Bihar Plains
18. Bihar Plateau
19. Madhya Pradesh East
20. Madhya Pradesh West
21. Orissa
22. Gangetic West Bengal

Figure 6. Major sorghum areas prone to drought.

are fairly well known. The southwest monsoon, which influences most of the sorghum belt with the exception of Tamil Nadu and a small portion of Andhra Pradesh, usually establishes towards the end of June and terminates before the end of September. The probable date of commencement of sowing rains, the months and weeks when rainfall probabilities are high and low, and the likely inter-spell duration between rains have been computed (Raman 1975). July is the least drought-prone month and October the most (George et al. 1973). Premature cessation of the monsoon by the beginning of September is not uncommon, and October rains are uncertain. Consequently traditional *kharif* sorghums may run out of moisture before flowering. The moisture status of the *rabi* soils, where sorghums are grown under residual moisture, is frequently unsatisfactory during the grain-filling period, resulting in serious yield losses. The deccan *rabi* used to be famine prone.

It is, then, the water balance that limits the length of the growing season. The mean duration of the crop-growing season for some sorghum-growing areas computed by Krishnan (1974) is summarized in Table 3. The justification for long-season sorghum seem to arise from such exercises.

A closer look at the present-day situation in areas represented by Jalgaon, Akola, and Amravati in Maharashtra, and Neemuch, Khandwa. and Indore in Madhya Pradesh, which are all in the drought-prone black soil belt, reveals that 100 -110-day hybrids with some built-in ability to stand grain deterioration when rains occur late have taken firm root, providing for assured single-crop sorghum and a possible second crop of safflower or chickpea. Areas with supplemental irrigation took to a sorghum-wheat rotation that was not possible with traditional cultivars.

Thus computed, crop-growing seasons at best indicate the longest possible growing period, and strategies to avoid failures should take into account the effective rainfall period with its attendant aberrations. One has to plan for assured single-crop yields within sole and intercropping systems in low rainfall areas, and two-crop sequences in high rainfall areas.

Table 3. Crop growing season in soma sorghum growing araas (Krishnan 1974).

Location	State	Av. annual rainfall (mm)	Av annual PET (mm)	Crop growing season: Actual duration	Crop growing season: No. of days	Remarks
Kurnool	Andhra Pradesh	674	1827	Jun 17-Oct 26	132	Alfisol-Kharif and Vertisol-Rabi
Cuddpah		743	1834	Jun 14-Nov 30	170	
Hyderabad		743	1834	Jun 14-Nov 30	130	"
Raichur	Karnataka	717	1951	Jun 12-Oct 28	139	Mostly Vertisol-
Gulbarga	"	753	1913	Jun 9 -Oct 21	135	*Rabi*
Poona	Maharashtra	715	1474	Jun 4 -Nov 21	171	"
Sholapur	"	742	1802	Jun 8 -Nov 2	148	"
Ahmednagar	"	677	1605	Jun 2 -Nov 8	160	"
Aurangabad		792	1774	Jun 5 -Nov 20	169	(Some *Kharif)*
Akola	Maharashtra	877	1730	Jun 5 -Dec 4	183	Mostly Vertisol-
Amravati	"	975	1769	Jun 4 -Dec 22	202	*Kharif*
Jalgaon	"	840	1912	Jun 9 -Nov 21	166	
Khandwa	Madhya Pradesh	961	1729	Jun 7 -Dec 30	207	"
Neemuch	"	895	1601	Jun 14-Jan 15	216	"
Hanamkonda	Andhra Pradesh	945	1787	Jun 4 -Dec 8	188	Alfisol- *Kharif* and Vertisol-Rabi
Bidar	Karnataka	977	1754	Jun 1 -Dec 13	196	Alfisol -*Kharif*
Indore	Madhya Pradesh	1053	1813	Jun 5 -Dec 27	206	Vertisol-Kharif

Statistical probabilities of the occurrence of drought have limitations, and the farmer's interest being always in the "current year," knowledge of soil and climate together with actual performance in normal, above-normal, below-normal, and aberrant years of rainfall would furnish a rational basis for decision making in the development of crop production strategies that would stand the test of time. Such years were encountered during 1964-66, 1972-74, 1975-76, 1976-77. 1980-81. etc., and both rainfall and yield data for diverse cultivars are available for analysis. This transitional period in Indian sorghums has thus furnished a valuable opportunity to assess the potentialities and limitations of alternate crop production strategies and arrive at rational conclusions. Such a strategy based on actual situations encountered seems to be the best suited to minimize climatic vulnerability and to maximize productivity when encountered with more favorable situations (Tables 4 and 5).

Genotype alterations coupled with management practices, alternate cropping systems, and contingency plans such as crop substitution under aberrant situations, furnish the means to meet adverse and favorable conditions. This leads us to a consideration of resource utilization through genotype-input-management interactions.

Genotype-Input-Management Relations

That selection must be oriented towards changing agronomic practices has frequently been emphasized. That plant breeders have more frequently selected for higher potential under favorable conditions associated with rapid rise in the use of agronomic inputs and that this may be an undesirable road to follow, more particularly, in the context of the need for increasing food production in developing countries and the limited resources of the small farmer has also been pointed out (Evans 1976, 1980). Since tropical sorghums involve developing countries and small farmers, the issues need examination.

While there have been attempts to orient breeding towards changes in agronomy such as mechanized agriculture, it is now the genotype change that initiated changes in agronomic practices, eventually resulting in production advances. This has been the case with cereals like wheat, rice, sorghum, etc., and is now beginning to reflect in grain legumes. I will examine the case of sorghum at some length.

Traditional technology emphasized "local improved" varieties, somewhat delayed plantings possibly to limit excessive vegetative growth, low seed rates, periodic application of organic manures, and limited use or absence of fertilizer application. This had no doubt a survival value, but its impact on productivity or stability of production has not been perceptible. On the other hand, the effect of an altered genotype in relation to input application and management has been more conspicuous, and this has been illustrated with *rabi* sorghums earlier.

Nutritional adaptation is widespread in nature and there are distinct genotypic differences for response patterns to nutritional elements, and

Table 4. Rainfall attributes over test locations.

	Year		
Rainfall attributes	1972/73	1975/76	1976/77
1. Total rainfall (mm)	634 (29)	989 (25)	917 (36)
2. Number of rainy days	42 (29)	69 (25)	59 (36)
3. CV (%) of monthly rainfall	153 (29)	136 (25)	142 (36)

Note: Figures in parentheses indicate number of locations on which the averages were based.

Table S. All India average yields (kg/ha) of released hybrids.

	Year		
Hybrids	1972/73	1975/76	1976/77
CSH-1	3602 (35)	2869 (32)	3138 (32)
CSH-5	3925 (35)	3658 (32)	3568 (32)
CSH-6	4013 (35)	3466 (32)	3090 (32)

Note: Figuress in parentheses indicate number of locations or which the averages were based toxicities as well. At an application level up to 50 kg N/ha, sorghum hybrids and some improved varieties have returned 15-28 kg of grain per kg of nitrogen against 6-8 kg for traditional locals. Further, in hundreds of nitrogen response trials conducted all over India during several years, we never observed crossing over of response curves to indicate that certain genotypes (including locals) were higher yielding at lower levels of nitrogen application or, conversely, where any hybrids were yielding less than others at lower levels but outyielded them beyond a point of fertilizer dosage.

Similarly, several studies on genotype responses to population levels in All India trials established the superiority of altered genotypes for community performance compared with the improved local cultivars. Population levels of 180 000 to 200 000 plants per hectare were optimal at the field level.

The response of the altered genotypes to fertilizer and population levels are more spectacular and coupled with their lower susceptibility to climatic variables, notably rainfall, their adoption rate is on the increase, although the level of fertilizer used on commercial sorghum fields is still low. The response patterns during *kharif* and *rabi* are illustrated in Figures 7 and 8.

Considering all agronomic inputs, including use of fertilizer, pesticides, etc., it has been stated frequently that the performance of high-yielding hybrids and varieties remains satisfactory only under optimal inputs (including irrigation water) and management, and that their yields will not be satisfactory under absence or lower levels of such inputs and management. Consequently, "high yield agriculture" is associated with "high input agriculture" and it is questionable whether this is applicable to the small farmers in developing countries. This aspect has been examined in a multilocation experiment conducted over 3 years (Vidyasagar Rao et al. 1980). The top-ranking hybrids and varieties maintained their relative ranks under both types of input-management

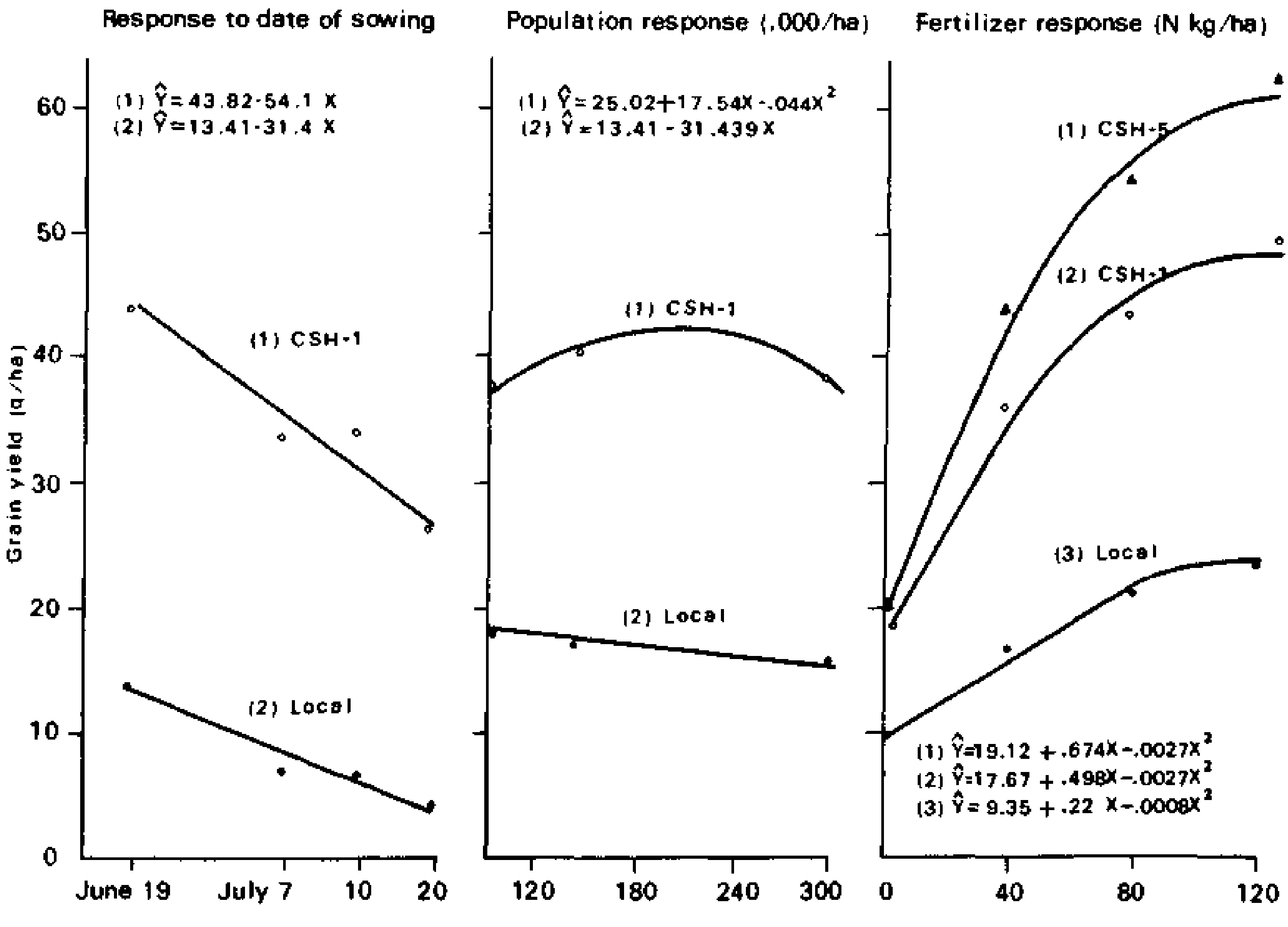


Figure 7. Components of production (kharif).

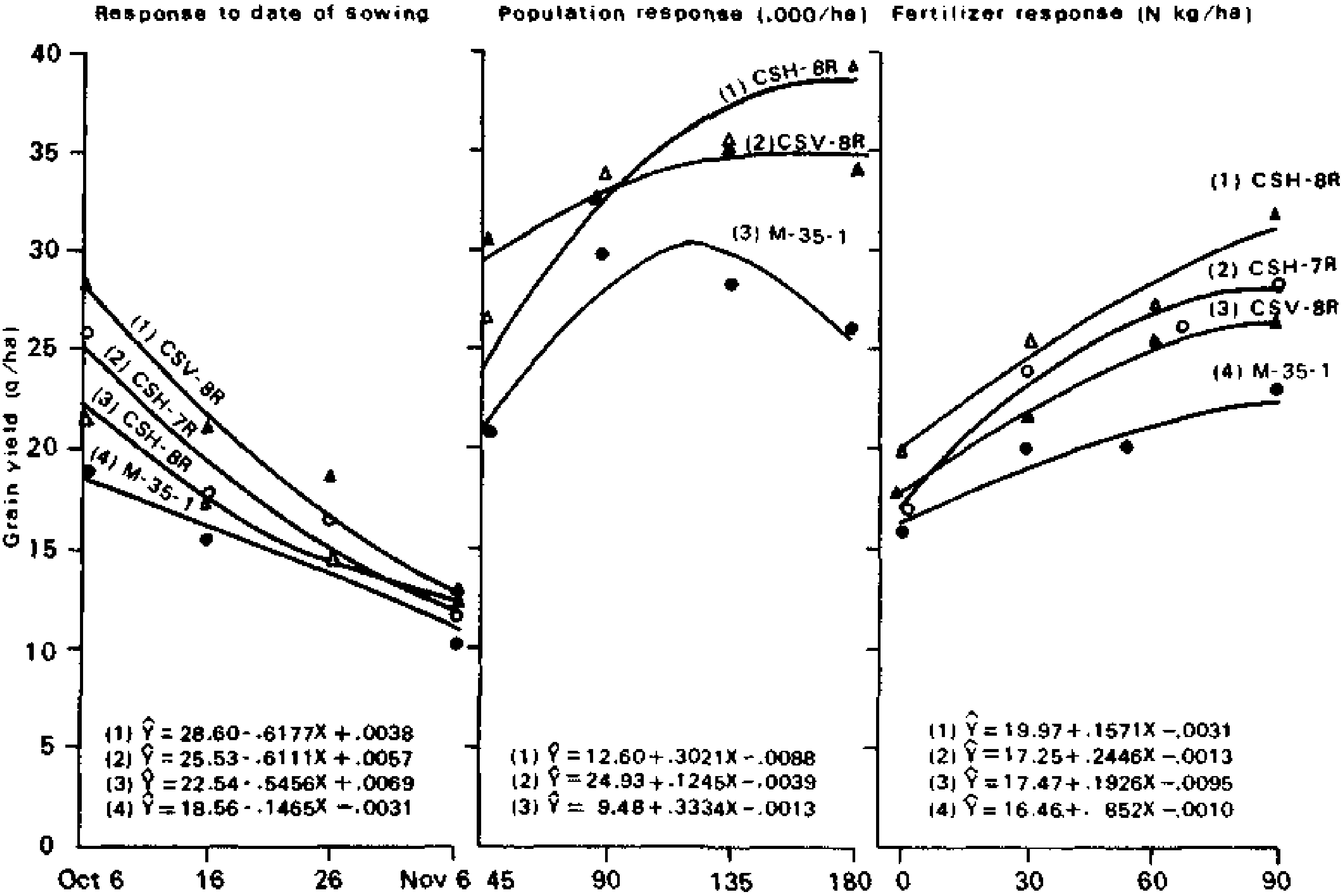


Figure 8. Components of production (rabi).

Table 6. Mean yields and ranks of some hybrids and varieties under high and low management during *kharif* seasons of 1974, 1975, and 1977.

	High management		Low management	
	Yield (kg/ha)	Rank	Yield (kg/ha)	Rank
Hybrids				
CSH-1	3569	4	2468	4
CSH-5	4514	1	3185	2
CSH-6	4125	3	3346	1
Varieties				
CSV-3	3200	5	1970	5
CSV-5	2622	6	1701	6

Table 7. Rank correlations between high and low managements.

Year	Trial	Coefficient
1974	Variety Trial	0.91**
	Variety/Hybrid Trial	0.94**
1975	Hybrid Trial	0.85* *
1977	Early Duration Trial	0.85**
	Mid Duration Trial	0.80**

*• Significant at 1%.

levels (Table 6). The rank correlations were highly significant (Table 7). The yield levels were no doubt different at different levels of management. The genotype x input-management interactions were significant only in a few cases, and even there the magnitude of the interaction m.s.s. was the lowest compared to the m.s.s for genotypes or managements.

These and various other studies indicate that agriculture based on altered genotypes is not incompatible with lower input levels, and the actual level and use of inputs gets into the realm of availability, supply, credit, and related matters rather than technology-imposed limitations. While the yield levels may vary depending on input use, altered genotypes did confer greater levels of stability and productivity. In some years and areas, the difference has been of the order of economic yields against total failure.

Traditional *kharif* sorghums in the Deccan used to be planted during mid-July. Sorghum hybrids based on temperate materials showed increased susceptibility to shoot fly under late plantings (Fig. 9a). The dominant mechanism of resistance to shoot fly is nonpreference for oviposition, and at times of shoot fly buildup, the hybrids were preferentially attacked. But once the advantages of planting with the onset of the monsoon for higher yields and avoidance of shoot fly were demonstrated, the practice caught on and virtually no insecticide is used for shoot fly control on commercial *kharif* hybrid sorghums. This is a management change leading .towards pest avoidance. At the same time, shoot fly control through carbofuran seed treatment, application of granules, etc., have been recommended and practiced under early *rabi* plantings in some areas and in seed production plots sown at altered timings (Rao 1979).

Similarly, the advent of early-sorghum hybrids and the consequent growing of early and late cultivars in the same area during initial years of hybrid spread resulted in extended periods of flowering conducive to rapid multiplication of sorghum midge (Fig. 9b), causing damage on late locals. The gains in hybrid yields were offset by reduced yields of local cultivars. A judicious policy of en-block coverage of hybrids of approximately similar maturities, in preference to a dissipated spread, resulted in the elimination of the causative factor of extended flowering and contained midge (Rao and Jotwani 1974). This is another example of a management change consequent to a genotype change. In fact, it may be said that the incidence of midge promoted hybrids in some areas.

Another example of a transitional problem is grain deterioration (Fig. 9c). Traditional cultivars normally maturing in December have clean grains. The reduction of duration to minimize climatic vulnerability caused them to ripen during mid or late October, with a low probability of occurrence of rains. Farmer reaction to the first hybrid was

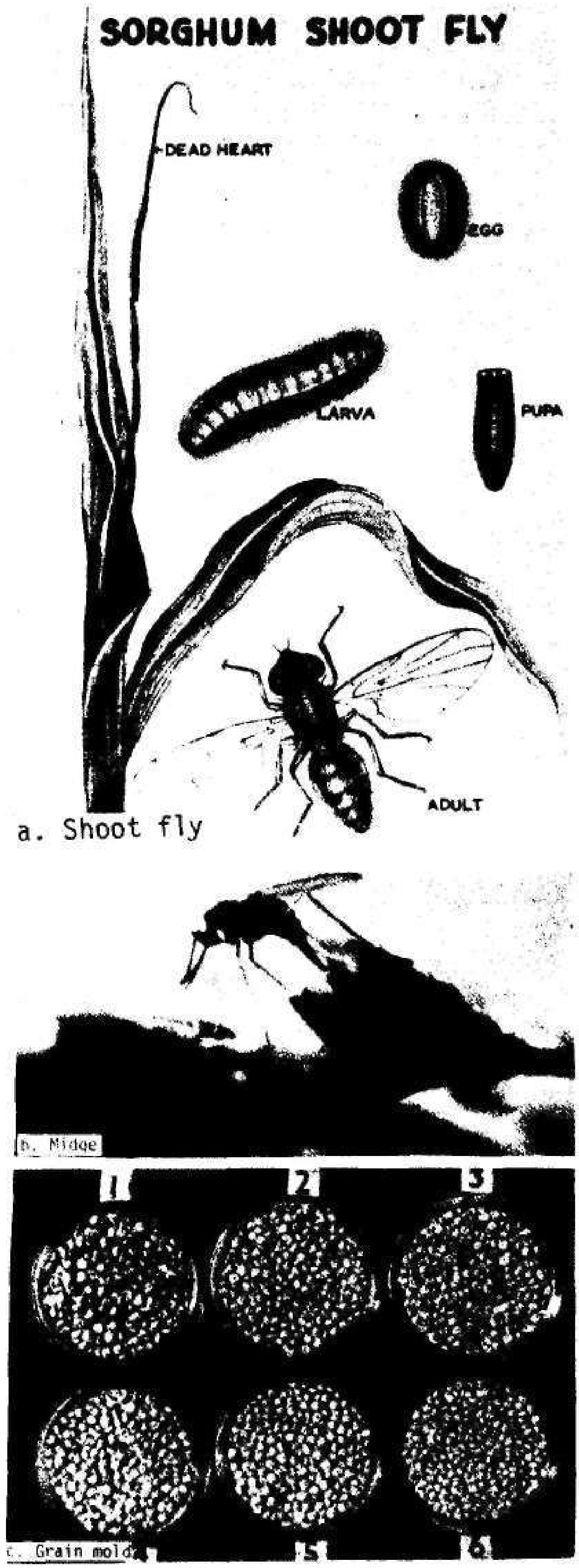


Figure 9. Problems encountered during the transition period from vulnerable to stable agriculture.

excellent in dry and low-rainfall years, since both yield and grain quality were good; but in years of extended rainfall poorer grain quality resulted and consequently the price received a setback. The demands of dry and wet years are apparently antagonistic and one has to find a satisfactory compromise. A clearer understanding of the problem of grain deterioration (Rana et al. 1978) and the development of hybrids like CSH-5, CSH-6, and CSH-9 not only reduced the magnitude of the problem of grain deterioration, but acted as an incentive to stay with early-maturing hybrids and increase yields further through the practice of sequence cropping in areas of assured rainfall.

Thus, during the period of transition from vulnerable to stable agriculture, such problems of transformation (Fig. 9a, b, c) are not uncommon, and one has to find ways and means to get over them till we move from a subsistence inequilibrium to a stable and productive equilibrium.

I will now turn to the effects of genotype modification on cropping systems. The role of mixed or intercropping in traditional agriculture has been idealized. In the African context, Abalu and D'Silva (1980) stated that while traditional intercropping systems have a socioeconomic rationale, most efforts at improvement have been towards sole crops, which have apparently not yielded anticipated results on farmer holdings. Furthermore, single crop technologies should be discouraged and in their place an approach that accounts for all crops of the farming system should be evolved. Jodha (1980) felt that the difficulties of incorporating high yielding varieties into intercropping systems may be one of the factors responsible for their limited spread. This raises questions whether sole crop technologies are at variance with intercrop technologies and whether different approaches are necessary.

One has to first realize that the component cultivars of the traditional intercropping systems are themselves the products of climate vulnerable subsistence agriculture. But for the spread of risk cover over species, they are essentially replacement systems characterized by low yields. Unless the components themselves undergo radical alteration, the system will not alter. Rao and Rana (1980) demonstrated that sole crop stability and productivity is a prerequisite for productive intercropping systems. Further, based on studies involving inter- and intra-species competition, genotype x density interactions and alternate planting patterns, Rao et al. (1981a) examined the design and practice of stable, productive and profitable intercropping systems. Summarizing data from several All India trials, Rao and Rana (1980) furnished evidence of such systems which involved sorghum as the principal crop with 90-95% of the sole crop yield and pigeonpea, soybean and groundnut as intercrops (Table 8). New and more remunerative crops like onion, garlic, etc., are now being experimented to enhance returns. Traditional intercropping systems which have given place to sole crops of hybrid sorghum have now been oriented towards more profitable intercropping (Rao and Rana 1980).

While such intercropping systems are advantageous in areas of relatively low rainfall, multiple cropping is more profitable in high rainfall areas with moisture retentive soils. A vast portion of the black soil belt of the Deccan and central Indian plateaus with 800 mm of annual rainfall which sustained 5-6 months' crops of traditional sorghums, can now take an assured crop of short-season hybrid in all years and a following crop of safflower or chickpea in normal and above normal years of rainfall (Fig. 10). Rao and Rana (1980) felt that the present shortages of grain legumes and

Table 8. Yields in sorghum based intercropping systems averaged over several experiments.

Intercropping system (monocrop/ intercrop)	Average yield (q/ha)			
	Sorghum (sole crop)	Sorghum (intercropping system)	Intercrop (sole crop)	Intercrop (intercropping system)
Sorghum/pigeonpea	35.811.9	32.4+1.4	16.5+0.9	9.410.4
Sorghum/soybean	33.0±1.9	32.211.8	13.9+0.7	5.510.3
Sorghum/groundnut	33.612.7	33.1+1.8	10.411.4	4.810.5

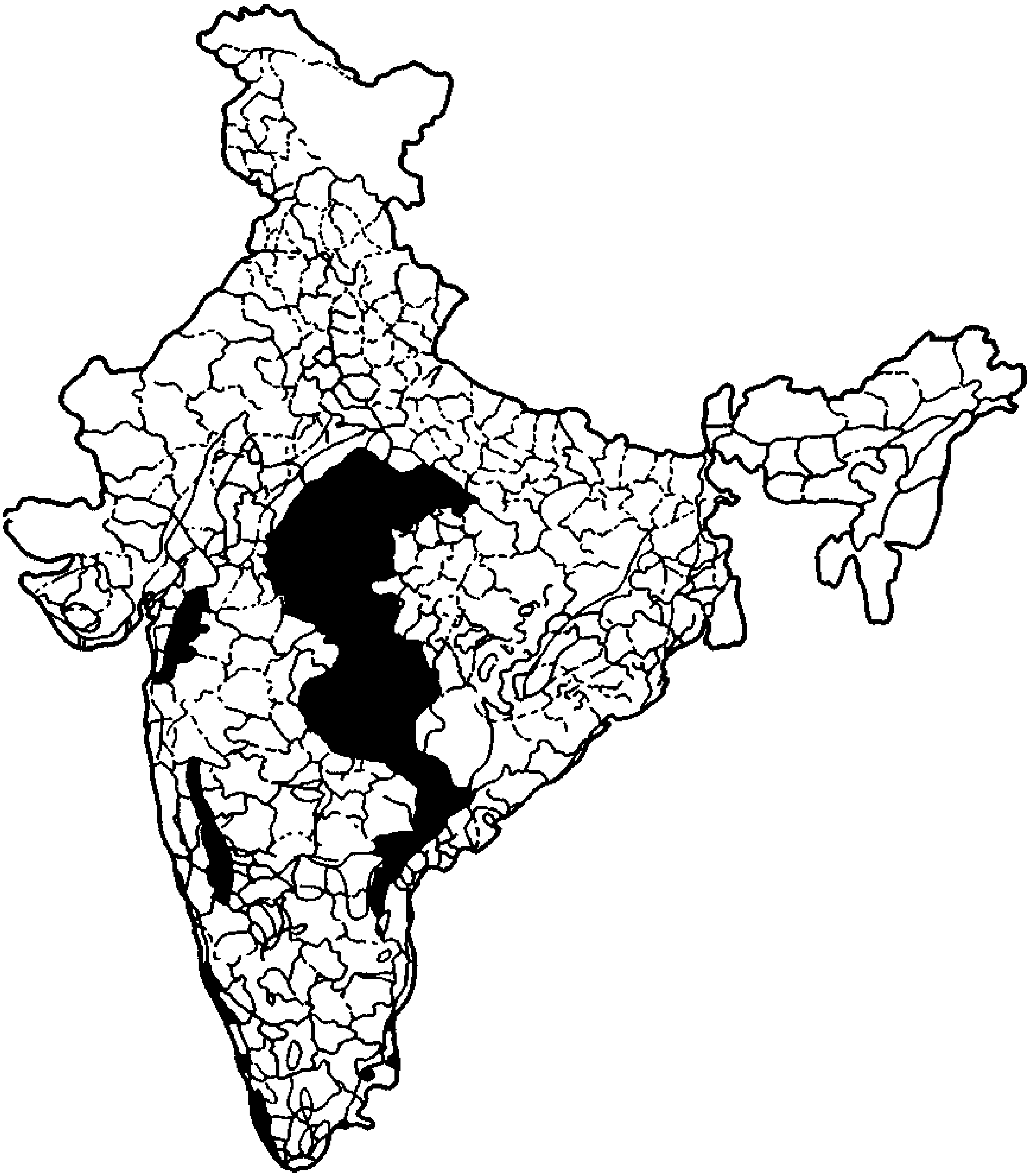


Figure W. Sorghum-growing districts for potential double cropping under rainfed conditions in India.

edible oilseeds could be met by the practice of sorghum based inter- and sequence cropping on existing sorghum acreages.

That productivity per year in the tropics will probably be achieved by attempts to maximize the number of crops rather than yield of each crop (Evans 1980) is relevant for areas where traditionally long season sorghums have been under cultivation in India and Africa. Emphasis on the manipulation of the cropping system based on modified cultivars will be more fruitful, as demonstrated in India, than attempts to breed improved cultivars comparable to late locals in maturity.

Ratooning hybrid sorghum has become a common practice in large areas of the Jalgaon district of Maharashtra, in some tank-fed areas of Andhra Pradesh, particularly when water is not adequate for rice cultivation, and under supplemental irrigation in several situations.

The advent of hybrid sorghums gave birth to an organized hybrid seed industry in the public and private sectors.

Some Case Studies

Any crop improvement strategy for rainfed lands should provide for assured yields even when unfavorable weather conditions are encountered. It should also furnish the means to maximize output if rainfall is normal or optimal. As discussed, genotype alterations coupled with management practices, alternate cropping systems and contingency plans provide ways and means to meet adverse as well as favorable conditions. This will be illustrated with a few examples.

All India national demonstrations of sorghum conducted in previous years on 1-ha plots revealed that in none of the years were average yields less than 2500/kg/ha, and maximum yields recorded were quite high (Fig. 11). In the initial years of hybrid spread during the *kharif* in the States of Maharashtra and Karnataka and their impact on overall *kharif* yields, projections were made on the possible impact of the total coverage on yields which turned out to be 2500 kg/ha. This indicates that the present average yields of *kharif* could be elevated to 2500 kg/ha. Higher order yields recorded are comparable to those obtained elsewhere in the world.

Another example is the performance of CSH-1 during the early years of its spread in the Harpanhalli taluq of Bellary district in Karnataka State. In one of the most difficult drought situations encountered, hybrid yields on an area basis were spectacular (Fig. 12).

The 1972/73 crop year witnessed widespread drought in many parts of the world including India. The yields of improved cultivars at 29 experimental sites all over India ranged from 2500 to 4000 kg/ha, against the near total failure of some late locals. Analyzing rainfall-yield relationships during this year, Rao et al. (1975) observed that the amount of variation in yield ascribable to rainfall was mostly determined by the number of rainy days and the coefficient of variation in monthly rainfall. The variation accounted by rainfall characteristics did not exceed 40% with any of the improved cultivars and it was only 15-20% with the hybrids CSH-1 and CSH-5. Early maturity coupled with hybridity conferred homeostatic advantages. The performance of CSH-1 during *rabi* in Andhra Pradesh is summarized in Table 9. This is based on early planting and fertilizer use in a year when rainfall was low.

The 1976/77 crop year was a case where rains were well distributed during July and August, but ceased abruptly by the first week of September in the Deccan and Malwa plateaus. The late locals suffered, but in Maharashtra State, where hybrids covered 52% of the *kharif* area, *kharif* sorghum production touched a record 2.96 million metric tons. The compensation of hybrids for failure of locals has been tremendous.

Assessing the results in the pilot project area of Indore in Madhya Pradesh, Choudhary (1980) reported that CSH-5 recorded the highest average yield among the various crops tried. Most farmers adopted only two practices—improved high yielding seeds and fertilizer. The technology was particularly beneficial to the small farmer. *Kharif* sorghum accounted for most of the cropping in otherwise *kharif* fallows, which would normally be cropped by rainfed wheat during *rabi.*

The minimum yield guarantee schemes of the Governments of Maharashtra and Andhra Pradesh with rainfed sorghums have been a phenomenal success. Data from Maharashtra are summarized in Table 10.

The best proof is on the impact of the hybrid coverage on *kharif* sorghum production in the States of Maharashtra and Karnataka (Table 11) where the coverages have been substantial. Other states could emulate this example.

So far, we have considered sole crop examples. The possible impact of productive inter- and sequence-cropping systems have been examined by Rao et al. (1979) and Rao and Rana (1980).

Economic Analysis

I want to conclude with a brief reference to some economic analyses.

Jodha (1980) stated that "the scope for dynamizing SAT agriculture is limited for want of viable technological options." As a solution, he com-

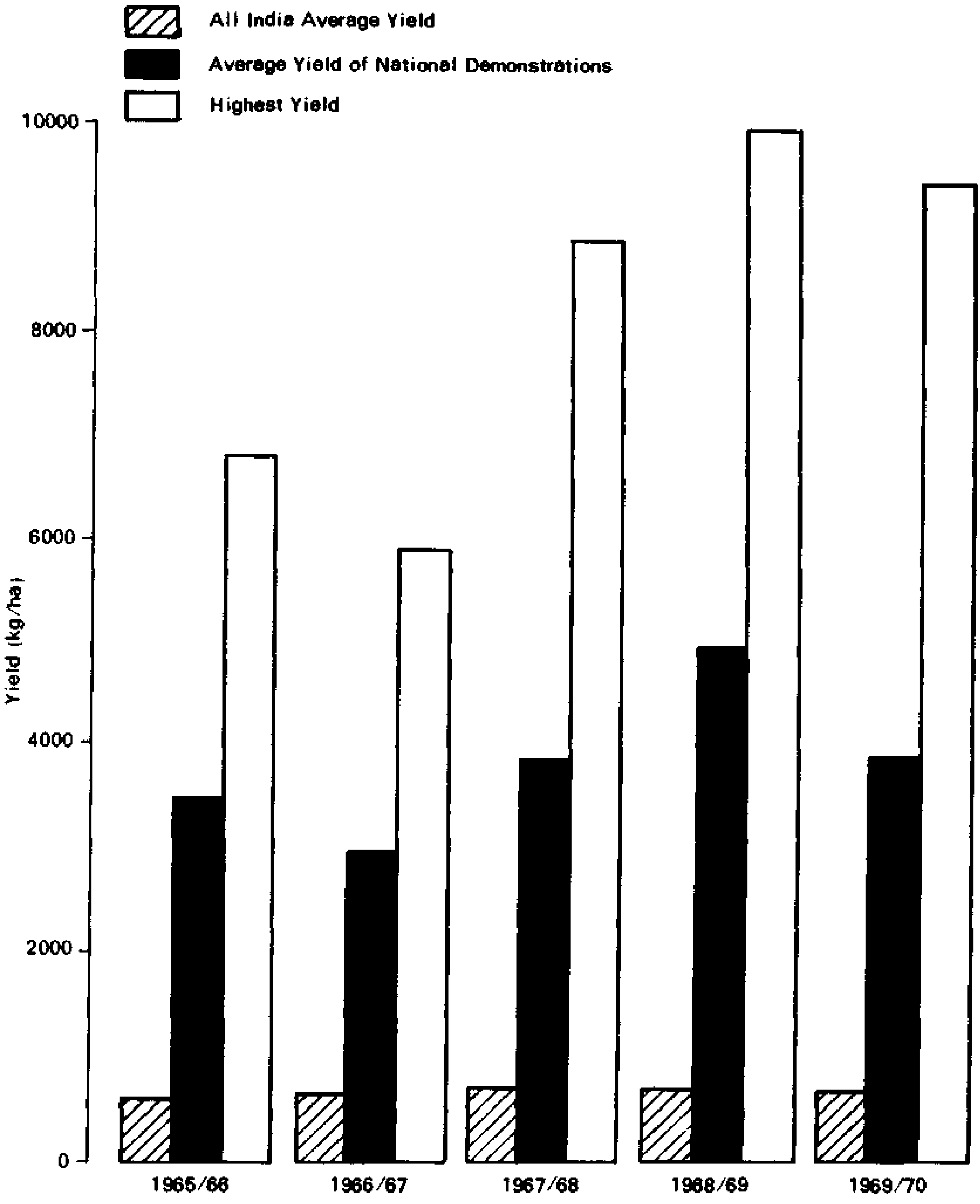


Figure 11. Yields obtained in All India national demonstrations with sorghum.

mends the resource centered approach, with the watershed as the unit, and involving land smoothing, semipermanent graded broadbeds and furrows, grassed waterways, small dams or tanks to collect runoff water for supplemental irrigation, together with agronomic inputs. It is apparent that this package is cost intensive. That risk graded technologies are irrelevant to SAT agriculture has

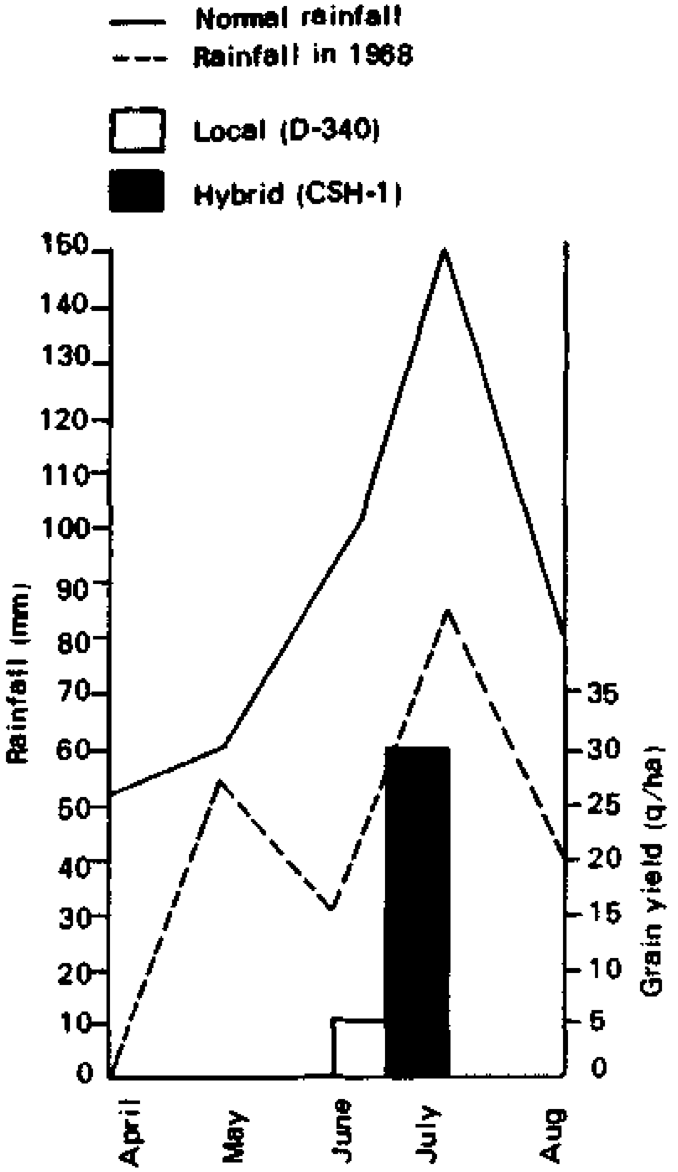


Figure 12. Performance of CSH-1 under extreme moisture stress in Harpanhalli taluq, Bellary district, Karnataka, India, kharif *1968 (rainfall received and average yield obtained over 10 000 acres).*

been borne out by the studies of Binswanger et al. (1980) and Vidyasagar Rao et al. (1981).

At the sorghum production workshop held at Udaipur. various questions were raised on the relevance and profitability of the sorghum production technology developed under the All India Sorghum Project (Rao 1979). The additional investment is primarily on seed and the level of fertilizers used. Since the technology was oriented towards quantum increases cutting through environmental limitations, its profitability was high. Its orientation towards system changes makes it more versatile. Approaches of en-block

Table 9. Number of crop experiments and mean grain yield in different Samathies of Khammam District, and Andhra Pradesh, *rabi* 1972/73.

	No of Experiments conducted		Grain yield (kg/ha)		
Samathi	CSH 1	Local	CSH-1	Local	Local
Wyra	3	3	4490	1318	340
Khammam	3	3	4983	2109	236
Burgampad	2	_	4457	—	—
Kothagudem	6	6	4915	1233	398
Yellandu	5	4	2683	1297	207
Bhadrachalam	1	1	4571	1186	385
Tirumalayapalem	8	4	4235	1742	243
Mean			4239	1477	287

Table 10. Grain yields from pilot project blocks on hybrid sorghum in Maharashtra State (rainy season).

Year	Coverage (ha)	No of experiments	Average yield (q/ha)
1976/77	75 063	5 579	27 40
1977/78	73 386	3 333	27. 30
1978/79	35 539	959	22 80
1979/80	20 832	805	22 70

transformation enhanced its acceptance. Its relevance was more to the small farmer.

The quantitative analysis of Ryan et al. (1980) termed "Steps In Improved Technology" analysis (SIIT) furnishes a sound basis for technological options. The LII (local improved variety, fertilizer use and improved soil and crop management) represents the improvement approach. The III (altered variety, fertilizer use and improved soil and crop management) represents the transformation approach for sole crops on drylands. There were various other treatments. Comparing all treatment in Alfisols and Vertisols, they concluded that both from the risk and profit point of view, the III technology (transformation approach) is beneficial. An investment of Rs. 100 in Vertisols on this

Table 11. Progress of kharif sorghum in Maharashtra.

Year	Area ('000 ha)	Production ('000 tonnes!	Average yield (kg/ha)	Area covered under HYV ('000 ha)
1970/71	2537	888	350	487
1971/72	2283	1080	473	320
1972/73	2494	907	364	330
1973/74	2763	1289	467	508
1974/75	2606	2118	813	433
1975/76	2795	2224	795	754
1976/77	3094	2958	956	1386
1977/78	3210	3487	1085	1724

approach could generate additional Rs. 1700 in net benefits (Fig. 13).

In the Hyderabad Alfisols also, the III approach was the best, the improvement approach also being profit-risk efficient. But here, the locals are of the same duration as the hybrids, whereas in most of the sorghum growing-areas the locals are very late and prone to climatic risk, and in bad years, input investments may be totally lost.

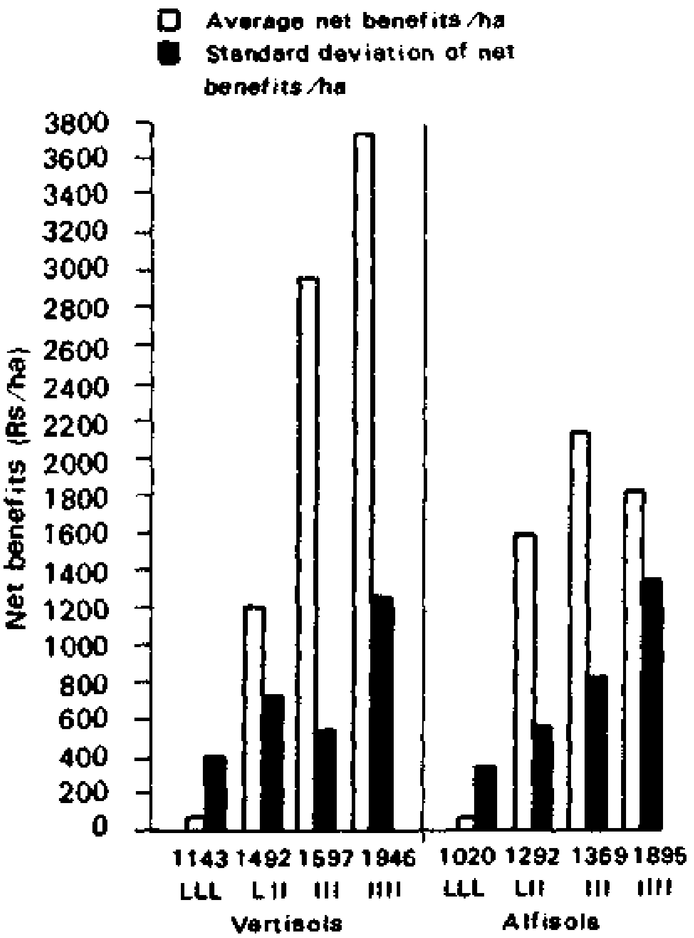


Figure 13. Average net benefits and variable costs per ha in steps-in-improved-technology experiment, (based on Ryan et al. 1980).

The advantages of Vertisol watersheds was much less compared to the SIIT experiments.

Permit me to be somewhat personal. I worked in the Indian Sorghum Program from the end of 1961 until the beginning of the 1980s. I have been deeply committed and involved in this venture. Apart from carrying out the improvement work, my colleagues and I analyzed each and every step of the technological aspects and tried to develop a rationale. Whatever I have spoken today comes from this experience. I sincerely feel that viable technological options are available for the amelioration of sorghum and that such a transformational approach is relevant to tropical drylands and could yield results, not only in other parts of India but also in the African context.

References

ABALU, G. O. I., and D'SILVA, B. 1980. Socioeconomic analysis of existing farming systems and practices in Northern Nigeria. Pages 3-10 *in* Proceedings, International Workshop on Socioeconomic Constraints to Development of Semi-Arid Tropical Agriculture, ICRISAT. 19-23 Feb 1979, Hyderabad, India. Patancheru, A.P., India: ICRISAT.

ANANTHARAMAN. P. V., ACHUTA RAO, K., KANDUKAR, S. S., and RAO, N. G. P. 1978. Genetic analysis of some exotic x Indian crosses in sorghum: XIX. Patterns of dry matter accumulation. Indian Journal of Genetics and Plant Breeding 38:333-338.

ANDREWS, D. J. 1975. Sorghum varieties for the late season in Nigeria. Tropical Agriculture 52:21-30.

BALARAMIREDDY, B., and RAO, N. G. P. 1981. Genetic analysis of some exotic x Indian crosses in sorghum: XXVII. Bridging the gap between hybrid and varietal performance. Indian Journal of Genetics and Plant Breeding 41:409-413.

BARAH, B. C, BINSWANGER, H. P., RANA, B. S., and RAO, N. G. P. 1981. The use of risk aversion in plant breeding: Concept and application. Euphytica 30:451-458.

BINSWANGER, H. P., JODHA, N. S., and BARAH, B. C. 1980. The nature and significance of risk in semi-arid tropics. Pages 303-316 *in* Proceedings, International Workshop on Socioeconomic Constraints to Development of Semi-Arid Tropical Agriculture, ICRISAT, 19-23 Feb 1979, Hyderabad, India. Patancheru, A.P., India: ICRISAT.

BRIGGS, L. J., and SHANTZ, H. L. 1914. Relative water requirements of plants. Journal Agricultural Research 3: 1-64.

CHAUDHARY, A. K. 1980. Socioeconomic field assessment of dry farming technology in the Indo-UK project, Indore. Pages 97-106 *in* Proceedings. International Workshop on Socioeconomic Constraints to Development of Semi-Arid Tropical Agriculture, ICRISAT, 19 -23 Feb 1979, Hyderabad, India. Patancheru, A.P., India: ICRISAT.

EVANS, L. T. 1976The two agricultures: renewable or resourceful. Journal of Australian Institute of Agricultural Science 42:222-231.

EVANS. L. T. 1980. The natural history of crop yield. American Scientist 68:388-397.

GEORGE, C. J.. RAMASASTRY, K. S„ and RENTALA, G. S. 1973. Incidence of droughts in India, Meteorological monograph, Agrimet No. 5. Poona, India: India Meteorological Department.

GOLDSWORTHY. P. R. 1970. The growth and yield of tall and short sorghums in Nigeria. Journal of Agricultural Science, Cambridge 75:109-122.

JOOHA, N. S. 1980. Some dimensions of traditional farming systems in semi-arid tropical India. Pages 11-24 *in* Proceedings, International Workshop on Socioeconomic Constraints to Development of Semi-Arid Tropical Agriculture, ICRISAT, 19-23 Feb 1979, Hyderabad, India, Patancheru, A. P. , India: ICRISAT.

KRISHNAN, A. 1974. Some climatological features of the semi-arid tropical regions of the world. Pages 53-91 *in* Proceedings, International Workshop on Farming Systems, ICRISAT, 18-21 Nov 1974, Hyderabad, India. Patancheru. A.P., India: ICRISAT.

RAMAN, C. R. V. 1975. A new approach to rainfall climatology over Maharashtra state for agricultural planning. Science Today.

RANA, B. S.. JAYAMOHANRAO, V. and RAO, N. G. P. 1978. Genetic analysis of some exotic x Indian crosses in sorghum: XVIII. Breeding for resistance to grain deterioration. Indian Journal of Genetics and Plant Breeding 38:322-332.

RAO, N. G. P. 1970. Genotype x environment interactions in grain sorghum hybrids. Indian Journal of Genetics and Plant Breeding 30:25-30.

RAO, N. G. P. 1972. Five years of sorghum breeding. Journal of Scientific and Industrial Research 31 498 -509.

RAO, N. G. P. 1977. Towards sorghum revolution. Indian Farming 27:3-9.

RAO, N. G. P. 1979. Technological basis and components of sorghum production programmes. Indian Farming 8:17-21.

RAO, N. G. P. 1981. Genotype alteration: The basis for agricultural transformation in tropical drylands. Presidential address to the Indian Society of Genetics and Plant Breeding. IARI. New Delhi.

RAO, N. G. P., and HARINARAYANA, G. 1968. Phenotypic stability of hybrids and varieties in grain sorghum. Current Science 38:92-98.

RAO, N. G. P., and JOTWANI, M. G. 1974. Sorghum midge. Indian Farming 24:9-11.

RAO, N. G. P., and MURTY, B. R. 1963. Growth analysis in grain sorghums of deccan. Indian Journal of Agricultural Science 33:155-62.

RAO, N. G. P.. and RANA, B. S. 1980. Sorghum based cropping systems to meet shortages of pulses and oilseeds in India. Current Science 49:622-626.

RAO, N. G. P. and VENKATESWARLU, J. 1971. Genetic analysis of some exotic x Indian crosses in sorghum ///. Heterosis in relation to dry matter production and nutrient uptake. Indian Journal of Genetics and Plant Breeding 31:156-176.

RAO, N. G. P., HARINARAYANA, G., ARUNACHALAM, V., TRIPATHI, D. P., and BALAKOTAIAH, K. 1973. Genetic analysis of some exotic x Indian crosses in sorghum VI. Character associations under selection. Indian Journal of Genetics and Plant Breeding 33:1 -6.

RAO, N. G. P.. RANA, B. S., and JOTWANI, M. G. 1977. Host plant resistance to major insect pests of sorghum. Pages 63-79 *in* Use of induced mutations for resistances of crop plants to insects. Proceedings, FAO/IAEA Advisory Group Meeting, Dakar, Senegal.

RAO, N. G. P., RANA. B. S., and TARHALKAR, P. P. 1981a. Stability, productivity and profitability of some intercropping systems in dry land agriculture. Pages 292-298 *in* Proceedings, International Workshop on Intercropping. ICRISAT, Hyderabad, India. Patancheru, A.P., India: ICRISAT.

RAO, N. G. P., RANA, B. S., JAYAMOHANRAO. V., and BALARAMIREDDY, B. 1982. Genetic analysis of some exotic x Indian crosses in sorghum: XXV. Development of new hybrids and varieties and their performance. Indian Journal of Genetics and Plant Breeding 42:213-219.

RAO. N. G. P., SUBBARAO, S„ and VIDYASAGARRAO, K. 1975. Rainfall fluctuations and crop yields Current Science. 44:694-697.

RAO, N. G. P., VASUDEVARAO, M. J., RANA, B. S., and JAYAMOHANRAO, V. 1979. Response to water availability and modifications for water use efficiency in tropical dryland sorghums. *In* Proceedings of a Symposium on Responses to Water Availability, Water Technology Centre, Indian Agricultural Research Institute, New Delhi.

RAO, N. G. P., VIOYABHUSHANAM, R. V, RANA, B. S, and JAYAMOHANRAO, V. 1980. Breeding sorghums for disease resistance in India. *In* Proceedings, International Workshop on Sorghum Diseases, ICRISAT, 11-15 Dec 1978. Hyderabad, India. Patancheru, A.P, India: ICRISAT.

REITZ, L. P. 1974. Breeding for more efficient water use—is it real or a mirage? Agricultural Meteorology 14:3-11.

RYAN. J. G., SARIN, R„ and PEREIRA, M. 1980. Assessment of prospective soil, water and crop management technologies for the semi-arid tropics of peninsular India. Pages 52-72 *in* Proceedings. International Workshop on Socioeconomic Constraints to Development of Semi-Arid Tropical Agriculture, ICRISAT, 19-23 Feb 1979, Hyderabad. India. Patancheru. A.P. India: ICRISAT.

SANCHEZ. P. A., and BUOL. S. N. 1975. Soils of the tropics and the world food crisis. Science 188:598-603.

SINGHANIA, D. L, and RAO, N. G. P. 1976. Genetic analysis of some exotic x Indian crosses in sorghum: XIV. Stability of hybrids and their parents. Indian Journal of Genetics and Plant Breeding 36:118-124.

SULLIVAN, C. Y. 1972. Mechanisms of heat and drought resistance in grain sorghum and methods of measurement. Pages 247-264 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi. India: Oxford and IBH Publishing Co.

THOMPSON. L. M. 1975. Weather variability, climatic change and grain production. Science 188:535-541.

TROLL, C. 1966. Seasonal climates of the earth. The seasonal course of natural phenomenon in the different climatic zones of the earth. Pages 7-28 *in* World maps of climatology, eds M E. Lindsberg et al. Berlin: Springer-Verlag.

USDA (United States Department of Agriculture). 1975. The world food situation and prospects to 1985. Pages 1-90 *in* Foreign agricultural economic report No. 98. Washington, USA.

VIDYASAGARRAO, K, SUBBARAO, S. and RAO, N. G. P. 1981. Genetic analysis of some exotic x Indian crosses in sorghum: XXIII. Genotype x input-management interactions in sorghum. Indian Journal of Genetics and Plant Breeding 41 : 54-58.

A Look Ahead into the 1980s

L. R. House*

This statement represents an effort to look into the 80s. Our priorities and activities in the future rest directly on our experience of the past.

We are aware of the vast differences in production capability of countries in different parts of the world. We are particularly concerned about some countries of Africa and Latin America where the rate of increase in population is exeeding that of production. We are aware that some of these differences are due to environmental factors that we cannot control or are very expensive to control. We are also aware that there are many factors that we can influence, and it is those factors in which we are most interested. An effort is made here to identify priority considerations and to comment on how we can approach them.

Objective

Our basic objective is to generate a positive change. This may mean a shift from traditional to technical agriculture involving credit and other goods and services. It may mean the generation of new hybrids in a competitive marketing situation where export interests are of concern. As research scientists from a range of backgrounds, there are many common features in our priorities. Nevertheless there are some differences. We need to seek ways of working together to maximize our return on the total investment in sorghum improvement and production. An end result is to provide a better living for the people that make their livelihood from agriculture.

Research Organization

Sorghum is an important food grain in the semi-arid tropics. Generally, the stover (stubble) is used for construction, feed, and fuel. Growing conditions in much of this part of the world are harsh, the farmers frequently poor, and the supply of goods and services are inadequate or almost absent. We recognize that in such conditions to attempt to maximize production with limited resources, the need is great for stability of production including resistance for important yield limiting factors. We are impressed that a solution to these problems involves input from a team of scientists. It is difficult to visualize an expatriate team in every country where there is need.

At ICRISAT we have identified an approach to respond to our mandate—implementation will be an objective in the 80s. We have divided the world into what we call geographic functional regions. Environmentally, these regions, are not homogeneous. In fact they contain different zones of adaptation and there are specific problems that may or may not be of concern across different adaptation zones (Fig. 1). Regions have been identified in such a way that there is geographic, social, and crop continuity and they are of such a size that coordination is expected to be effective. Geographic functional regions are identified in Table 1.

A number of national and international agencies are involved with programs in these regions. There are situations where an agency provides support both on a bilateral and regional basis. Coordination across input by different agencies, if attempted, is generally undertaken by a national agency—less often is there regional coordination. There is a need to improve interaction and today several agencies are concerned that a coordination activity on a regional basis is feasible and desirable.

There is a rising interest among universities and research agencies in research and training relevant to the developing world. This involves research and training within the university or

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International Crops Research Institute lor the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru, A.P., India. Patancheru. A.P. India: ICRISAT

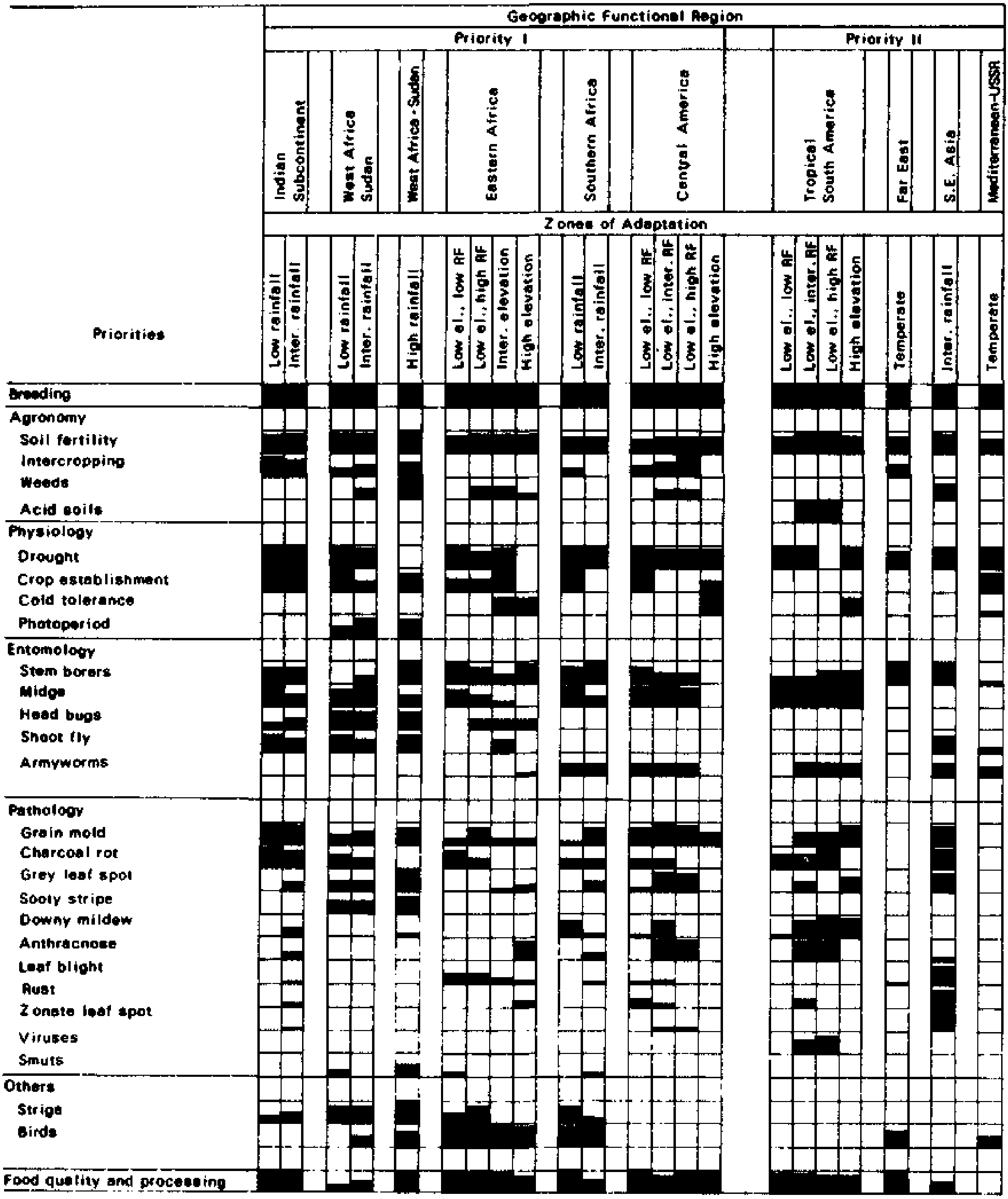

Figure 1. Distribution of priorities for sorghum improvement by geographic functional region and zone of adaptation.

Table 1. Geographic functional regions for sorghum improvement.

1.	Indian Sub-continent
2.	West Africa—low-intermediate rainfall
3.	West Africa—high rainfall, long season
4.	East Africa—Yemens
5.	Southern Africa
6.	Central America
7.	Tropical South America
8.	Far East
9.	South-east Asia
10	Mediterranean—USSR
11	Oceania
12	Temperate Americas

agency or cooperative research with an institution in another country. INTSORMIL, a program of USAID, in the USA consists of a group of universities participating in and receiving grant funds for research both in U.S universities and overseas. Institutions such as the Commonwealth Overseas Pest Research organization, the Max Planck Research Institute, and others conduct research with international objectives and inputs.

Particularly in West Africa there are several regional agencies interested in sorghum. With SAFGRAD, CILSS, Institute du Sahel, and ICRISAT, cooperative working mechanisms have been developed and are being further developed.

It is apparent that we have a research need requiring a team approach. The team should operate regionally, largely if not completely, within the national program structure and there should be a substantial component in training. This mechanism provides expertise in the array of disciplines required—and the composition of the team can change with developments. It is economic in keeping numbers of specialists low, and is structured to strengthen national program capability as a function of the regional program. The better we can organize our input into research and development, the faster will be the rate of progress and achievement.

Support from funding agencies may be essential for national and regional activities. The regional program needs identification and can be associated with agencies such as ICRISAT, INTSORMIL, FAO, and others. The regional base provides a vehicle for other inputs, such as coordinating regional trials in Africa by SAFGRAD. Cooperation with institutions primarily in the developed world is essential to the solution of relevant more fundamental aspects of the problem. Important to all of this activity is the strengthening and ultimate independence of local research organization. I am reflecting, to a considerable degree, concepts being developed at ICRISAT. This is a way much of the input has to be developed. At ICRISAT we are seeking to respond to our mandate—we realize that this will be an important aspect of our activities in the 80s. Within ICRISAT, we visualize considerable independence of regional activity. There are situations where it may be desirable for ICRISAT to base a regional program and situations where others should do this and ICRISAT cooperates.

The Technical Input

A list of traits of priority concern for research for different geographic functional regions is presented in Figure 1. This array of traits has been developed at ICRISAT for our 10 year projection based on contacts with numerous sorghum workers over the world. This is not a static array of priorities but we have gained confidence that at this time, it is reasonably accurate. The relationship between environment (zones of adaptation) and traits of priority concern, are associated in this future.

It is apparent that there are differences that will require a somewhat tailored response. Midge is almost a universal problem, sooty stripe is widespread but of priority concern in West Africa. Birds are a nuisance in many areas but a major limiting factor to production in Eastern and Southern Africa. Weeds are a greater problem in wet as compared with dry areas. Anthracnose is important in the high elevations of Ethiopia where *Striga* is not serious, but in lower elevations the reverse is true. Anthracnose is serious in northern India but not in the central nor southern parts of the country. Shoot fly can frequently be avoided by early sowing; in India shoot fly is a more severe problem in the postmonsoon season than in the monsoon season. These are examples; many more cases could be identified.

When one realizes that the farmer requires a stable crop combining many traits, and that a solution to such problems as indicated above is important to this stability, one appreciates a complexity that is staggering. It is not much help to have varieties resistant to grain mold if yield is lost to midge. Input into many of these problems has taken place—certainly, there is much that can be done to improve the situation. The problem can be approached by looking at aspects of it—the development of agronomically elite types, the development of sources of resistance and quality traits, and combining the two.

The Development of Agronomic Eliteness

Germplasm

The world collection of sorghum now has some 22 000 entries. This is a valuable source of new genes contributing to improved varieties and hybrids. Probably, most sorghum breeders in the world are making use of zera zera types originating in central Sudan and the Gambella area of Ethiopia. Interesting results are beginning to appear in segregates from crosses between cultivated and wild types. Breeders have made collections of sorghum dating back many years. This will continue for many more years and on a more professional basis through the IBPGR, the activities of the Genetic Resources Unit at ICRISAT, the seed repository of the USDA at Fort Collins and others.

Utilization of the collection has been direct, by intergression. and by conversion. It has been an important source of genetic variability and will continue to be so. It is important that we develop the necessary mechanisms and facilities for proper maintenance, evaluation, and utilization. A stronger regional capability would contribute much to making these functions more effective. Germplasm centers have developed, for example at Addis Ababa in Ethiopia and Izmer in Turkey; there is a concern for a center in West Africa. These and additional storage facilities are important. We need to decide where we need major repositories and where we need to house working collection. As yet, we have not identified a systematic way to increase and describe germplasm in areas of adaptation, preferably near to where accessions were collected. The concern to preserve germplasm has gained momentum—we must now increase our concern on its maintenance and evaluation. Free exchange of germplasm is essential to crop improvement and to the speed of crop improvement. It is important that we encourage attitudes of free exchange among all who are interested.

Breeding is central to the development of superior varieties and hybrids. The concern is very much for yield and stability of yield. The full array of breeding techniques is used—pedigree, backcrossing, and population improvement. All have contributed—all will continue to contribute.

The identification of varieties that will substantially outyield locals in environmentally harsh conditions with low input remains questionable. The value of heterosis, by hybrids or synthetics is important to this question and certainly provides one of the strongest mechanisms that we have to respond to this situation. The need to diversify the germplasm base of our A. lines to develop hybrids adapted to an array of environments is an important consideration for the 80s. I believe that we need to move cautiously ahead with hybrids recognizing the input into a seed industry that will be required—this becomes part of the strategy and is expected to be of increasing concern in the coming decade. There is concern about genetic vulnerability, i.e.. sudden occurrence of susceptibility to a pest associated with the cytoplasmic genetic male-sterility system in the seed parent of hybrids. There is also interest in the use of apomixis enabling the vegetative propagation of hybrids through seed. We are interested in other possibilities such as the farmer use of synthetics carrying one or both ms_3 and ms, male-sterility factors; as with hybrid seed production this may raise increased concern because of the increased susceptibility of male-sterile plants to ergot.

Superior varieties that will compete successfully with good locals are more likely in environmentally favorable situations. Increase in yield in many instances will no doubt be of sufficient magnitude to attract investment into fertilizer, water, and other inputs. Heterosis will contribute in these areas also, and increasingly varieties may be used primarily when there is a shortfall of hybrid seed. This represents a transition period through which many countries have passed, some are in the process, some will and some will not, in the 80s. The pace should be such that the system required to provide adequate quantities of good quality seed on a timely basis can be developed. It is clear that varietal improvement is a necessity of itself and to a hybrid program so the two are compatible.

The most relevant approach to increasing production will vary with the situation. If hybrids prove useful in high elevation areas, seed parents adapted to those conditions will need to be developed. Experience has indicated the need for a 40 or 50% increase in yield, from variety or hybrid and from management to initiate change away from traditional agriculture. The approach in areas of lower moisture stress will likely lead the way as yield changes justifying a greater expenditure on inputs is possible. Special techniques, such as ways to conserve moisture, may be inexpensive and feasible in dry areas, and along with good varieties and hybrids begin to start a change that hopefully would increase in rate with time. Obviously, different environmental situations will require a different approach to maximize production. It is important that relevant factors are identified.

Population breeding has attracted a lot of attention. Progress with population breeding at ICRISAT has been rewarding in terms of useful derivatives that are now contributing in many places in the world. We may be approaching a situation where the general usefulness is being restricted by lack of broad enough multilocation testing. A resolution of how to manage populations as we respond to an international mandate is an issue immediately before us. The usefulness of populations for the simultaneous incorporation of several traits is widely recognized and will no doubt be increasingly employed. Sorghum is an important component of intercropping systems and has been used traditionally as a means of stabilizing food availability. It can also be employed in different situations to select types that "fit" better the relationship between crops and also to provide a means to better utilize a growing season. Ganga Prasada Rao is interested in exploring the use of shorter duration sorghums with a better harvest index as part of a cropping system in the longer rainy season as found in Nigeria. The cropping systems approach is a valuable approach and new varieties and techniques will continue to provide new opportunities in the years to come.

The method to identify stability is by multilocation evaluation. Such testing serves both the purpose of evaluation and the distribution of elite varieties and hybrids. There is concern that numbers of entries are balanced with the burden that such tests place on local research station capability. It is possible to so burden a local research facility, that little opportunity is left for local imagination and input. There is need for international cooperation so that contributions from anyone can first be evaluated as a function of regional centers so that only the most contributing material enters national programs. This, of course, will vary in different parts of the world. Coordination on a regional basis is obviously relevant and its further development is of continuing concern.

Experience has shown that some local varieties fail to respond economically to inputs whereas others are more responsive and also combine well with exotics providing useful selections in the F_2 and advanced generations. Evaluation of locals for broad adaptation and responsiveness to inputs is potentially rewarding both in terms of direct use with improved management, and as parents in crossing programs. Selected locals would be prime candidates for conversion for use in temperate zone sorghum improvement programs. At present, there appears to be promise following careful evaluation of locals in Mali. Experience over the last 20 years in India has established that valuable varieties and hybrids, with substantial yield increases over locals, can come from introduced material. The use of responsive broadly adapted local cultivars and good introductions, frequently involving progeny from crosses between the two, appears to be rewarding. There is concern that varieties and hybrids do respond in low fertility situations. Experience indicates that varieties that yield well under high levels of fertility do best also under low levels. Suitable testing is required to understand performance of new cultivars across an array of fertility levels. It is clear that we will see an increased input into nitrogen fixation in the decade ahead.

Breeding for Resistance and Quality Traits

The speed with which resistance and quality traits can be incorporated into elite material depends on our capability to screen and on the complexity of inheritance. The need for an agency such as ICRISAT is to develop relatively simple tests that can be readily applied to large numbers of samples. Techniques need to be developed that can be applied in the areas where a problem is important. A detailed screening procedure to screen for resistance to shoot fly has been developed at ICRISAT but is likely to be too expensive for scientists in national programs to use. Such procedures can be used to identify the source and to develop stronger levels of resistance in varieties with good agronomic traits; however, it will be difficult to introduce the trait into varietal materials adapted to environments different from the one at ICRISAT. The technique is then not useful to finally incorporate the trait into breeding stocks that must be selected for adaptation in the area for which the varietal material is destined. We find, however, that we can develop useful simple procedures and this is a major undertaking for us in the future. We are also aware of the need for scientists in a region who can develop and adapt techniques and manage screening programs.

Once sources of resistance are identified there is concern about their stability across environments. Multilocation testing on an international basis is important to this function. Experience indicates that generally, in the absence of a qualified scientist, useful results are not recovered. Again the need for specialists working as a team is apparent—and as mentioned before, this function of evaluation and screening need to be undertaken incorporating a strong training component in order to stabilize these acivities within the local structure. We should be able to make substantial inputs in this area in the 80s.

We have been interested in looking into the opportunity to find components of quantitatively inherited traits that can be simply screened for and at times are simply inherited. The problem of stand establishment is being examined from several points of view—hypocotyl length to permit deep sowing which would delay germination until the soil moisture situation was more adequate; germination through a crust; and the effect of soil temperature on emergence. The glossy and trichome traits are simply inherited and are contributing to resistance to shoot fly. The group at the Commonwealth Overseas Pest Research organization is looking in detail into the *Chilo* stem borer-plant relationship helping to identify particular traits that may be more readily selected for than stem borer resistance per se. A search for traits useful for screening germplasm for resistance and quality traits is not new; a more intensive search in the coming years is likely. These research activities offer an excellent opportunity for cooperation with institutions in the developed world.

There is concern about the simultaneous incorporation of resistance for several traits into agronomically elite germplasm. We are aware that as the number of traits increases the gain per generation of selection for any particular trait is reduced and it is questionable that more than three traits can be efficiently selected for at the same time. There are indications that this is true for the population breeding approach also. More thought and experience would be worthwhile in this area. We are looking for varieties that already show promising levels of resistance to more than one trait. We feel that varieties can be blocked into maturity groups, be tan in plant color, and with visually good quality seed. On this as a common base we can couple other factors for incorporation. This coupling can be based on traits that tend to appear together; for example, drought resistance, resistance to charcoal rot, and resistance to *Striga.* Factors can be coupled based on a response need in certain environments, for example, early maturity, resistance to grain mold and to midge. There is no need to incorporate resistance to shoot fly and *Striga* into materials for the Americas or greenbug resistance into materials for Africa or Asia. We are also interested in heritabilities of different traits and how these may influence breeding procedures. For simply inherited traits, simply backcrossing into elite stocks may be the easiest and fastest without worrying about more than one trait. As we attempt to work more internationally, and our capability to screen for various traits improves, we will be more and more involved with these considerations.

Cooperation in screening can be improved and we need to seek ways of doing it. Midge is constantly severe at Sierra Talhada in north east Brazil; *Busseola fusca* is severe at Samaru in northern Nigeria. "Hot spots" can be identified for many traits of economic importance. If we could give thought to the development of a network where national or regional programs in an area could provide an international opportunity for screening it would enable us to evaluate our best material effectively and competitively and should help us mobilize useful germplasm more rapidly than at present.

We have been relatively successful in India in identifying locations and seasons where we realize a different severity of attack for both insects and diseases. Where relevant, this will permit screening at lower levels of severity in early generations and at higher levels on later generations. We feel at ICRISAT that the first several years of the 80s will be devoted to development and perfection of techniques for screening and that more extensive application will follow. Again this is not new, but we must further resolve this opportunity particularly in Asia and Africa.

One of the difficulties faced while screening is to prevent another problem from interfering with the trait being measured. Stem borer can nullify a charcoal rot screen, head bugs can interfere with the screening of midge. It is necessary that all concerned clearly differentiate farming from the growing and managing of experimental crops.

Pest management is a relatively recent term, probably not fully understood by many. Pest management for midge and birds would apply immediately as farmers begin to use earlier maturing varieties and hybrids in areas where longer season traditional types are commonly grown. Midge was a problem in India building up on CSH-1 and severely damaging later maturing locals; there are indications that the same will happen in Africa. Block planting of a variety or hybrid of the same maturity at the same time has been beneficial in several places in the world, including India, and holds promise for other areas as well. A better understanding of pest management is required as well as an adjustment of our own attitudes about how or with what precautions we want to introduce new material into the farming community.

Predators can be valuable—the lady bird beetle will control aphids on sorghum in India, and a small shiny black Cocinellid beetle will contribute to the control of mites. A better understanding of this and of ways of using insecticides so as not to reduce the beneficial effects of predators is an important consideration.

Food Quality and Technology

The quality that people like in their food is conditioned from childhood. There are situations where grain of different varietal types has been refused because of food quality, and examples of where poor quality types have been accepted. It is reasonable that a variety or hybrid contributing substantially to yield will be accepted even if the grain quality is not so good. On the other hand, the closer we can approach preference, the more easily and quickly a new variety or hybrid will be accepted both because of taste and because of market value.

Major foods from sorghum can be classified as leavened and unleavened bread made from fermented or nonfermented dough; thick and thin gels or porridges; rice like preparations and beer. Grain hardness has been found to be an important criteria for different preparations assuming there is no bitter taste and that the color is acceptable. It is possible to develop relatively simple procedures to evaluate these preparations. Reproduceability and a capability to identify good from not good, are basic. It is clear that visually attractive grain may not make a good food and that grain from some varieties is good across a number of preparations; CSH-5 is in this category. Input into food quality considerations has expanded in the last few years and is destined to be an important aspect of crop improvement in the future. International evaluation involving traditional food preparations, milling, industrial food preparation, and determination of physicochemical parameters has already begun, representing a coordinated input to evaluate selected grain types. This is certainly an example situation that should be encouraged in other areas also.

In many traditional societies grain is pearled by pounding. This is generally done by women using a heavy wood pedestal with grain in a wooden-mortar. It is a laborious time consuming job frequently not continued in urban situations. During the 70s, steps have been taken, notably by the IDRC, to develop simple effective pearling machines and they have reached pilot operation in several places. Dr. Perten, working in the food technology laboratory in Khartoum has contributed to processing sorghum to be sold in stores in sealed bags. We have not yet evaluated varietal variation enabling one to make foods normally from pounded (pearled) grain, but without pounding. I have been impressed that if a solution could be found to this problem we would reduce a daily burden of many women. Sorghum flour has long been blended with that of wheat and maize—this is still a topic of research that will continue into the 80s.

We were encouraged by the genes contributing to high lysine found in two accessions from Ethiopia (IS 11758 and IS 11157) and from mutation studies at Purdue (P 721). Problems have developed in their use that conjure up the complexity of problems encountered with opaque-2 maize. There is some division of opinion about the effort that should be placed on nutritional traits but there is a universal consensus that yield and yield stability is a higher priority than work on nutrition. Considerably more has been learned about tannin, but many food grains are low in these compounds and where they are not, the grain is generally made into beer or treated with wood ash that reduces or eliminates undesirable nutritional aspects. This has been of concern in relation to bird resistant sorghums and a research input in places where *Quelea* is a problem may deserve consideration.

We have been concerned about results reported from feeding children in Peru where sorghum has been found poor in terms of nitrogen and energy retention. This is a flag that should stimulate more research—particularly the effect of food preparation on these retention aspects. Work along this line is already under way at Purdue University and is apt to expand in the decade ahead. Interest will be in terms of selection criteria (Purdue has developed a test) and in terms of trying to extend different preparation procedures that enhance nitrogen and energy retention. This could be a more rewarding effort for the 80s in the area of nutrition than a concern for lysine.

Conditions of Research

I have long been concerned that a great effort is made on an international basis to educate scientists, and very little if any thought is given to the conditions of research in which these scientists work. The opportunity for many scientists to effectively utilize their education is all too frequently lost because conditions of research are poor. Frequently, experiment station development and operation is poorly understood and the so-called farm superintendent has no stature with the scientific community. In many countries, I suspect that 50% or more of the useful results that could come from field research are lost because of poor station development and management. This is costly in terms of time and money.

This is not a particularly attractive area for donors who frequently want easily identifiable results to justify expenditure. Yet. as we enter this decade a much greater input is required in this area if our progress is to be as rapid as it can be. Increased levels of education and training would help and International Institutes should look more seriously at this. Education is required for those who will actually manage an experiment station as well as for administrators who need to better understand experiment station personnel requirements. Universities could help by insuring that their students from other lands are adequately exposed to their own experiment station management operations. This is an important need for the 80s.

The Community of Goods and Services

The concern that we have is to increase and to sustain an increased production of food with sorghum being important among the food grains. The objective in some places is to shift traditional agriculture to a more technical agriculture, and where the agriculture is already highly technical, to increase production even more than it is now.

A look at locations with a highly technical agriculture indicates the kinds of goods and services required. These include a range of inputs: rural credit in support of short term production goals and for long term investment —wells, equipment, etc; increased availability of fertilizer and other chemical inputs; established markets and facilities for postharvest management of the grain; an established seed industry with quality control; an effective extension agency; government awareness of needed changes and the establishment of policies that encourage and support new technology; availability of improved farming equipment and the services required to keep it running; and ultimately food processing and marketing systems to supply packaged food of known quality. This is a complex array of diverse inputs, but all are relevant. A well developed and proven technology can fail or yield only a limited reward if government policy is discouraging.

A proper seed industry requires inputs into propagation of seed by breeders, foundation seed stocks agencies, and producers of the commercial seed. Quality control requires seed laws, certification, and seed testing laboratories. An input into processing equipment is required as well as a marketing system for the seed. This aspect of availability of quality seed is in itself a complex of diverse inputs. Significantly, many of these inputs are being considered in this symposium.

The situation that we face in the 80s is diverse—in some countries these inputs are effective and efficient; in others, they exist, but efficiency could be improved; and in others these inputs must essentially still come. There will be changes required in all of these areas if we are to move forward in the 80s.

Session 1 Setting the Scene

J. C. Davies* Discussant—1

The papers presented in my view gave a very useful background to the Symposium and highlighted the successes, the failures and the problems we face in the 1980s in increasing the supply of sorghum as a food at a time when significant shortfalls in production are forecast.

Both Doggett and N. G. P. Rao drew attention to the success in India over the last 10 years in significantly increasing production. Are there lessons to be learnt from this in the 80s and how much is applicable to Africa? Most papers, particularly that by Leng placed the shortfall situation clearly in perspective. In my view throughout our discussions we must focus our concern on Africa. The forecasts for India are, that production will approximately keep pace with demand and population growth, but in Africa the rapidly increasing population and forecast decline in production trend, as will be noted by Ryan later (these Proceedings), make the future bleak.

Papers highlight the importance of a sound germplasm base and utilization of this base to the full in breeding programs, if we are to meet the challenges of the 80s. Time is possibly running out and valuable landrace material is being lost. Possibly we could encourage adoption of the Ethiopian method of training collectors to obtain full details of the collections made, to ensure conservation. The question of grow out and safe storage should be addressed. All of us are familiar in recent years with losses of complete collections in Africa of both collected and advanced breeding material. How can such waste of resources be avoided?

I believe that the papers, except for that by Cummings, touch only marginally on a point which scientists choose to play down—and that is the effect of government policy on production through marketing policy and strategy. This is a matter which has concerned me for the last 25 years, as I was appointed originally to Africa as a result of the fact that a price was set for maize which resulted in a huge surplus. This surplus was an embarrassment as all stores were filled, and poor storage resulted in large insect losses in store. Subsequent price changes resulted in such a paucity of maize that I was unable to carry out experimenal work, as maize was almost unobtainable in sufficient quantity. Is much of the problem of production related to low farm gate prices which are adopted to provide low food prices for the articulate and politically aware urban population?

The question of the merits of hybrid sorghum vis a vis varieties is one which merits attention. It is clearly brought out in the papers that hybrids have produced quantum jumps in production in India and elsewhere. These increases have led to many beneficial effects for the farmers as a whole and encouraged innovative methods and improvements, including fertilizer and pesticide usage. However infrastructures must be considered. Doggett notes that some of the newer varietal lines from plant breeding programs are producing yields in wide-scale testing not greatly different from those of hybrids currently in use. In the African situation there are certainly problems with production of hybrid seed—not all of them technical and the use of hybrids does demand effective production techniques and efficient delivery and marketing systems if benefits are to be reaped. The question of hybrids and varieties is one I feel sure will be addressed many times in the next week. Possibly the emotive subject of government versus private company seed production is one which may also be addressed. Clearly any cultivars released by government or private seed companies should in no way increase the risk to farmers of damage or loss from whatever cause. In this context I am sure that participants will discuss and make recommendations on popu-

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lation breeding approaches. It is rightly observed in the papers, that conventional breeding and the population approach are not mutually exclusive, but go hand in hand. A wide genetic base for Africa is a must to effect rapid improvement. As an 'outsider' to the debates on population versus conventional approaches I find this self evident. In this context a more important issue, as far as I can judge, is the fact that we must realistically face the fact that the cultivars which will help or hinder the solving of the forecast food shortages of the late 1980s are already in the pipeline. It does, after all, take up to 10 years to adequately test, multiply and widely distribute a proven line. This is clear from both the Doggett and N. G. P. Rao papers. It is equally clear from Leng that the 'crunch' is almost with us.

A clear picture of the major stress factors reducing yields emerges from the papers. A trebling of the current yield averages in sorghum from their pitifully low 500-700 kg/ha would be a major contribution. To do this, incorporation of identified resistance factors into higher yielding agronomically desirable palatable types is a must —but we do not need, though it would be nice to have, the 8000 kg/ha cultivar. Administrators, donors, publicists must guard against setting too much store in assessment of success or failure on these high, perhaps unrealistically high figures.

In obtaining improvements in observation of stress factors we clearly need improved screening techniques in the 1980s. This is particularly so in the area of *Striga* and drought. These techniques as is clearly brought out must be made available to national programs which are strong, adequately funded and well staffed, which is a point stressed by House and others. It is a sobering fact that in spite of years of training effort and input, it is possible that the amount of research effort going into coarse grain production in developing countries this year, may be less than it was 10-15 years ago. Both Cummings and Doggett note the importance of the fact that sorghum is grown as a food mainly by the small farmer of very limited means and that it has important features of increased dependability in erratic rainfall and soil conditions. The specter of duplication of effort in research to serve this farmer, which is increasingly being raised, is to my mind a phantom fear. What is needed is more people actually working on the ground in the different functional regions discussed by House. The Augean stable is large, the shovellers are few—but the reviewers and pundits are a multiplying breed.

The comparative advantages of different organizations be they regional bodies such as SAFGRAD and CILSS, developed or developing country universities, national programs and IARCs need to be clearly understood and stressed. A little overlap in programs is both desirable and necessary, but as stressed by Cummings, communication needs to be improved. Perhaps in the next week or so we will do our bit to improve this communication at both organizational and personal levels -a factor stressed by House. How is this to be achieved—through training at various institutions and through regional organizations presumably?

Several of the papers, particularly Rao's stress the importance of risk aversion and intercropping in strategies for the 1980s. This is a topic which needs detailed study in the next week. What elements of the technology being developed, for example in the USA where there is adequate funding and staffing for sorghum research, are applicable to a situation such as India with adequate infrastructure and to Africa where the situation is perhaps less developed? Rao raises very real issues when he discusses whether our efforts in the 1980s should be directed towards improvement of existing systems (cultivars). He even suggests that the virtues of photosensitivity in tropical situations have been overemphasized and that a transformation strategy is required utilizing suitable cropping systems. I hope these theories will be squarely addressed and debated in the coming week. In the context of cropping systems, possibly the importance of soils and the water storage capacity of the soil profile and the effects of erratic rainfall have perhaps been underestimated. Hopefully this will be corrected in the course of the week. Certainly there are indications that the data base in agrometeorology is being examined and improved in many countries and could, as N. G. P. Rao states, possibly give useful guidance and formulating strategies for both cultivar development and optimizing water usage in the SAT. The importance of the 'reliability' of cultivars grown by farmers vis a vis their apparent drawbacks with regard to plant population density and response to fertilizer, are subjects in which I am sure our physiologist and agronomist participants will have a considerable input. Certainly it appears that for the small farmer situation, more detailed work is required on the performance of improved cultivars in intercrop situations compared with the existing ones being grown.

Clearly the 1970s saw a big improvement in breeding for acceptable food quality, possibly as a result of the Sorghum in Seventies symposium. This effort needs to be reinforced. The contribution of red/brown seeds, of lower food quality, to resistance to birds, diseases, and insect attack needs evaluation in the light of improved food processing techniques. Useful pioneering work has already been done in Senegal, Sudan and East Africa.

Finally I believe all the papers indicate that more effort is needed to capitalize fully on information on sorghum becoming available in developed countries and in assisting developing countries in establishing sound research bases in disciplines relative to sorghum production. I hope this conference will make positive statements and proposals on how this can be done. We appear to be in a declining actual fund situation for research on sorghum — maximizing the utilization of scarce financial resources for the benefit of all, is a very important consideration at this time.

I would like to compliment the authors of these papers on setting a useful tone for our conference and I hope that they stimulate good and fruitful discussion and realistic and worthwhile recommendations by the end of the week.

Session 1 Setting the Scene

R. Nicou* Discussant—2

In most of the papers presented, the writers are happy about the results obtained during the last 10 years owing to the selection of early varieties, with short straw, and thus better adapted to rainfall cycles, and yielding more than the local varieties. It appears from all this that considerable progress has been made in this field. Furthermore certain projects have been launched with the aim to develop varieties resistant to the major parasites, diseases and to *Striga.*

A few authors have laid much stress on breeding for better utilization of water, not only through plant adaptation to the cycle, but also through a better development of the root system and in-depth physiological studies on the plant's adaptation characteristics to drought conditions.

But little has been spoken about the breakthroughs in sorghum agronomy which are very tmportant. Certain organizations, such as IRAT have been concentrating on these problems in West Africa for 20 years. ICRISAT for almost 10 years, has been trying out farming techniques on Vertisols.

In agronomy, striking results have been gained in techniques of soil preparation, sowing, and weeding of crops. Even the simple control of weeds can often increase yields considerably Regarding mineral and organic fertilization, many detailed research programs have been pursued on the use of natural phosphates which are present in several West African countries. Research on transformation of vegetable waste into manure, compost and biogas is being conducted in West Africa and India, and very interesting results have been obtained. The problem of crop succession, especially toxic effects, of sorghum on the following crops in sandy or clayey soil has also been investigated. There is still much to be done in agronomy, but a lot has already been achieved.

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Despite all the hopes of progress raised by the research results, it is disappointing to learn that yield is still low in many countries. Some techniques are not transferred, and certain varieties are not popularized. While conversing with scientists or with the cultivators themselves, we observe that many questions remain unanswered. They are either general or basic, but most often they are down-to-earth. We should discuss them here and I now draw your attention to a few examples:

1. A basic question to begin with is what is the future of sorghum as a food crop? In West Africa, one often hears specialists saying that in time sorghum will lose its ground to millet which is resistant to drought, climatic hazards, and will grow in sandy soils, and whose area will extend to the south in drought years; and also lose to maize which has responded spectacularly to research and is expanding towards the north, due to greater adaptation.
2. Concerning varietal improvement, a number of reproaches have been made to the different research organizations They have been accused of using too much exotic material, hybridization and not working on local cultivars. Between 1940 and 1960 a lot of work had been done in this field but should it not be resumed in the light of present knowledge?
3. The improved varieties and hybrids have been known to adapt with difficulty to rural cultivation conditions. They are accused of being too sophisticated and less hardy. What is the truth?
4. Much is spoken about work on drought resistance. Is breeding alone sufficient? Should not agroclimatological knowledge be better utilized in this field? Should not the techniques of water economy at the plot level (soil-preparation, ridging) and also at the level of land management (level terraces or furrows, watersheds...etc) play an equally important role?

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5. Is not agronomy necessary *at first,* if we aim to improve the yields due to the poor natural fertility of the soils? The major mineral deficiencies (nitrogen, phosphorus), the organic condition of the soils, the tendency towards acidification all together cause yields to remain stagnant and often sorghum stops growing even if the varieties are good.
6. Should we think of working on sorghum as it is, or in terms of a farming system? Should we consider, as some persons are advising, that sorghum is a food crop which can benefit only from improvements brought to the cash crop which precedes it? In the framework of a farming system, in what way can the vegetable residues be used?
7. Is it not necessary that postharvest technologies and a better organization of a marketing network be known at the village level for the transfer of techniques and varieties proposed by the research? This last item may not be directly relevant to this meeting, but I think that this is one of the conditions which would encourage the farmer to produce more.

These seven points should not be taken as affirmations, but I would like you to reflect upon them and discuss them so that our future research will be more relevant, at the village level, to the real problems which affect the sorghum crop.

Session 1 Setting the Scene

Discussion

Bunting

It seems to me that price, in many circumstances determines the volume of output and the level of technology that the farmers are willing to apply to improve yield per hectare. Perhaps Dr. Leng would care to comment on the influence of price on levels of yield.

Leng

Many factors other than the price of the product influence levels of technology and yield.

Andrews

I would like to highlight the menace of *Striga* in Africa. I have just returned from an extended visit there and *Striga* on sorghum (and pearl millet) is the worst I have seen in 20 years We can see from Dr. Leng's figures that there is good potential for increasing sorghum yields — the Mexican and Indian figures testify to that. Dr. Doggett however mentioned *Striga* as a major problem, I would go farther than that and say that the potential of high yielding varieties and agronomic inputs can and will be set by *Striga*—there will be no lasting progress in dryland cereal yields in Africa until the problems of breeding resistance for and controlling *Striga* receives full recognition.

Jotwani

I would like to comment on Dr Doggett's remark about resistance to the sorghum stem borer. In India satisfactory progress has been made on resistance to *Chilo* Numerous sources of resistance have been identified and we have highly promising derivatives like E-302, E-303, P-37 and P-151 which possess desirable agronomic characters as well as a moderate level of resistance to the borer

Doggett

The statement made was that better sources of resistance are needed. I completely accept Dr. Jotwani's comment but believe that the 'moderate' level of resistance which he mentions needs to be strengthened.

Vartan

I feel that the role of sorghum as a food in Mexico and Central America is not adequately appreciated in comparison to sorghum as a feed grain.

House

The ICRISAT sorghum program in Mexico is trying to help in improving the production and yield of sorghum in Central America and Caribbean countries where the yield of sorghum ranges between 0.8-1.2 t/ha and up to 90% of the production is used for food. I question whether the extent of food use of sorghum in Central America is adequately appreciated elsewhere Sorghum is an important food in Haiti. El Salvador, Honduras and Guatemala. There is interest in the Dominican Republic and Mexico. The sorghum flour is mixed in a range of proportions in maize. The rather extensive use of sorghum as a food tends to be lost in the feed use.

Davies

The food sorghums are important in Mexico; however the spectacular increase in sorghum production is for feed Sorghum can have an important place in two ways; feed substitution and for admixture with maize in *tortillas.* The ICRISAT program is aimed at sorghum for food.

Gebrekidan

How much of the phenomenal yield increase in Mexico is due to sorghum research done in Mexico and how much is due to sorghum research in the U.S.?

Leng

I think most of it is due to sorghum improvement research in the U.S., particularly in Texas, mostly replacing maize.

Gebrekidan

To what extent has the increase in sorghum production in Mexico resulted from the work of the Mexican National Program and to what extent is it the result of work by U.S. seed companies?

Leng

From what I understand it results almost entirely from adoption of modern technology and U.S. developed hybrids. The U.S. seed companies have played the principal role in this development.

Stoop

In connection with Dr. Leng's observation on decreasing sorghum yields in Africa and Dr. Rao's comments on the need for transforming sorghum farming in Africa, I want to make some comments.

In West Africa farmers have until recently practiced a system of shifting cultivation. In that system, neither land management nor technological inputs are practiced. We are now dealing with only the first or at most the second generation of farmers practicing a permanent or settled agriculture. In this settled agriculture, land management in terms of erosion control and fertility maintenance is vital to maintain long term soil productivity, especially on the widespread sloping and low fertility soils. However, most farmers still lack these management skills nor are they sufficiently aware how to manage the new technology made available (e.g., animal drawn equipment, herbicides, fertilizers, etc), although these important technologies did permit farmers to expand their farms considerably. In some cases this expansion has clearly led to further soil degradation.

Thus a major problem remains, i.e., the implementation of improved technology for farmers; a far stronger extension program than presently exists in African countries, will be required to overcome this constraint.

Norman

Two speakers. Drs. Leng and Doggett emphasized the significance of yield per hectare of sorghum and the poor results in Africa compared with India. Because of the differences in the land/labor ratios in the two regions this is not necessarily a useful comparison. Farmers wishing to maximize their net return will maximize their returns to the most limiting factor (resource). In India, land is generally more limiting than labor and therefore assuming a positive correlation between net return and yield, yield per hectare is indeed relevant. However in much of Africa, labor is often more limiting than land and therefore yield per man-hour put in during the labor bottleneck period is much more relevant. Comparisons between Africa and India would, therefore, I believe, be more relevant if expressed in terms of rates of change in production—which is in turn determined by a combination of yield per hectare times the number of hectares devoted to sorghum.

Morris

As Dr. Bunting hinted, the sorghum millet production decline on a per capita basis is almost certainly a result of a relatively low price (or return per man-day of work) and it is not so much a problem associated with the production. Considering the increase in imports of wheat and rice in the coastal countries this is not surprising.

The increases in producton which have occurred have been the results of an increasing number of farm families and hectares cultivated. However, there is a small number of farmers that are capable of successfully intensifying as well as extensifying with cereal yields, two or more times the average. We would suggest that a study of their production would be more profitable than attempting the proposed transformation in West Africa.

Grain losses after harvest were studied by Gordon Yaciup in Senegal. In this area farmers select the best grains for seeding.

The possibility of increasing demand by providing a high quality degummed sorghum flour in the cities—as will be discussed by Axtell, Ejeta, Munck—offers a great potential to reduce imports of grain and to increase urban consumption of sorghum (and millet).

Nwanze

Dr. Rao, have you thoroughly tested the African material and how much experience do you have in the African region to recommend the use of hybrids or Indian material? This question is based on the existing differences between India and Africa in insect pests and diseases and environmental factors.

N. G. P. Rao

I have not recommended any specific materials. What I emphasized was the approach which is based on limited African experience during the past several years. The materials will emerge if the approach is followed.

Bunting

Regarding adaptation of local varieties. I disagree with Dr. N. G. P. Rao. In respect to resistance to loss in storage, traditional varieties stored may lose 2-3% whereas introduced ones may lose up to 20-30%.

Rana

Are we not narrowing the germplasm base—all tan plant color types in Kenya are susceptible to the *H. turcicum.* Does ICRISAT plan to respond to all problems from the Center or from regional bases?

House

ICRISAT will try and develop a regional capability to respond to problems, particularly those not expressed in India. In no way do we anticipate responding to all problems from the Center.

Jotwani

Mention was made in one of the papers about screening techniques for resistance to pests. As far as the shoot fly is concerned, we have a pretty good standard method but for stem borer and midge there is some difficulty. I suggest that advantage of this symposium be taken to outline the screening procedures for major pests for the use of different workers.

Kambal

Mr. R. Nicou raised a question regarding the future of sorghum as a human food. In the Sudan there was much concern about this matter arising from the marked increase in wheat consumption following migration from rural areas to towns, and education of girls. However, two new developments encouraged sorghum consumption. The first was production of flour from decorticated grains. This flour was readily accepted not only for mixing with wheat for bread making, but for making the local preparations *Kisra* and *Asida.* Secondly, a successful attempt was made to mechanize *Kisra* production. In Yemen, there is no immediate danger for sorghum as it sells at a much higher price than introduced wheat.

Rana

The high yielding varieties are expected to spread rapidly because of ease of seed production, but it is the hybrids which are adopted more by farmers in spite of high seed costs. How much emphasis is needed to be given to hybrid development relative to varietal development in the 80s?

House

I believe that all breeding programs should know experimentally, how hybrids compare with varieties. A variety improvement program is basic to a hybrid program. I believe that use of heterosis is one of our strongest tools tor the harsh environment. I cannot say how much emphasis should be given, but where the area sown to sorghum is large enough to justify a hybrid seed industry. I believe that a significant part of the crop improvement program should be directed to hybrid improvement.

Obilana

I want to dwell on the production graphs shown by Dr. Leng. The differences in production figures for sorghum as shown by him and given by FAO, between developed and developing countries, are very evident though not very comparative! Our job in this symposium is to deliberate on how to close the gap as much and as soon as possible. What we should consider as reasons for the discrepancy are: who produces the sorghum, where, and why is it produced. Sorghum in the developed world is produced with high technology and for agro-industry as animal feed. Contrastingly, in most of the developing countries, sorghums are produced for human consumption by small holding farmers; this latter poses the problem of acceptability for food quality. Consequently, the farmers still grow their high quality local sorghums in the absence of acceptable improved sorghums and thereby still maintain their low yield levels of 800-1200 kg/ha.

Parameswarappa

There is an urgent need to look at the palatability and cryptic quality characteristics of fodder of improved varieties and a need to improve them, in case they are inferior to local cultivars.

House

I am aware, in India, that some farmers find that the processing of stover from new hybrids into hay is more difficult than it is with locals. However, by research it may be possible to improve the quality of hay. thus providing a better feed. This would be valuable research for the All India Coordinated Sorghum Improvement Prject. At this time. ICRISAT does not have a mandate to work on forage.

Adkoli

Is it not possible to evolve a composite type of sorghum utilizing varied germplasm collected in the 1970s? Hybrid seed does involve a technologically cumbersome procedure to harness hybrid vigor. Is this a goal for sorghum improvement in the next decade at ICRISAT?

House

We are interested in the use of heterosis in areas where there is no seed industry. We are currently evolving synthetics with (ICRISAT Center) and without (ICRISAT—Mali) genetic male sterility. Hopefully, these will be useful as efforts are made to establish ways to produce and market hybrid seed.

Vidyabhushanam

It is significant to note that all the speakers in the session made references to the sustained progress made in the Indian sorghum programs leading to a production advance. Dr. N. G. P. Rao in his presentation suggested the possibility of obtaining similar transformation in the African situation and the material developed in India may be useful for this purpose. Since the breakthrough in production in India has gone about mainly through large-scale adoption of hybrids, I wish to know how this transformation using the Indian material can be brought about in Africa?

N. G. P. Rao

I have emphasized more on the approach rather than specific Indian materials. If the approach is adopted, it is possible we may identify some agronomically desirable materials for immediate use in the form of hybrids or varieties. The emphasis is on an altered broad genetic base on which further improvement could be superimposed.

Bunting

In northern Nigeria, sorghum varieties are very closely adapted in phenology to the date on which the rainy season plantings begin. A hybrid from India may by good fortune, have such an adaptation and consequently succeed in an appropriate place in Nigeria, but in general one would not expect to succeed with materials that had not been bred for specific adaptation. One additional attribute of great importance is resistance to pests in storage.

N. G. P. Rao

As Prof. Bunting pointed out, sorghum varieties of northern Nigeria sown at the beginning of the rains, flower after the cessation of rains. This in itself has been the primary reason for their low and uncertain yields and lack of progress in accomplishing perceptible improvement over the years. This has been the case with traditional Indian sorghums and researches to improve them till recent years. Rainfall analysis in northem Nigeria reveals that the beginning and end of the rainy season have their own uncertainties and there is a well marked stable period. If critical growth periods are adjusted to suit this stable period, yield levels could be elevated and stabilized. Hence reoptimization of critical stages of growth to such a phenology is essential. Flowering should preferably take place at periods of optimal moisture rather than towards the end of the rains which during several years may cease prematurely. The problem of insect pests, diseases and nitrogen management should all be viewed in this context and the necessary attributes incorporated.

I have not suggested any specific Indian hybrids or varieties. In fact present Indian hybrids and varieties are largely based on African zera zeras and I will not be surprised if they find a place in some African situations.

What is most important to me is the identification of an altered and broad genetic base which is highly productive and stable. Once this is accomplished, attributes which confer specific adaptations in terms of pests, diseases, etc., could be added rapidly.

Kanwar

It is evident from discussions that we need new technology which can better utilize the environment; so we should improve management, Some techniques have been identified and more are needed.

In subsequent discussion Dr. Leng raised two issues: (1) remove the limitations to production; (2) develop a delivery system. Dr. Doggett said that new technology has given rise to second-generation problems such as *Striga.* charcoal rot, and birds. So we should be prepared for them. He realized that some good screening techniques for identification of resistance traits have been developed and more needs to be done. The following questions were raised. (1) establishment of gene banks, (2) the degree of emphasis on varieties vs hybrids, (3) gene transfer by conversion, (4) development of screening techniques and creation of networks for international evaluation of resistant lines.

Dr. Kanwar emphasized that the success of progress will depend on the strength of national programs.

Session 2

Sorghum and its Environment

Chairman: R. L. Vanderlip
Co-Chairman: M. Lira

Rapporteurs: N. Seetharama
B. V. S. Reddy

The Physical Environment

M. V. K. Sivakumar and S. M. Virmani*

It is appropriate that the technical sessions of the Sorghum in the Eighties Symposium should start with the physical environment because it is the medium in which the biological material expresses itself. The "properties" of the medium such as radiation, rainfall, temperature, and soils control the rate of the biological processes such as nutrient uptake, photosynthesis, respiration, dry matter accumulation, etc. An understanding of the interactions between the properties and processes should lead us to develop principles for improved productivity of the sorghum crop.

There is a wide range of environments in the world in which sorghum can be grown. In this paper, characterization of sorghum climates is limited to the semi-arid tropics (SAT). It should be mentioned here that the boundaries for delineation of the SAT in this paper have been drawn according to the classification given by Troll (1965). Because of the limits imposed by the parameters used in Troll's procedure, the reader may find that these SAT boundaries differ from others published. For reasons of simplicity and space the discussion here is limited to Troll's SAT areas but this in no way should be taken to imply that sorghum growing areas falling outside these boundaries are any less important.

An extended description of the agrometeorology of sorghum and millet growing areas of the SAT will be the subject of an ICRISAT/World Meteorological Organization Symposium to be held at ICRISAT in November 1982. For additional information on the physical environment of sorghum the reader is referred to the proceedings of this symposium. The SAT are the areas located in the seasonally dry tropical climates, spread over four continents and 48 countries. The mean annual temperature in the SAT is > 18°C; rainfall exceeds potential evapotranspiration for only 2 to 4.5 months in the dry SAT and for 4.5 to 7 months in the wet/dry SAT (Troll 1965). The coefficient of variability of rainfall in the SAT is 20-30%. Over 55% of the world's sorghum production comes from the SAT (Davies 1980).

Using average production data for sorghum from 1974 to 1978 in different countries in the SAT, von Oppen and Ryan (1981) calculated the amount of sorghum production in the different SAT regions. From the data on sorghum distribution in the SAT they showed that India is the largest single sorghum-producing country in the world contributing 34% of the SAT total. Pakistan and Thailand are the other major producers in Asia. In Central and South America, Mexico and Argentina together contribute 34%. We have, however, no data to show whether sorghum production in Mexico and Argentina comes solely from the semi-arid tropical areas of those countries or from other climatic regions also. The next region in importance is West Africa which contributes 15% of the sorghum production in the SAT. The major sorghum-growing countries there are Ghana, Niger, Nigeria, and Upper Volta. About 10% of the sorghum in the SAT is produced in eastern Africa, the countries of major importance here being Ethiopia, Kenya, Sudan, and Tanzania. In southern Africa, Malawi, Mozambique, Zimbabwe, and Zambia are the major producers. In west Asia, Saudi Arabia, and Yemen Arab Republic contribute together 3% of the total sorghum production in the SAT. Over 65% of the total sorghum in the SAT is produced in Asia and Africa and our assessment of the sorghum environment focuses primarily on these two continents.

Because sorghum in the SAT is grown mostly in developing countries, and also because the pace of economic and social progress in these countries varies from country to country, the advance of meteorological knowledge has been different. Accordingly, the availability of climatic data varies

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across these countries. We have drawn generalizations at several places for this reason and we hope the reader will appreciate the reasons for so doing.

Environment of Sorghum-growing Areas in Africa

Radiation

Direct measurements of global solar radiation are few and far between in Africa (Cocheme and Franquin 1967). Empirical estimation of solar radiation has been a common practice, especially using the data on sunshine hours. The mean annual solar radiation in semi-arid Africa ranges from 16.7 to 20.9 MJ/m^2/day (Thompson 1965). Areas situated in the northern and southern boundaries of semi-arid Africa receive the highest solar radiation amounts.

Cocheme and Franquin (1967) and Brown and Cocheme (1973) calculated the global solar radiation for several stations in West and East Africa. Monthly global solar radiation for selected stations in these areas is presented in Table 1. Average monthly global solar radiation at Nairobi varies from as high as 24.6 MJ/m^2/day during February to 13.8 MJ/mVday in July. During the sorghum-growing season at most locations the global solar radiation averages about 18.8 MJ/mVday. In areas north of the equator the yearly minimal values of solar radiation normally occur around the month of August. This period coincides with the wettest period of the year with increased cloudiness.

Temperature

In general, temperature determines the rate of plant growth and development. The effects of temperature stress on each critical stage of development of sorghum are discussed by Peacock (1982). We briefly describe here the range of temperatures under which sorghum is grown in semi-arid Africa. Africa is the world's hottest continent; the average annual temperature exceeds 21 °C. As shown in Table 2, daily mean maximum temperatures are consistently high during the growing season and the seasonal variation is relatively small, especially for areas closer to the equator. The cooling effect of the rains reduces the mean monthly temperatures. In general the lowest air temperatures are recorded in the month of August, which is also the wettest month of the year. The highest air temperatures normally occur at the beginning of the growing season. In the highlands of East Africa temperatures lower than 22°C are also recorded. For sorghum-growing areas south of the equator, maximum screen temperatures in January of up to 32°C are recorded in Zambia and Zimbabwe. At Sucoma in the Shire valley of Malawi maximum

Tabic 1. Monthly mean iglobal radiation (MJ/m'/day) at selected stations In Africa.

Location	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Sokoto (Nigeria)	19.2	20.9	20 1	207	21.1	21 3	187	168	197	21 8	20 5	19.0
Kano (Nigeria)	18.9	20 1	206	20.3	214	20.3	186	164	20 1	21.7	20.5	18.8
Navrongo (Ghana)	20.1	224	21.5	207	206	199	177	16.7	18.3	21 2	20.5	19.8
Maradi (Niger)	20.0	21 5	23.0	229	223	22.5	197	184	208	21.7	20 1	19.2
Niamey (Niger)	19.3	208	20.8	21 0	21.2	20.7	189	17.6	193	21.0	24.3	18.2
Ouagadougou (Upper Volta)	18.4	19.4	206	19.5	20.0	17.9	17.1	153	179	20.2	189	166
Asmara (Ethiopia)	21.3	233	24.8	25.3	256	23.0	17.7	17.4	227	23.0	208	200
Nairobi (Kenya)	23.0	24.6	23.0	19.5	172	16.4	13.8	14.7	188	20 1	19.5	20.9

Table 2. Mean maximum and minimum air temperature (°C) during the sorghum-growing season at selected locations In Africa.

Location	June Nov*	July Dec	Aug Jan	Sept Feb	Oct Mar	Nov Apr
Accra (Ghana)	28.9 226	27.3 21 8	27.2 21.3	285 21 8	296 22.3	30.9 228
Navrongo (Ghana)	32.7 232	307 22.5	29.6 223	306 21 9	33.4 21 9	35.9 20.1
Bobo Dioulasso (Upper Volta)	31.8 21.3	30.1 207	295 20.6	307 20.4	328 206	34.4 19.2
Ouagadougou (Upper Volta)	33.1 229	31.2 22.2	303 21 4	31 8 21.3	35.6 21.8	36.9 20.0
Maradi (Niger)	36.7 23.8	323 22.0	306 21.1	321 21 5	359 193	35.5 15.4
Niamey (Niger)	36 7 25 1	33.2 232	31.3 225	330 227	372 230	37.2 19.0
Sokoto (Nigeria)	35.4 241	31.5 221	299 21 4	31.4 21.5	347 21 0	35.4 17.8
Kano (Nigeria)	33.6 225	304 21.1	292 208	309 209	33.9 19.8	33.7 16.0
Muguga (Kenya)	21 6 11.2	22.4 9.9	22.5 12.1	23.9 12.7	25.4 12.8	23.4 13.1

* Months in the lower column apply to locations south of equator

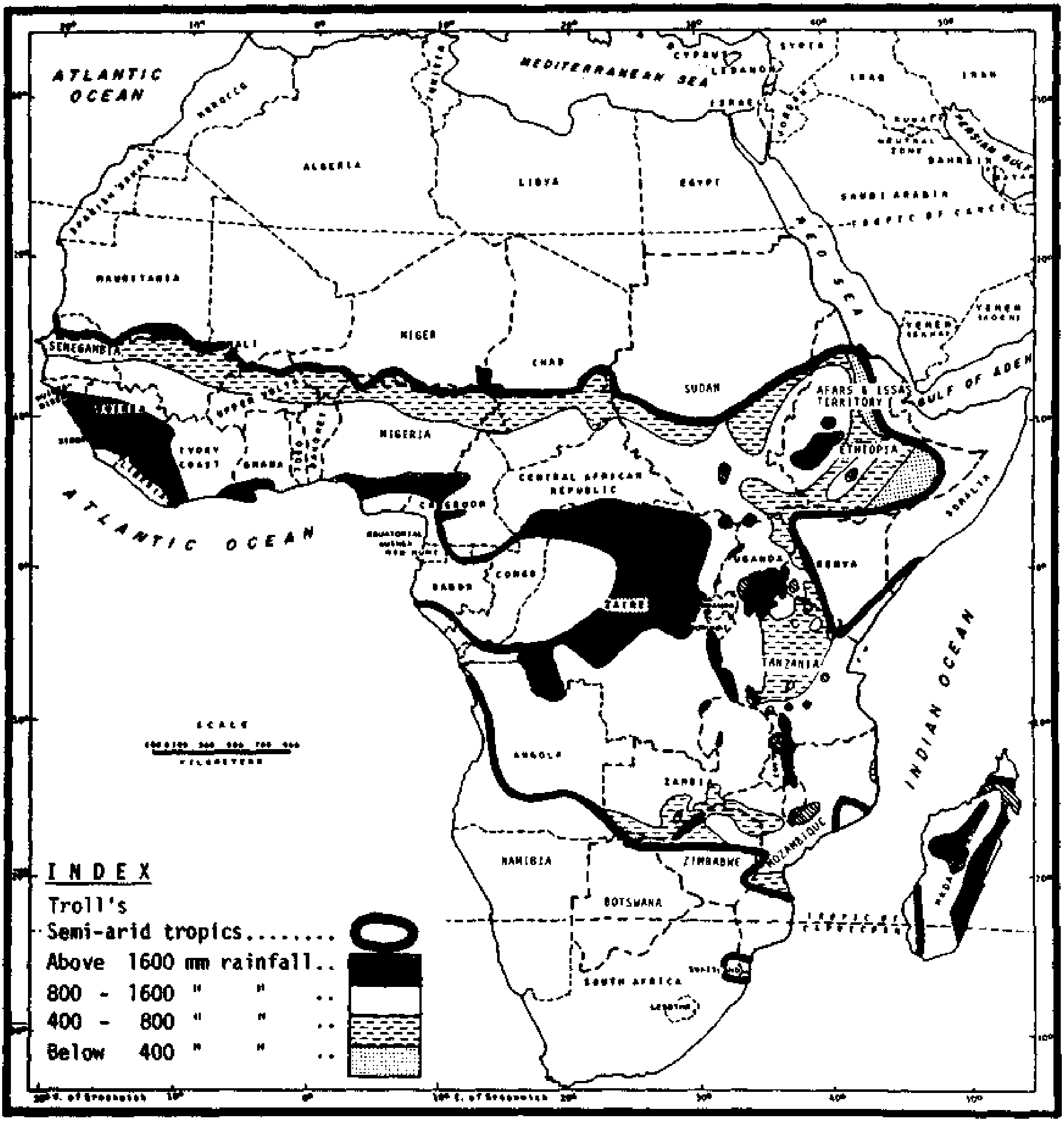
temperatures of 35°C are not uncommon (SVADP 1975). The diurnal range in temperature in the sorghum-growing areas north and south of the equator is very similar. In the highlands of East Africa, temperature variation due to altitude differences is important.

Rainfall

The pattern of air circulation over the African continent is determined by the earth's rotation and the temperature difference between the tropical and polar regions.

The intertropical convergence zone, commonly called the ITCZ or ITZ, has a particular role in this circulation. At a specific time during the season, the air in the equatorial region becomes very heated and rises to condense at a high altitude over the zone of maximum rainfall. These air currents of varying dryness move at great height towards the tropical high pressure anticyclone zone and then drop vertically, become compressed, warm up, and loose the rest of their moisture over the desert zones of the Sahara and Kalahari. These currents then move horizontally toward the ascending ITCZ, thus closing the cycle. Deflected by the earth's rotation, they then become tradewinds which blow from northeast to southwest in the northern hemisphere, and from southeast to northwest in the southern hemisphere. The ITCZ passes over the same region twice a year; there are two rainy seasons in the countries lying on both sides of the equator.

In Africa, the southward and northward influence of the ITCZ is clearly seen (Fig. 1). In West Africa.the mean annual rainfall varies from 250 to 1250 mm. Studies by Cocheme and Franquin (1967) for the semi-arid areas south of Sahara in West Africa showed that rainfall isohyets run parallel with the equator with bands or zones



receiving more rain the further south they are. On the dry north side of the area, the decrease in rainfall with longitude is most pronounced in Niger. The rainy season is short and the dry season is severe. In Niger most areas receive rainfall ranging between 200 and 800 mm (Sivakumar et al. 1980). Mean annual rainfall in Upper Volta ranges from 400 to 1200 mm, with the southwest region bordering Mali and the Ivory Coast receiving the largest amounts of rainfall in the country. The mean annual rainfall in Nigeria varies widely from north to south but. in the northern semi-arid states, the rainfall ranges from 500 to 1250 mm/yr. Kowal and Knabe (1972) showed that for the northern states of Nigeria annual rainfall decreases by 119 mm for every degree of latitude. The variability in the annual rainfall also increases with aridity from south to north. Cocheme and Franquin (1967) calculated coefficients of variability in annual rainfall for the semi-arid regions in West Africa south of Sahara that range from 15 to 38%. In West Africa the monthly mean rainfall increases gradually from the beginning of the rainy season in late spring or early summer to a maximum in August. The duration of the rainy season varies with mean annual rainfall (see discussion below in the section under growing period).

In East Africa, the rainfall zones are more complex because of the Ethiopian highlands with altitudes of 3000-5000 m. Brown and Cocheme (1973) presented consolidated and simplified maps of annual rainfall isohyets for the highlands of eastern Africa. The mean annual rainfall for two-thirds of the stations investigated is between 600 and 1200 mm, the remainder being stations receiving amounts in excess of 1200 mm. The highlands receive generally more rain than adjoining lowlands. On the western scarp of the high pattern in the Ethiopian highlands, rainfall exceeds 1200-1300 mm/yr, while on the eastern scarp the rainfall is less. Latitudinal effects are largely concealed by those of height and of the exposure complex (Brown and Cocheme 1973). Whereas latitude is a fair guide for the annual rainfall variations in West Africa, in East African highland stations it is not possible to forecast with any degree of accuracy the annual rainfall in terms of the geographical coordinates. Rainfall zonation in Sudan also is fairly precise as one moves towards the equator. Rainfall variability in southern Africa is again fairly large. For example, in the Republic of Zambia, the mean annual rainfall varies from 700 mm in the south to 1400 mm in the northwestern areas.

Average rainfall figures do not yield information on the dependability of precipitation. Hargreaves (1975) has defined dependable precipitation (DP) as the amount of rainfall which could be received at 75% probability. The moisture availability index (MAI)—defined as the ratio of dependable precipitation to potential evapotranspiration —could give an idea of the precipitation adequacy for crop growth. Monthly values of MAI during the sorghum-growing season at selected locations in semi-arid Africa are shown in Table 3. The data show that in West Africa moisture availability for sorghum growth is fairly adequate until September. October and November are very undependable. In eastern Africa, particularly at Mombasa and Dar es Salaam moisture availability is fairly low. Moisture availability at Livingstone in Zambia is comparatively favorable.

Table 3. Moisture availability index (MAI) during the sorghum-growing season at selected locations in the semi-arid tropics.

	June	July	Aug	Sept	Oct	Nov
Location	Dec*	Jan	Feb	Mar	Apr	May
Ouagadougou (Upper Volta)	047	1 00	1 47	0 75	006	000
Kano (Nigeria)	048	1.07	1.76	0 59	0.00	0.00
Geneina (Sudan)	007	0.67	1 36	0.29	000	0.00
Mombasa (Kenya)	0.17	0.02	001	010	055	1 20
Oar Es Salaam (Tanzania)	022	009	015	040	1.45	001
Inhambane (Mozambique)	0.37	0.32	0.36	0.36	0.36	0.31
Livingstone (Zambia)	0.62	0.80	0.55	0.29	003	0.00

• Months in the lower column apply to locations south of equator

Length of the Growing Period

For a rainfed crop such as sorghum to be successful, it is necessary that its growth cycle should be of such a length that it is comfortably contained within the available growing period. Failure to match these characteristics does not completely exclude cultivation of the crop, but can result in reduction of yield and quality. There are several methods of calculating the growing period. But the methods adopted by the agroecological zones project of FAO (1978) appear to be useful. The growing period is defined as the period (in days) during a year when precipitation exceeds half the potential evapotranspiration, plus a period required to evapotranspire an assumed 100 mm of water from excess precipitation stored in the soil profile. The choice of 100 mm was based on experimental evidence from East and West Africa which indicates that the crops of the study can utilize stored soil moisture in the range of 75-125 mm by the time of harvest.

The length of the sorghurrvgrowing period (FAO 1978) in the sorghum-growing areas of semi-arid Africa ranges from 90 days in Senegal, Mali, Upper Volta, Niger, and Chad on the northern Sahelian boundary to 270 days in southern regions of Ghana, Nigeria, and Sudan. South of the equator the sorghum growing season is again reduced to 90 days in parts of Namibia, Botswana, Zimbabwe, and Mozambique. Medium growing period lengths of 150-210 days are common throughout the sorghum-growing areas in SAT Africa. The importance of the length of growing period and the adaptation of local photosensitive varieties to the long growing seasons has been extensively studied at the Institute of Agricultural Research in Samaru, Nigeria (Andrews 1970; Kowal and Andrews 1973; Kassam and Andrews 1975). For example, Kassam and Andrews (1975) showed that for short Kaura, a photosensitive Nigerian sorghum, total dry weight and grain yield decreased with delay in sowing after 26 May at rates of 1700 kg/ha per week and 360 kg/ha per week respectively. Bunting and Curtis (1968) showed that the date of heading of the local sorghum is closely related to the average date of the end of the local rains.

Soils of Sorghum-growing Areas in SAT Africa

The growing periods calculated above take into consideration only the water supply and water demand at a given location. However, the soil profile serves as a means of balancing, over time, the discontinuous water supply with the continuous atmospheric evaporative demand. The properties of the soil profile obviously affect its moisture retention, runoff, and drainage as well as the losses of water by evaporation and transpiration (Russell 1980). The soil map of Africa published by FAO (1977) identifies 53 broad soil regions in Africa. In the sorghum-growing areas of semi-arid Africa, 11 major soil zones were identified. The grouping here is done with the purpose of identifying a broad soil type, and it is necessary to point out that the soil type identified in a given zone often will have associated soils and other soil types. For a comprehensive description of the soils of Africa the reader is referred to FAO (1977), Swindale (1982), and Jones and Wild (1975).

Arenosols

These are sandy soils (up to 95% sand) that occur extensively, mostly on flat to undulating topography, in the northern boundary of SAT Africa in Upper Volta, Niger, Nigeria, Sudan.and along the southern boundary covering Mozambique, Zimbabwe, and Zambia. In Upper Volta, Nigeria, Zimbabwe, and Zambia, Cambic Arenosols predominate while in Niger, Luvic Arenosols occur. In Mozambique, Cambic and Luvic Arenosols coexist. Cambic Arenosols are sandy soils with a slight color or structural B horizon. The clay fraction is made up of kaolinite and oxides of iron and aluminum. Luvic Arenosols occur in moister climates than the Cambic Arenosols. The clay fraction in the B horizon could exceed 14%. Charreau (1974) reports that for Cambic Arenosols at Bambey, Senegal, volumetric water content (cc/cc) at field capacity varies from 12 to 15%, and the permanent wilting point from 3 to 4%.

Luvisols

Luvisols or Alfisols occur in the more moist climates of the Sudanian ecological zone in Ghana. Upper Volta, Niger, Nigeria, and Sudan. Ferric Luvisols, which are underlain by indurated ironstone, are most common. The clay fraction is dominated by kaolinite and other low-activity clays. The associated soils include Gleyic and Plinthic Luvisols. Volumetric water content (cc /cc) at field capacity varies from 17 to 22%, and permanent wilting point ranges from 7 to 8%.

Ferralsols

These are the most weathered soils which are situated towards the wet boundary of a region. These occur in Nigeria and Zambia. Orthic ferralsols are yellowish brown to reddish brown in color, and Rhodic Ferralsols are red, while Xanthic Ferralsols are yellow to yellowish brown. In Nigeria all the three types coexist, while in Zambia Rhodic and Orthic Ferralsols are common. Physical constants data for Ferralsols in Africa are not available, but for Rhodic Ferralsols located at Jaiba in Brazil, it was reported (Swindale 1982) that volumetric water content (cc/cc) at field capacity varies from 28 to 32% and wilting point from 20 to 22%.

Vertisols and Gleysols

These soils occupy large areas in Sudan and Ethiopia. Chromic Vertisols are slightly yellower, browner or redder and are contiguous with Pellic Vertisols. The clay fraction predominates, with 50-60% in most horizons. The water-holding capacity of Vertisols is normally above 200 mm. The Gleysols are poorly drained and the hydromorphic properties dominate others.

Nitosols

Humic Nitosols occur in the tropical highland zones of Ethiopia. The weathering stage of Nitosols makes them more fertile than Ferralsols. These are considered good agricultural soils.

Regosols

Large areas in Ethiopia and Kenya are covered by Calcaric Regosols. These are weakly developed soils on unconsolidated materials. The suitability of these soils for agriculture is extremely limited and they need good management for better crop production.

Cambisols

They are found in the sorghum-growing areas of SAT Africa, mostly in Ethiopia. They are characteristic of a recent stage of soil formation and in the Ethiopian highlands Dystric Cambisols and Humic Cambisols occur in hilly topography. Dystric Cambisols are poor soils. However, the associated Eutric Cambisols in Ethiopia are good soils, rich in nutrients.

Acrisols

These soils are insufficiently weathered to be Ferralsols but more strongly leached than Luvisols (Young 1976). In Tanzania, mostly Ferric Acrisols occur where the ecological conditions are severe. They have a coarse or medium texture, and are considered poor.

Fluvisols

These are alluvial soils developed from recent alluvial deposits in many African valleys; where water is available the soils are amenable to irrigation. They are well endowed with exchangeable bases and with total P_2O_5.

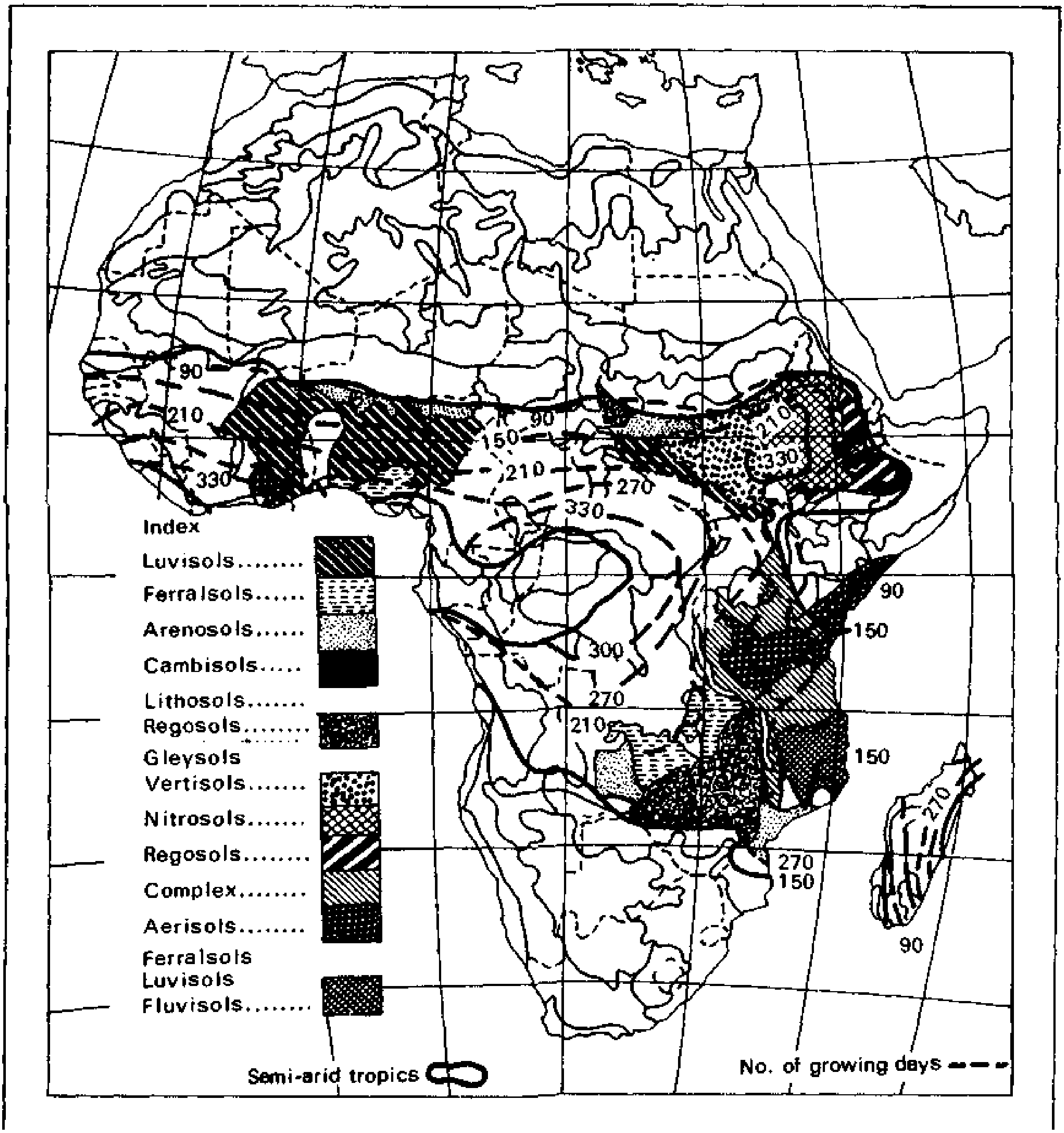
Lithosols

Soils with continuous hard rock at <10 cm depth. Because of dissected topography with steep slopes and of rockiness and stoniness of the substraction, the suitability of these soils for crop production is limited.

Complex of Soils

The soil complex indicated here includes Nitosols, Lithosols, Cambisols, Vertisols, Ferralsols, Acrisols, Gleysols, and Fluvisols in most of Tanzania. In addition the complex of soils in the southeastern Tanzania includes Regosols, Arenosols, and Ferralsols.

From the above description of the broad soil zones in Africa and the length of the growing period it can be concluded that, even where the soil type is favorable, potential yields of sorghum could be limited by the length of the growing period and vice versa. The length of the growing period superimposed on the soil type reveals some interesting features (Fig. 2). In the Arenosols soil region on the northern boundary of SAT Africa, the growing period is between 90 and 150 days, while on the southern boundary the growing period extends up to 210 days. These soils also generally lack adequate nutrient elements. Luvisols in West Africa and Sudan have a richer chemical composition and a better growing period, but they need better erosion control. Ferralsols in southern Ghana and Nigeria have a low natural fertility, but the growing period there is over 270 days. Vertisols and Gleysols in Sudan come under the 150-210 day growing period and.



Source: FAO, World Soil Resources Report, 1978.

Figure 2. Length of the growing period on broad soil zones of some of the sorghum-growing areas in semi-arid tropical Africa.

with good management, should be most suitable. The same applies to Humic Nitosols in the Ethiopian highlands, but Calcaric Regosols and Dystric Cambisols in Ethiopia cannot hold enough water in spite of the better growing period.

Environment of Sorghum-growing Areas in India

Nearly 13% of the gross cropped area is devoted to sorghum in SAT India. Karnataka, Andhra

Pradesh, and Maharashtra are the most important sorghum-growing states followed by Gujarat, Madhya Pradesh, and Tamil Nadu. Based on the data available on the sorghum area and production data for 1979-80, it was estimated that of the total area of 16.4 million hectares under sorghum, 60% is under rainy-season sorghum (the *kharif* crop in India) and 40% is under the postrainy season sorghum (termed as *rabi* crop). About 66% of the annual production comes from a rainy season crop while 34% is contributed by the postrainy season. In view of this, we felt the need to distinguish between the climatic characteristics in the two seasons in our discussion.

Bapna et at. (1980) classified the sorghum-growing districts in India into three categories: (a) >15% of sorghum area to district cropped area and >0.5% of sorghum area to all India sorghum area, (b) >15% to district cropped area and <0.5% to all India or <15% to district cropped area and >0.5% to all India, and (c) <15% to district cropped area and <0.5% to all India. Based on this classification, we defined districts under categories (a) and (b) as core districts and districts under category (c) as satellite districts. Further to emphasize the seasonal production, we define rainy-season sorghum districts as those where the area under sorghum in the rainy season is more than 75% of the total area under sorghum. A similar definition applies to those districts which are classified as postrainy-season sorghum districts. Districts where the area under sorghum in any of the two seasons is less than 75% of the total area under sorghum are termed as rainy- and postrainy-season districts. Therefore we propose six classifications of sorghum-growing areas in India, as shown in Figure 3. Over 99% of the sorghum in India comes from the SAT areas. From this map it is evident that core rainy-season sorghum areas extend from 9°N (Madurai) to 25°N (Hamirpur). On the other hand, the core postrainy-season sorghum-growing areas are restricted to a narrow belt of 14°N (Nellore) to 21 °N (Dhule). The reasons for this interesting zoning become more evident when we look at the soils and the length of the growing period.

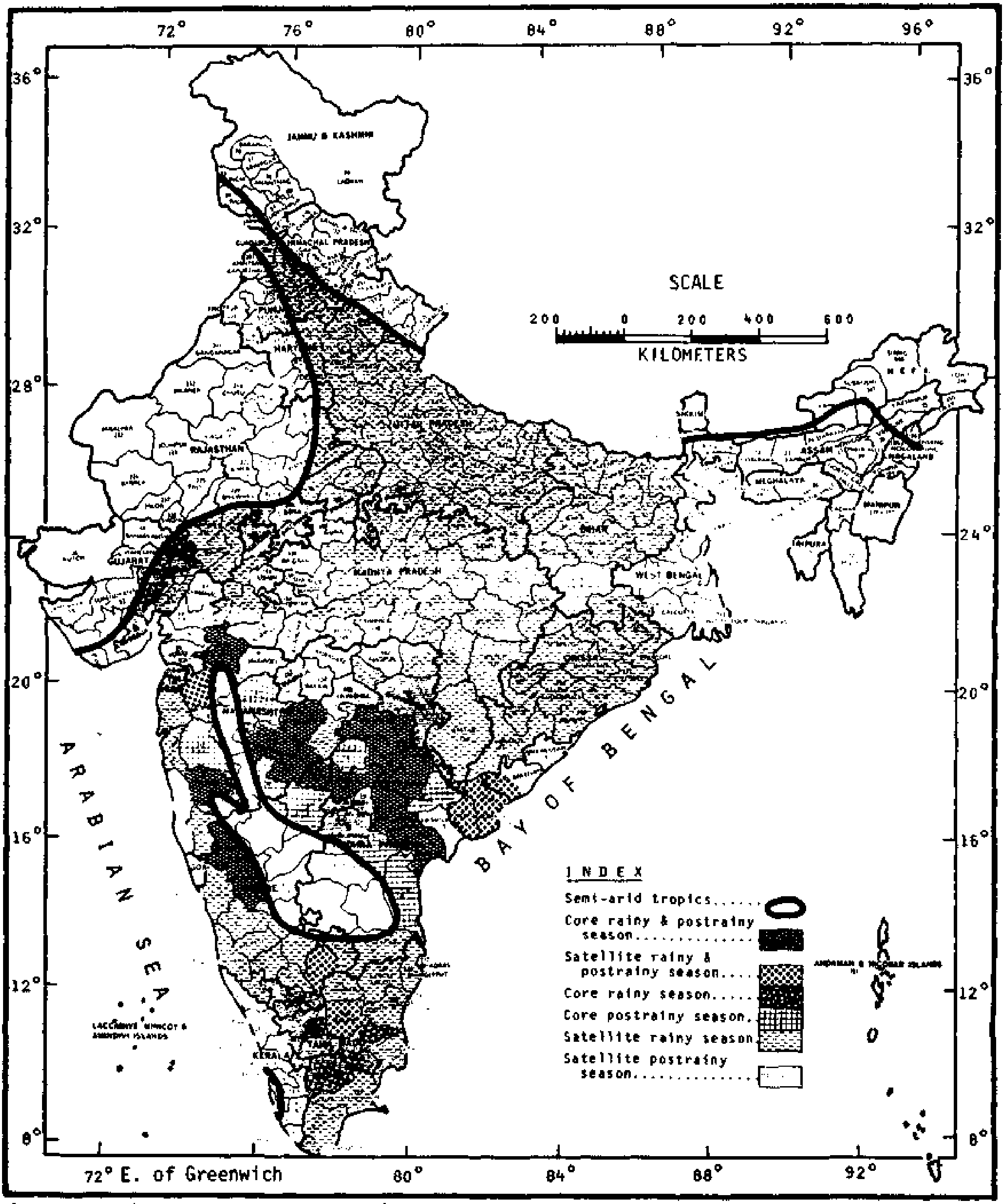
Temperature

The temperature variation between different sorghum growing areas in each of the six zones shown in Figure 3 has to be mainly viewed in terms of the two growing seasons. Based on 30-year normals (IMD 1967), the average, maximum, and minimum air temperatures during the growing season were calculated for the rainy and postrainy seasons. As shown in Table 4, during the rainy season average temperatures vary from 31° in June to 23°C in November. The data are shown for a 6-month period because sowing and harvesting of the rainy- and postrainy-season crops vary in different regions. In the postrainy season, average temperature varies from 22° to 29°C. Average temperatures, however, could be misleading and it is more important to examine maximum and minimum temperatures. The seasonal variation in the average maximum and minimum temperatures calculated from 25 representative stations for each season along with the average dates of anthesis and physiological maturity for CSH-6 (a rainy-season hybrid sorghum) and CSH-8 Ft (a postrainy-season hybrid sorghum) are shown in Figures 4 and 5. It is evident from the data that the maximum temperature variation during the rainy season is not significant, but the minimum temperatures decrease from 25°C to about 20°C by physiological maturity. In the postrainy season, however, the maximum temperature increases from 30°C at the end of October to 35°C by March. What is relevant in terms of the crop phenology is that the diurnal range in temperature is rather small in the rainy season and the uniformly high temperatures should promote good vegetative growth and grain filling. In the postrainy season,the diurnal range in temperature, especially around flowering, is rather large and the minimum temperatures are consistently low. Implications of these temperatures are discussed in detail by Peacock (1982).

Peacock (1982) suggests that the extreme temperatures are as relevant to sorghum growth as the average temperature. The highest and lowest air temperatures recorded in the rainy sorghum-growing season at selected locations are shown in Table 5. Maximum temperatures could reach as high as 45°C, as at Jhansi, while the temperature dip could extend to as low as 8°C in November at Indore. During the postrainy season (Table 6) highest temperatures of up to 40°C could be recorded, while minimum temperatures of 8°C are not uncommon.

Solar Radiation

Average global solar radiation during the rainy season varies from 16.7 to 18.8 MJ/mVday while



Source: Agricultural situation in India 1981

Figure 3. Sorghum-growing districts in semi-arid tropical India.

in the postrainy season solar radiation on an average is reduced by 0.4 to 1.7 MJ/mVday. As with temperatures, average values could be misleading and the highest and lowest values of solar radiation recorded at any location depend on the cloud cover and the geocoordinates of the region.

Table 4. Average temperatures during rainy and postrainy sorghum-growing seasons in semi-arid India.

Season	June / Oct*	July / Nov	Aug / Dec	Sept / Jan	Oct / Feb	Nov / Mar
			Mean average temperature (°C)			
Rainy	31.2	27.8	27.0	27.1	26.3	22.9
Postrainy	26.5	23.9	22.2	22.8	25.1	28.5
			Mean maximum temperature (°C)			
Rainy	36.4	31.4	30.5	31.3	32.4	30.1
Postrainy	31.8	30.3	29.4	30.1	32.8	36.2
			Mean minimum temperature (°C)			
Rainy	25.9	24.1	23.4	22.8	20.1	15.7
Postrainy	21.1	17.5	15.0	15.4	17.4	20.8

*Months in the lower column apply to postrainy seasons.

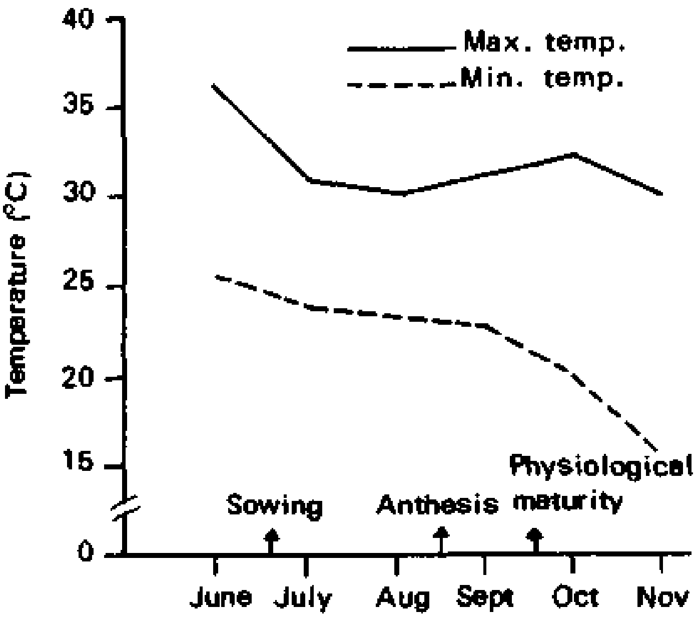


Figure 4. Seasonal changes in maximum and minimum air temperatures during the rainy season in India.

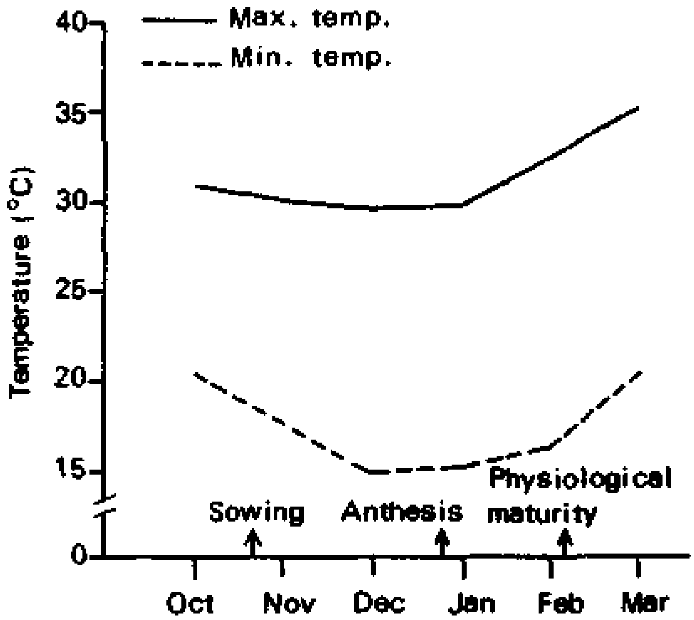


Figure 5. Seasonal changes in maximum and minimum air temperatures during the postrainy season in India.

Rainfall

The success of sorghum as a rainy or postrainy crop depends to a large extent on the available soil moisture which is largely modulated by the rainfall and the soil type. The rainfall isohyets superimposed on the sorghum-growing areas show that the annual rainfall varies from 700 mm to 1400 mm (Fig. 6). It is also interesting to note that almost all the core rainy-season sorghum-growing areas are located between the 800 and 1000 mm/yr rainfall isohyets. The core postrainy-season sorghum-growing areas are mostly located in the belt with low and undependable rainfall areas with 800 mm/yr. Based on a moisture index defined as $\frac{(P\text{-}PE) \times 100}{PE}$, where P is the precipitation, and PE is the potential evapotranspiration, Krishnan (1972) showed that the moisture deficiency during the rainy season is accentuated from east to west. In southern India, deficiency exists in Andhra Pradesh, interior Maharashtra, Karnataka, and Tamil Nadu. During the postrainy season

Table 5. Highest and lowest air temperature (°C) recorded in the rainy sorghum-growing season at selected locations in semi-arid India.

Location	June	July	Aug	Sept	Oct	Nov
Akola	422	36.2	31.4	35.0	35.6	33.6
	22.5	21.8	21.7	21.1	14.7	10.6
Hyderabad	39.9	34.0	33.0	328	33.3	31.5
	21.2	21.0	20.9	203	158	11.8
Indore	40.0	34.1	31 5	32 6	33.2	31 2
	21.4	21.0	20.4	18.9	13.0	8.2
Jhansi	44.9	39 6	355	35.6	36.0	334
	23.8	23.1	22.7	21.6	14.7	88

Table 6. Highest and lowest air temperatures (°C) recorded during the postrainy sorghum-growing season at selected locations in semi-arid India.

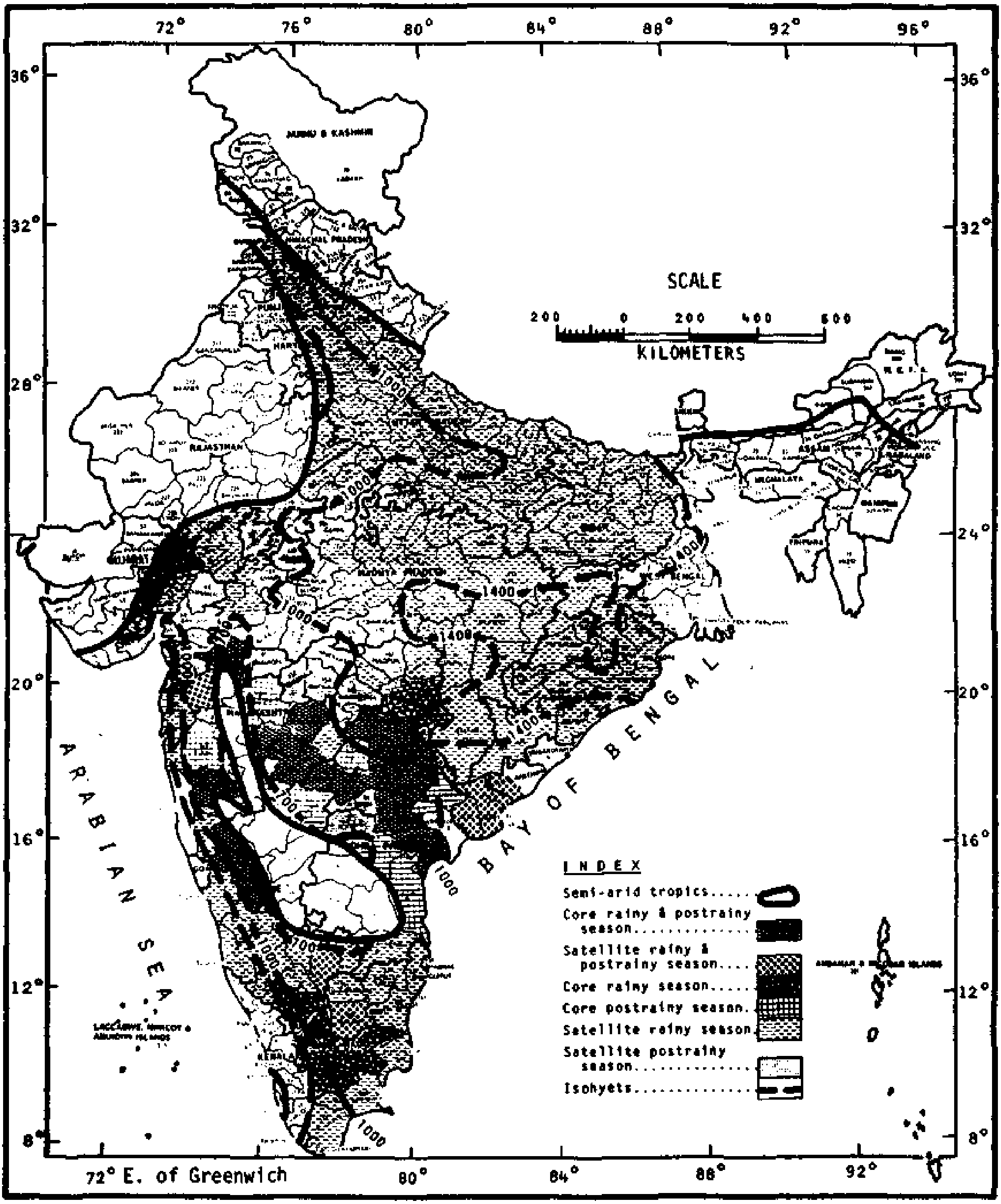
Location	Oct	Nov	Dec	Jan	Feb	Mar
Bljapur	33.6	31.8	31 4	32.7	358	385
	17.0	12.9	11.1	12.0	14.1	17.3
Gulbarga	34.4	32.8	31.5	327	36 1	394
	16.8	12.9	10.5	11.7	14.3	174
Sholapur	34.7	32.2	31.9	33.3	364	397
	16.6	12.9	107	11.3	13.1	167
Ahmednagar	33.5	32.2	31.1	320	34.4	385
	14.5	105	8.0	80	96	130

Table 7. Moisture availability index (MAI) in the raliny months of sorghum-growing areas at selected locations In semi-arid India.

Season	Location	June	July	Aug	Sept	Oct
Rainy	Hyderabad	031	076	066	088	0.15
	Akola	0.38	1.10	0.60	060	0.03
	Nagpur	0.74	2.54	1 64	073	007
	Indore	025	1.44	1.13	067	003
Postrainy	Sholapur	038	0.41	041	0.72	0.13
	Ahmednagar	0.40	0 34	0.23	0.67	0.13
	Chitradurga	0.24	037	034	047	0.40

moisture deficiency extends over the entire country except for a small belt in eastern Tamil Nadu. The deficiency accentuates from south to north in peninsular India and from east to west in north India.

As described earlier, a measure of the dependability of the annual rainfall in meeting crop water needs could be given by comparing the potential evapotranspiration (PE) with dependable rainfall. Moisture availability index (MAI), as defined ear-



Source:- ICRISAT, AgroclImatology Progress Report - 2 {197

Figure 6. Mean annual rainfall in the sorghum-growing districts of semi-arid tropical India.

lier, for the rainy months at selected locations in the rainy- and postrainy-season sorghum-growing areas (Table 7) shows that MAI in the rainy-season sorghum-growing areas is consistently high in comparison with those areas where sorghum is grown only in the postrainy-season. The low MAI values at Sholapur. Ahmednagar. and Chitradurga bear ample evidence of the farmers' preference to crop these areas only in the postrainy season.

Length of the Growing Period

Length of the growing period calculated by the agroecological zones project of FAO (Frere 1980, personal communication) for the sorghum-growing areas in semi-arid India is shown in Figure 7. Most of the core rainy-season sorghum-growing areas show growing periods between 120 and 180 days.

Soils

Murthy and Pandey (1978) prepared a soil map 6f India. A superimposition of the soil map of India over the sorghum-growing areas shows (Fig. 8) that the core sorghum-growing areas are in the black soil and red sandy soil belts.

The black soils are usually poorly drained and possess a low hydraulic conductivity. The texture of the topsoil is always clayey (40 - 60%) which leads to pronounced shrinking of the soil during drying. Black soils are hard in the dry season, but muddy and sticky in the wet season. The soil depth varies usually between 1 and 2 m and the available water-holding capacity ranges from 150 to 300 mm.

The red soils or Alfisols are relatively shallow, well-drained, and have a reasonable hydraulic conductivity. The texture of the surface soil ranges from sandy in Andhra Pradesh, Tamil Nadu, and Karnataka states to loamy soil in Madhya Pradesh and Orissa. The water-holding capacity of the soil is variable, depending on the depth, but ranges usually between 100 and 150 mm. In the dry season the soils are difficult to cultivate because of surface hardness.

The alluvial soils, or Entisols, are usually deep, possess good physical qualities, and are moderately permeable. The available water-holding capacity is lower than that of Vertisols, and varies from 150 to 200 mm. The texture of the surface soil may range from drift sands to loams and from silts to heavy clays.

The sorghum-growing area under laterite soils or Oxisols is fairly limited. The surface soil texture is loamy or clayey. The topsoil is of varying depth underlain by ferruginous deposits which harden on exposure.

As mentioned earlier, the soil profile characteristics play an important role in the plant-water relations. Using a water balance model to give estimates of weekly changes in available soil water for the shallow, medium, and deep soils, with 50, 150, and 300 mm water-holding capacities respectively, Virmani et al. (1978) showed that available soil moisture contents (mm) at the commencement of the rainy season for the three soil types are 16, 66, and 72 mm, respectively. At the commencement of the postrainy season the available soil moisture is 7. 80, and 204 mm for the shallow, medium, and deep soils. These data emphasize the need to consider the soil characteristics rather carefully in analyzing crop productivity over different seasons.

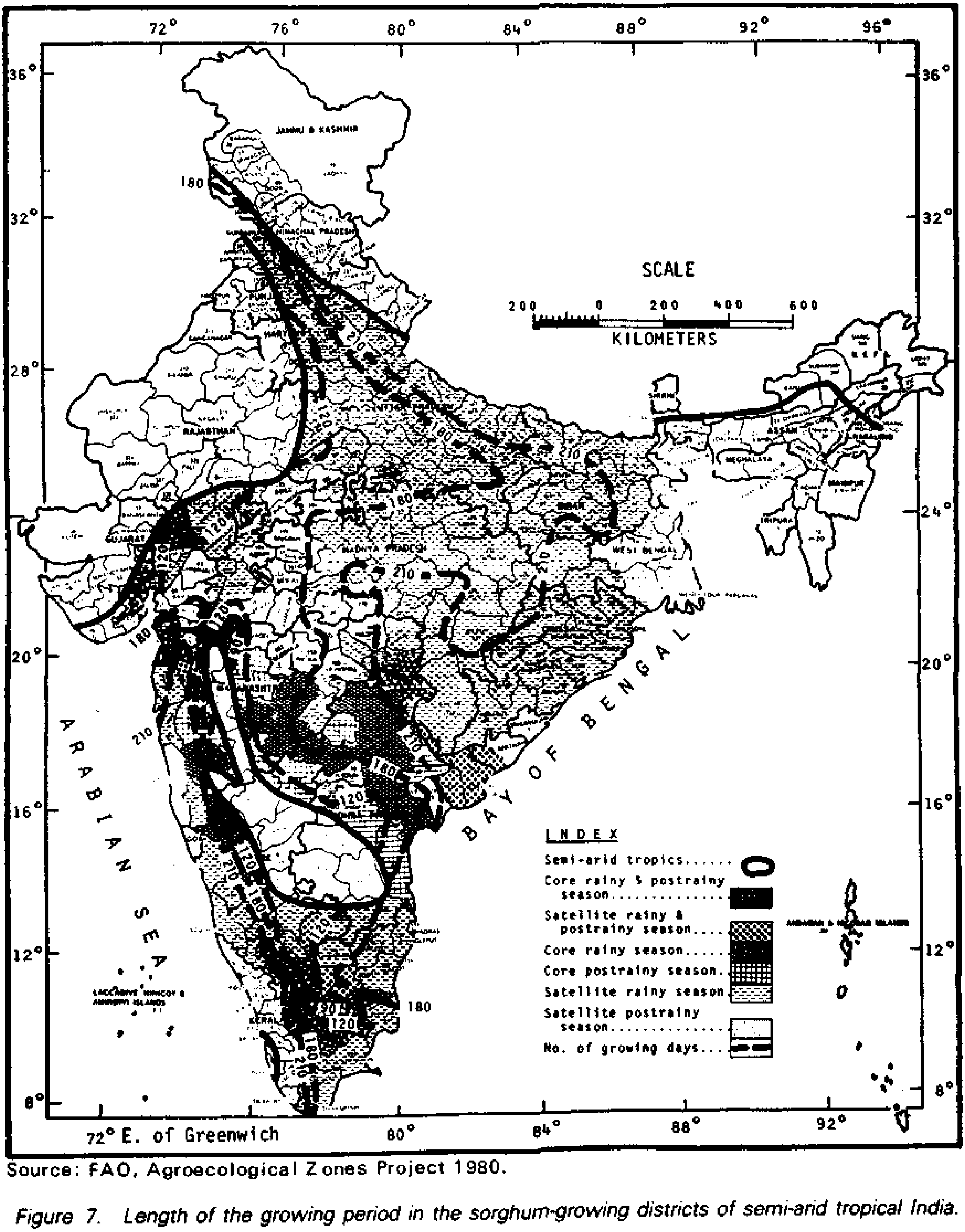
Based on soil climatic zonation. Kanwar (1972) pointed out that the most efficient sorghum regions are in the peninsular region or the central and south Indian states. This area lies in the climatic belts where the precipitation deficit (when compared with the potential evapotranspiration) could extend up to 40%, and on black soils that have higher moisture retention capacity.

Summary

The physical environment of the sorghum growing areas in semi-arid Africa and India has been evaluated by examining the temperature, radiation, and rainfall regimes with respect to soils of these areas. Analysis of the sorghum-growing areas in Africa showed that considerable potential exists in terms of the climatic suitability of the areas growing sorghum. Considering the differences in the two major sorghum-growing seasons in India, i.e., the rainy and postrainy seasons, emphasis was placed on describing the physical environment in the two seasons and the cropping potential that exists, particularly in the black soil areas of India.

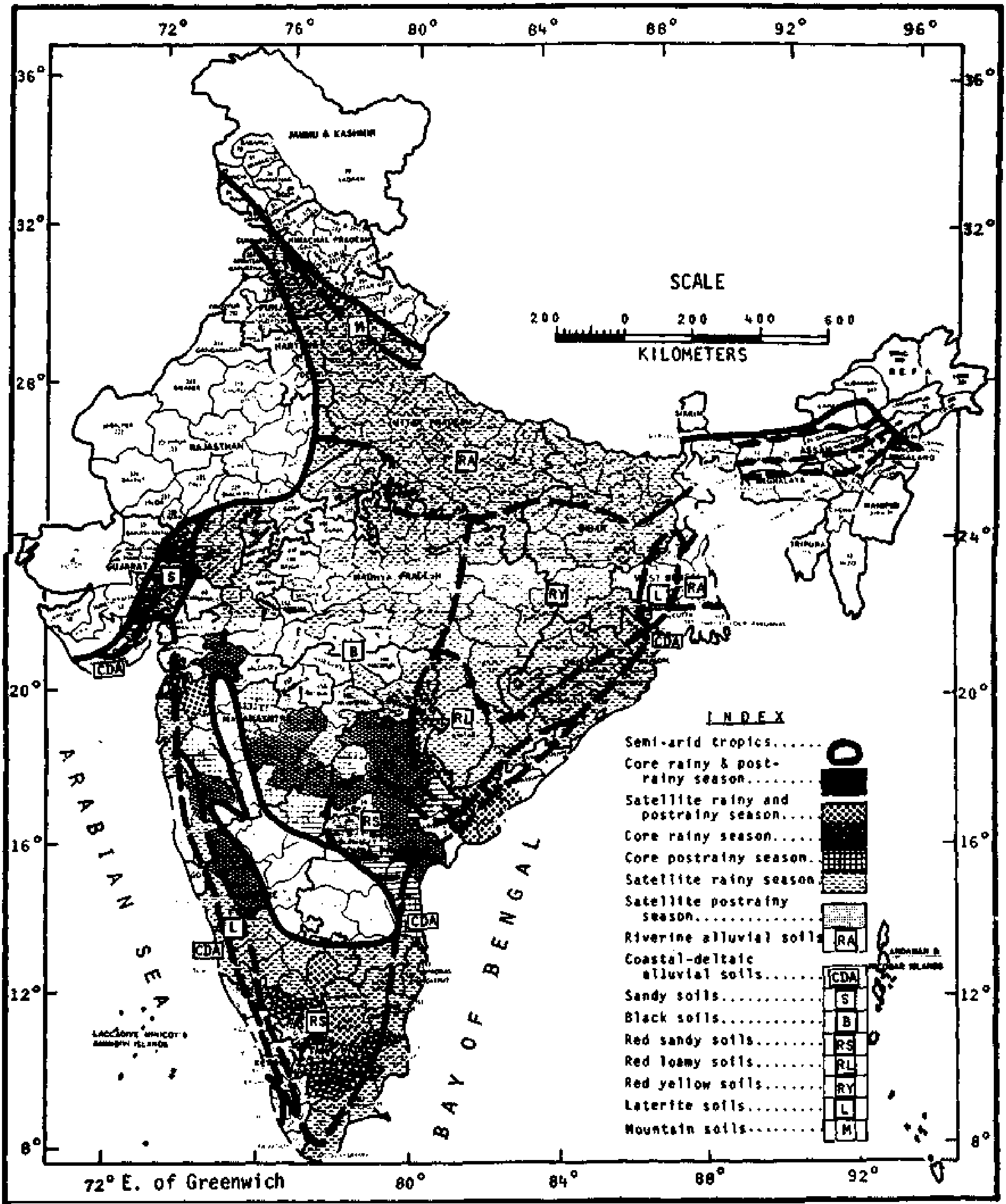
References

ANDREWS, D. J. 1970. Breeding and testing dwarf sorghums in Nigeria. Samaru Research Bulletin no. 121.



Source: FAO, Agroecological Zones Project 1980.

Figure 7. Length of the growing period in the sorghum-growing districts of semi-arid tropical India.



Source :- Murthy and Pandey (1978) Delineation of Agro-Ecological Regions of India

Figure 8. Soil regions in the sorghum-growing districts of semi-arid tropical India.

BAPNA, S. L, JHA. D., and JODHA. N. S 1980. Agroeconomic features of semi-arid tropical India. Paper presented at the International Workshop on Socioeconomic Constraints to Development of Semi-Arid Tropical Agriculture, ICRISAT, 19-23 Feb 1979, Hyderabad, India.

BROWN, L. H., and COCHEME, J. 1973. Study of the agroclimatology of the highlands of Eastern Africa. Technical Note no. 125. Geneva: World Meteorological Organisation. 197 pp.

BUNTING, AH., and CURTIS, D.L 1968. Local adaptation of sorghum varieties in northern Nigeria. Samaru Research Bulletin no. 106.

CHARREAU, C. 1974. Soils of tropical dry and dry-wet climatic areas of West Africa and their use and management. Ag. Mimeo 74 - 76. Ithaca, USA: Cornell University. 433 pp.

COCHEME. J., and FRANQUIN, P. 1967. An agroclimatological survey of a semi-arid area in Africa south of the Sahara Technical Note no 86. Geneva: World Meteorological Organisation.

DAVIES. J C. 1980 ICRISAT's International Cooperative Program. Pages 8-11 *in* Proceedings. International Workshop on Groundnuts, 13-17 Oct 1980. Patancheru, A.P., India: ICRISAT.

FAO 1977. Soil map of the world. Vol. VI. Africa. Paris, France: UNESCO. 299 pp.

FAO 1978. Report on the agro-ecological zones project. Vol. 1, Methodology and results for Africa. Rome,Italy: FAO 158 pp.

GRIFFITHS, J. F. (ed.) 1972. Climates of Africa. World Survev of Climatology 10. Amsterdam: Elsevier. 604pp.

HARGREAVES, G. H. 1975 Water requirements manual for irrigated crops and rainfed agriculture. EMBRAPA and Utah State University. Publication no. 75-D 158. Brazilia: EMBRAPA. 40 pp.

IMD (India Meteorological Department). 1967. Climatological tables of observatories in India (1931-60). Pune, India: India Meteorological Department.

JONES, M. J., and WILD, A. 1975. Soils of the West African savanna: the maintenance and improvement of their fertility. Commonwealth Bureau of Soils, Technical Communication no. 55. Farnham Royal, UK: Commonwealth Agricultural Bureaux. 246 pp.

KANWAR. J.S. 1972. Cropping patterns, scope and concept. Pages 11 - 38 *in* Proceedings of the Symposium on Cropping Patterns in India. New Delhi, India: Indian Council of Agricultural Research.

KASSAM, A H.. and ANDREWS. D.J. 1975. Effects of sowing date on growth, development and yield of photosensitive sorghum at Samaru, Northern Nigeria. Samaru Research Bulletin no 245. 18 pp.

KOWAL, J., and ANDREWS, D.J. 1973. Pattern of water availability and water requirement for grain sorghum production at Samaru, Nigeria. Samaru Research Bulletin no. 188. 12 pp.

KOWAL, J.M., and KNABE, D.T. 1972. An agroclimatological atlas of the northern states of Nigeria. Samaru, Nigeria: Ahmadu Bello University Press. 128 pp.

KRISHNAN, A. 1972. Climatic approach to cropping pattern adaptability in Western Rajasthan. Pages 165- 172 *in* Proceedings of the Symposium on Cropping Patterns in India. New Delhi. India: Indian Council of Agricultural Research.

MURTHY, R.S., and PANDEY, S 1978. Delineation of agro-ecological regions of India Commission V, 11th Congress of the international Society of Soil Science. 19-22 June 1978, Edmonton. Canada.

PEACOCK. J.M. 1982 Responses and tolerance of sorghum to temperature stress. These Proceedings: ICRISAT.

RUSSELL. MB 1980. Profile moisture dynamics of soil in Vertisols and Alfisols Pages 75-88 *in* Proceedings of the International Workshop on the Agroclimatological Research Needs of the Semi-Arid Tropics. 22 - 24 Nov 1978. Patancheru. A.P India: ICRISAT.

SIVAKUMAR, M. V. K.. VIRMANI, S. M., and REDDY, S.J. 1980 Rainfall climatology of West Africa: Niger. Information Bulletin no 6 Patancheru, A.P., India: ICRISAT.

SVADP. 1975. Atlas of the lower Shire Valley, Malawi. Shire Valley Agricultural Development Project, Malawi.

SWINOALE, L.D. 1982. Soils of semi-arid tropics—their limitations, potentials and prospects. Paper presented at the 12th International Congress of Soil Science. New Delhi. 1982.

THOMPSON. B.W. 1965. Climate of Africa. Nairobi: Oxford University Press. 132 pp.

TROLL, C. 1965. Seasonal climates of the earth. Page 28 *in* World maps of climatology, eds. E. Rodenwalt and H. Jusatz. Berlin: Springer-Verlag.

VIRMANI, S.M., KRANTZ, B.A., and SARDAR SINGH. 1978. Use of soils information for crop planning in semi-arid tropics. *In* Uses of soil survey and classification in planning and implementing agricultural development in the tropics, L D. Swindale (ed.) Honolulu: University of Hawaii.

VON OPPEN, M.. and RYAN, J.G. 1981. Determining regional research resource priorities at ICRISAT. Economics Program, report.

YOUNG, A. 1976. Tropical soils and soil survey. London, UK: Cambridge University Press. 468 pp.

The Plant and its Environment

G. L. Wilson and J. D. Eastin*

At the Sorghum in the Seventies Symposium (Rao and House 1972), an extensive discussion of sorghum did not provide for a distinct consideration of physiology, of which only some aspects were covered. In the intervening decade several reviews of the physiology of cereals have appeared and a number of these crops have been dealt with individually. The only separate treatment of sorghum is a recent review by Eastin (1981) in which there is some emphasis on reproductive behavior and the development of grain yield. The excellent review of the comparative physiology of cereals by Evans and Wardlaw (1976) can draw on little information for sorghum when discussing many important aspects of crop behavior. The botany of sorghum has been described by Doggett (1970), Freeman (1970). Purseglove (1972) and House (1980).

To some extent it is suitable to proceed on a phenological basis. Of various schemes for the recognition of growth stages, that of Eastin (1972) has been widely accepted. It distinguishes the period from sowing to panicle initiation as Growth Stage 1 (GS1); from initiation to anthesis (synonymous with bloom and flowering) as GS2; and from anthesis to physiological maturity, identified with the formation of the black layer at the base of the grain (Eastin et al. 1973), as GS3. These stages are based on reproductive development. However the production of other organs is also important, but their initiation, growth and activity do not correspond with the three conventional growth stages. For example, leaf initiation occurs only during GS1. expansion occupies all of GS1 and some of GS2, while photosynthesis and water use continue until the end.

What is largely an account of physiology might have been structured on processes, but this is done only for dry weight production and water use. A need to emphasize the plant has led to descriptions of the growth of seedlings until emergence, and then of the plant parts, with environmental influences being introduced as appropriate. Dry weight increase and reproductive development are then integrated in grain yield.

Germination and Emergence

Seed must be viable in the sense that it is at least capable of germinating. A comprehensive account of seed viability is given by Roberts (1972). It would not appear that there is important genotypic variation in sorghum in capacity to produce viable seed, but differences may develop either in the formative stage or in subsequent handling. Maximum germinability is reached before physiological maturity of the seed and may decline in later stages of development (Srivastava and Pinnell 1963). These authors have also shown that the source of the seed, within a genotype, has important effects on germination behavior. Retention of viability in storage follows the usual pattern of decline with age. increased temperature and higher moisture content. Sorghum seed can tolerate low water content, although too rapid uptake from such levels can cause damage to the seedling which is produced (Nutile 1964). This could be prevented by raising moisture content before sowing. High temperature can damage seed in an immediate way, in contrast to the longer term deterioration effect during storage (Ross and Webster 1970).

The viability of seed can be assessed in standard laboratory germination tests, but very commonly overestimates effective germination in the field under conditions which would be expected to permit it. The discrepancy is often

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attributed to what is known as vigor, whose definition (e.g.. Woodstock 1973) involves not only germination but also emergence characteristics, in which additional factors are operative. Nevertheless some continuing capability is involved and it includes more rapid germination. It seems likely that this capability includes superior capacity to mobilize seed reserves for the processes of germination and subsequent elongation growth. Various tests have been devised in an attempt to distinguish levels of vigor but it is not clear that they provide a reliable improvement on standard germination tests (Yaycock et al. 1975). Suh et al. (1974) examined the effect of seed size within a narrow range of variability about normal and found none on emergence; nor any subsequent growth and yield characteristic. Maranville and Clegg (1977) have shown that high density in seeds improves emergence.

It would appear that deterioration of seed quality leads not only to reduced germination percentage, but to reduced vigor, and therefore crops based on poor seed may suffer the multiple defects of reduced plant numbers, inferior emerged seedlings (i.e. smaller plants as the basis of approximately exponential growth which should follow for some time) and secondary problems such as less effective competition with weeds. Because one of the major problems in sorghum production is crop establishment, studies of seed quality should be given some emphasis.

Germination (and emergence) are affected not only by the characteristics of the seeds but also by the soil environment in which they are sown. A recent conference (Ministry of Agriculture, Food and Fisheries 1980) has dealt with a number of important aspects, the two well known influences being those of temperature and moisture supply.

Most research having occurred in those areas where sorghum is grown at high latitudes with relatively short growing seasons, emphasis has been placed on behavior at low temperature. Miller (1982) has shown that there is a substantial genetic variability. Upper limits of temperature have received less attention but it is becoming recognized that in the semi-arid tropics, soil temperatures may be far above optimum. This subject is dealt with by Peacock (1982). Optimum temperatures for emergence (independent of germination) do not appear to have been examined, beyond Evans and Stickler's (1961) observation that shoot elongation was greater at 28℃ than at 16℃.

The study of moisture effects are difficult in view of complex seed-soil moisture relationships involving initial seed water content, amounts and potential of water in the soil, hydraulic conductivity of the soil, and seed-soil contact. The main experimental work has examined germination in relation to water availability of the seed environment. Mali et al. (1979) showed substantial differences between varieties in water uptake from soil by the time of germination, and also differences within varieties in the rate of and amount of uptake, according to the water potential of the soil. They draw attention to the possible agronomic value of genotypes which may take up insufficient water for germination when soil water availability is low. Stout et al. (1980) reported delayed initiation, slow rate and reduced final percentage of germination at low water availability. In RS 610. germination was reduced at -8 bars and fell to zero at -15 bars. There were differences between the two cultivars examined. They also showed that the use of osmotic solutions to simulate effects of soil water potentials gave quite different results. Therefore the numerous investigations based on that method, such as that of Evans and Stickler (1961), may be of limited value. Nevertheless, the observation by these latter authors that there was not only variation between genotypes in response to osmotic potential and temperature, but also variation according to the source of seed of one genotype, is worth noting.

Because certain seed water contents have to be attained for satisfactory germination, the idea of increasing water content before sowing has developed, and has been shown to be useful (Phillips and Youngman 1971). This is known as priming of seeds, but has been developed in additional ways. Raising seed water content in osmotic solutions which delay uptake is claimed to result in better subsequent performance (Heydecker 1974).

Mali et al. (1977) showed that soil bulk density imposes a limitation on seedling emergence, and that there are cultivar differences in ability to emerge.

Prediction of times to germination and emergence has been based on temperatures but always assuming adequate water supply, e.g., Arkin et al. (1976), Angus et al. (1980). Horrocks and Cloninger (1974) incorporated sowing depth in their model.

Leaf Area and Canopy Development

Leaf area is the basis of growth and yield. In the photoperiod insensitive types, in which most of the leaf area produced is likely to persist until about grain maturity, such area is likely to be a major limitation to yield. Where soil water deficits occur, it is possible that a lower leaf area may be necessary in order to reduce the rate of depletion of soil water so that sufficient remains for later stages of growth.

Leaf area per plant depends on the number of leaves, rates of expansion, eventual sizes of leaves, and senescence. Leaf area per unit of land area, Leaf Area Index (LAI), is agronomically more important, and depends also on plant populations. Extent of tillering is another factor. The physiology of leaves, especially in regard to radiation interception and photosynthetic conversion, depends not only on the amount of leaf but also on its arrangement in the canopy, whose structure has therefore to be considered.

The number of leaves produced is strongly related to factors determining panicle initiation, in which genetic variation is large, and for photoperiod sensitive types, daylength has of course a major effect. Quinby et al. (1973) examined aspects of this in some detail and showed differences in the numbers of leaves produced, rate of leaf production and time to panicle initiation depending on cultivar, temperature and photoperiod. Boyer and McPherson (1975) draw attention to effects of water deficits on leaf initiation in general, and Whiteman and Wilson (1965) have recorded some effects in sorghum.

The importance of leaf expansion rates and dependence on environmental influences has determined a large literature for crops in general, but little for sorghum. In the absence of other limiting factors, rate of expansion in sorghum is temperature dependent (Arkin et al. 1976). Wade et al. (unpublished) observed leaf expansion to be strongly dependent on air temperature and that there are marked genetic differences in response.

Presumably the effect of water status is similar to that described for maize by Boyer (1970), and clearly mineral nutrition is important. Much of leaf expansion occurs concurrently with development of the panicle during GS2 and there is a belief that the two are competitive for substrate (Eastin 1972; Brown 1978). Leaf area depends not only on rates of expansion but also on senescence, which is influenced by a number of factors such as water stress and nutrient deficiencies. Attempts to model leaf area production will have to take account of such loss, as do Arkin et al. (1976).

Stems

The growth of stem is relatively abrupt. It comprises a very small part of the plant until soon after panicle initiation, but then elongates rapidly during most of the remainder of GS2. The extent of such elongation is under the important control of genes which modify internode length (Doggett 1970). The adaptation of sorghum to mechanized harvesting has depended on the incorporation of dwarfing genes. Leaf number and therefore internode number, under both genetic and photoperiodic controls, has an additional effect. There are consequences of such variation in stem length for panicle development, canopy structure and grain yield, which are considered later when these topics are discussed.

Roots

Roots occupy that part of the plant's environment over which we have potentially the most control, by way of soil preparation, irrigation and fertilizer application. In most areas of cultivation, mineral nutrients and water supply are major limiting factors and root systems are usually seen in relation to uptake activity. They do however have additional functions (e.g., temporary storage, Chamberlin 1978, and suppliers of growth substances to above ground parts, Michael and Sieler-Kelbitch 1972). Jordan et al. (1979) recorded reduction of plant growth when root numbers were reduced although there was no apparent interference with the supply of water and minerals to the shoot.

No very detailed descriptions of sorghum roots have been published, although earlier references to the botany of sorghum contain some material, and Jordan et al. (1979) briefly describe the pattern of development. There are problems in measuring the effective size of root systems. The most important attributes are root density and activity in that part of the soil volume which has been least depleted of water and mineral nutrients. These are not measured by total root weight or limits of extension. Jordan and Miller (1980) pay attention to this.

The extent, and particularly the depth, of the root system varies with many factors, both soil and plant. There is some balance between shoot and root growth, perhaps controlled at least in part by competitive access by shoots to photosynthetically derived assimilates (Eastin 1972; Hultquist 1973; Rice 1979). Many reports indicate maximum rooting depth of the order of 1.5 m (Lavy and Eastin 1969; Mayaki et at. 1976; Kaigama et al. 1977) and lateral extension of well over 2.0 m from the crown is described by Lavy and Eastin (1969). In spite of the depth of penetration, the main development of root is at a relatively shallow depth. For example, Mayaki et al. (1976) found about 80% of the mass in the top 30 cm. similar to that reported by Myers (1980). Genetic variation in the extent of root systems is covered by Jordan and Sullivan (1981).

There have been numerous studies of effects of moisture supply on root growth, but there is little basis of comparability because of plant ages at which measurements have been made, genotype differences, actual measurements made, and differing conditions under which plants have been grown. Jordan et al. (1979) draw attention to the great importance of soil moisture at the soil surface at the time the crown roots, which become the main root system, are being produced. They observed that substantial reductions in numbers of such roots can be compensated for by a greater development of each, but that there is a lower limit beyond which plant growth is adversely affected. Hemsath and Muzurak (1974) studied the penetration of seminal roots at an early seedling stage and found elongation positively related to the matric potential of the soil but interpreted the effect as that of soil resistance. Merrill and Rawlins (1979), working with larger plants, likewise found that penetrometer soil strength was the main constraint on root elongation, but only below -5 to -10 bars.

Kaigama et al. (1977) compared root distribution of irrigated and nonirrigated crops and found a greater proportion of the mass at depth in the non-irrigated, as did Merrill and Rawlins (1979) under less frequent irrigation. Mayaki et al. (1976) however, observed little effect.

The rate of exploitation of soil volume and the duration of extension are of particular interest, and some aspects will be considered later. It is reported that growth is completed by. if not before, anthesis (e.g., Kaigama et al. 1977; Myers 1980), but there are exceptions (McClure and Harvey 1962).

Tillering

The agronomic arguments in favor of and against tillering are numerous and need not be presented here. There must be physiological factors determining its occurrence, and consequences for yield but little is known about either. Agronomically the main interest attaches to basal tillers which from by the growth from buds at the lower nodes. If these form early they can give heads which mature more or less concurrently with that of the main stem, although general observation shows that there is genetically based variation in this. It is clear that such tillering tends to occur more prolifically at lower temperatures, and at high temperatures in most cultivars, it is unusual to find any tillers although there are striking exceptions. The only experimental work which comes to notice is that of Downes (1968) who found, in one cultivar, that the basal buds did not expand when the daily mean temperature exceeded about 18°C, and that the stimulation by lower temperature was effective only between the four and six (expanded) leaf stages. He suggested that higher temperatures may have been suppressive because of the promotion of leaf expansion and hence competitive use of assimilates in the leaves. At least this hypothesis agrees with the frequent observation that serious reductions in grain numbers or enhancement of photosynthesis after flowering, both of which result in assimilates surplus to the requirements for grain filling, cause late tiller growth. Perhaps the reduction in tillering at high population densities arises from light competition and reduced assimilate supply.

Tillering has consequences similar to an increase in population density, although giving less horizontally uniform dispersion of foliage. The extent to which tillers form independent roots seems to vary, but the significance of this is not known. Insofar as tillers are in an unfavorable situation in competition for light, especially at higher populations, biological inefficiency may result because the harvest index of tillers is low compared with that of the main stem, and thus an equal population of main stems only might give better grain yield for the same utilization of environmental resources.

Reproductive Growth

Grain yield correlates more positively with seed number per unit land area than with seed weight. Therefore, the events of GS2, associated with development of spikelets, are very important in the determination of yield.

Panicle Initiation

Sorghum is a quantitative short day plant, inflorescence initiation being promoted by short days, although not necessarily independent of[1] temperature. Doggett (1970) reviewed most of the earlier pertinent literature. Lane (1963) described daylength and light quality effects on panicle initiation. Reaction to daylength for a range of sorghum was investigated by Miller et al. (1968) by altering field sowing dates in Puerto Rico where the daily temperature variation was of the order of 2°C. Caddell and Weibel (1972) found that photoperiod sensitivity, which signals the end of a juvenile stage, is attained at about 15 days if 5 leaves have been expanded. Kassam and Andrews (1975) observed that exposure to long days at this time reduced the number of short days required for initiation.

Some temperature effects on flowering have been described by Fryer et al. (1966), Caddell and Weibel (1971) and Quinby et al. (1973)

The cultivation of sorghum at higher latitudes is, because of temperature requirements, only possible during a period centered approximately on mid-summer, when daylengths are such that the original more tropically adapted types would not flower sufficiently early. Therefore daylength sensitivity has been greatly reduced by temperate zone plant breeders. Quinby (1972) reviewed the expression of height and maturity genes. Some recent tropical improvement programs have emphasized relative insensitivity but care must be taken to avoid maturation during the rainy season with attendant grain mold problems.

Water stress generally delays panicle initiation, according to its length and severity (Whiteman and Wilson 1965).

Paulsen (1962) described the transition of sorghum from vegetative to floral status, signalling the end of GS1. Lee et al. (1974) provided a more detailed anatomical description of apex transformation and subsequent development up to anthesis (GS2). Substantial genetic variability in GS1 duration exists and is conditioned by environment. The relatively insensitive RS 610 varied from 27 to 52 days depending on calendar month of sowing (Paulsen 1962). Variability is much lower amongst adapted U.S. hybrids because of selection to fit a limited growing season. Eastin (unpublished) found a range for 20 hybrids of 32.7 to 44.5 days in GS1 with the equivalent of 203 to 301 growing degree units (15°C temperature base). Seetharama (1977) compared 48 lines under climatic conditions tending to reduce GS1 to a minimum and recorded a range of 31 to 48 days. The consequences of GS1 length on leaf area development in relation to grain yield are not well known.

Panicle Development

Since seed number potential is set during GS2. knowledge of the impact of environmental influences (chiefly water, temperature and photoperiod) on differentiation and development of spikelets and florets is critical. Panicle development, as detailed by Lee et al. (1973). is paralleled by essentially all of stem elongation, much root development and expansion of about six leaves in U.S. sorghum types (Eastin 1972). Presumably there is competition for available assimilates between these simultaneously expanding plant parts. Usually, vegetative development is less adversely influenced than is floral development when stresses occur (Eastin 1972, 1981; Eastin et al. 1981; Brown 1978).

Eastin et al. (1976) reported yield reduction of the order of 25 to 36% in sorghums held 5°C above near optimum at night during GS2 and GS3. The yield reductions were closely associated with seed number reductions, an effect presumed to be introduced during GS2 since little post anthesis abortion was noted. The elevation of night temperature reduced duration of GS2 by 9%. Increasing day temperature from 29 to 34°C reduced GS2 by an average of 17%.

Hultquist (1973) showed the greatest sensitivity in seed production to water stress to be near the beginning of peduncle and panicle rachis elongation which is near the floret differentiation stage (early boot). Lewis et al. (1974) showed yield sensitivity during the boot stage to low water stress in the field. Bennett's (1979) glasshouse data show similar water stress effects. Also Castleberry (1973) demonstrated the capacity of sorghum to differentiate greater seed numbers and maintain yield when stands were thinned about 27% up to near the floret differentiation stage. The thinned stands permitted more light per plant which was used to differentiate sufficiently higher seed numbers to offset loss of plants. Brown (1978) demonstrated a similar positive seed number response to enhanced light. The combined results of these studies demonstrate (a), the ability of sorghum to respond favorably in terms of seed number to production inputs up to about the floret differentiation stage and (b). the high sensitivity of yield influenced by seed number, during the period from floret differentiation to bloom.

Ogunlela (1979) further showed the sensitivity of RS 671 to elevated temperatures by subjecting small field plots to temperatures of ambient +5°C for weekly intervals during GS2 and the first week after anthesis. The most sensitive period was the floret differentiation stage (2 to 3 weeks after panicle initiation) where 5°C above ambient reduced seed number and yields 28% and 30%, respectively. The weekly temperature treatments had no visible effect on general plant growth including leaf area. Production efficiency during grain fill (grain produced per plant per GS3 day) was reduced in direct proportion to seed number reductions effected a month earlier during panicle development. The impact of sink size potential (seed number per unit land area) on production efficiency of the leaves (grain yield per day) was surprisingly high.

These large seed number and yield reduction (about 30%) induced by mild night temperature elevation (5°C) above optimum occurred at yield levels in excess of 6 t/ha. Tests have not been run to evaluate less than optimum or stress effects on floret differentiation in the 0.5 to 1.5 t/ha yield range. Percentage reduction may be quantitatively lower.

As inferred above, duration of GS2 influences seed number and yield. J.D. Eastin (unpublished) recorded GS2 durations of 20 U.S. hybrids from 33.9 to 38.2 days or 277 to 298 growing degree units (15°C base). Seetharama (1977) recorded GS2 duration varying from 29 to 64 days in 48 lines more adapted to tropical conditions.

In order to better understand the morphological responses described during GS2, expressed later as seed numbers, the underlying physiological reactions must be elucidated. Brown (1978) observed in the hybrid E 57 that where numbers of higher level spikelets were reduced because of unfavorable conditions prevailing at critical stages in their development, increased numbers of grains eventually formed on lower branches. Muchow and Wilson (1976) applied spikelet removal treatments at about anthesis for testing source-sink relationships in several hybrids and in one case, the expected reduction in grain number did not occur; that is, spikelets which would not have formed grain, did so. Apparently, in the normal course of development, more fertile spikelets develop than would give "normal" sized grains under the expected grain-filling conditions, and a late adjustment of number occurs to bring grain storage and supply into balance. If this is so. it provides an explanation of the remarkable constancy of grain size within a genotype in spite of a large variation in plant size, except when grain filling is restricted by a serious decline of dry weight production, and hence of material for the attainment of grain size.

Grain Growth

Dickinson (1976) found grain growth to enter the linear dry matter accumulation phase 2 to 3 days after anthesis which is very soon compared to corn (10-11 days). The linear growth continued up to 2 days before black layer. He elevated temperature by placing plastic bags over panicles in the field at 3-day intervals and noted effects on seed number and seed size. The most sensitive period was 6 to 9 days after anthesis at which time serious reductions in seed weight resulted. Apparently this is the period when seed volume potential is influenced and probably corresponds to active cell division in the endosperm. Limitations to seed size possibly may be imposed not only by numbers of endosperm cells produced, but also by limitations placed on cell wall plasticity.

The nature and timing of the determination of seed volume potential seems pertinent to the question of source-sink-transport limitations to grain filling which have been discussed for sorghum by Muchow and Wilson (1976). They concluded, as did Fischer and Wilson (1975a), that there is not a restriction imposed by transport in the hybrids which they examined. While the latter authors took the simple view that the ability of grains to grow larger than they do indicates a source limitation, Muchow and Wilson (1976) argued that this conclusion is justifiable only if there are no competing sinks elsewhere in the plant, which there often are. Thus they preferred to accept simultaneous source and sink limitations in the several hybrids which they examined, concluding that source was the major limitation in three of them, whereas source and sink limitations were more evenly balanced in a fourth. Fischer and Wilson (1975a) observed that in some low yielding open pollinated cultivars there was little capacity of remaining grains to grow larger when some spikelets were removed at anthesis, but U. Jayasuriya (personal communication) finds that even in some low yielding parents of hybrids where there is clearly a large surplus of source supply, removal leads to some increase in grain sizes.

Reconsidering experimental approaches used in such studies, another question arises, following from the quite different times of attaining maximum volumes and weights of grains. Spikelet removal treatments were always applied at or very soon after anthesis. To what extent were consequent increases in grain weights at maturity associated with corresponding increases in early volumes? The grains may not have grown heavier because there was overall more material to fill them, but because some influence at or soon after fertilization allowed the grains subsequently to store more material. Thus whereas the experimental manipulation had sought to increase source in relation to a fixed sink in each grain, it had in fact increased the size of that sink. Fischer and Wilson's (1975a,b) data show that either grain removal or enhanced illumination one week after anthesis increased potential grain size, but less so when these treatments were imposed at or before anthesis.

It is not proposed to consider this issue further, but clearly some new experimental work is required to clarify a fundamentally important question in yield improvement. It does incidentally reopen the question of importance of grain numbers as a yield determinant. They had been ruled out as a limitation to yield because the growth capacity of individual grains seemed not to have been utilized, but this capacity may not in fact have existed. To the extent that this is true, some explanation is provided for the remarkably high correlation between grain numbers and yield; which on the basis of simple reasoning, implies a limitation resulting from grain number.

Relatively high linearity of grain growth persists over a wide range of environments for reasons unknown. Gerik (1979) noted the corresponding values for respiration rate vs temperature in vegetative sorghum plants to be about half the b values for the panicles after anthesis. Mahalakshmi (1978) noted a similar low respiration temperature response in panicles and also found a very low response of bound starch synthetase to temperature. These low temperature response characteristics may relate to the linear rate stability of grain growth.

Giles et al. (1975) detailed the ontogeny and structure of the black layer. Darkening in the general placento-chalazal area appears to result in sorghum as a consequence of mucilage and pectin accumulation in the phloem parenchyma of the pedicel. By contrast in corn, embryo development seems to crush the cells in the placental area when the characteristic darkening associated with maturity occurs (Kiesselbach and Walker 1952). In both cases, content of cells on the endosperm side of the placento-chalazal area diminishes before characteristic black layer appearance. Kiesselbach and Walker (1952) suggest that endosperm digestion by the expanding scutellum occurs at that time. If embryo expansion could be delayed perhaps greater seed size could be attained in sorghum.

Eastin (1981) reviewed some of the work pointing to the importance of yield compensation potential in terms of seed weight when seed number has been unduly limited by environment during panicle development. Hultquist (1973) showed the capacity of a stress resistant hybrid to increase seed weight to 20% greater than that of the normal hybrid in glasshouse pots. Heinrich (1981) reported that three genotypes most stable to environmental stresses under a range of field conditions maintained production by maintaining higher comparative levels of both seed number per unit land area and high seed weight. The seed weight yield component as it relates to black layer formation (senescence), length of grain fill and rate of grain fill merits considerable attention (Eastin 1981).

The total duration of GS3 is highly variable, with both genotype and environmentally induced variation. J.F. Angus (personal communication) recorded reduced duration with increasing temperature in several cultivars. I. Baker (personal communication) observed large reductions as day or night temperatures increased over the range 25°/20° to 35°/25°C in two genotypes, the effects being much greater than on durations of earlier growth stages. Chowdhury and Wardlaw (1978) made a careful study of the time course of grain growth in RS 610, and found the duration to be reduced independently of the rate of filling. Therefore the end of filling was not brought about by the attainment of some particular size of grain; nor was it apparent that the higher temperatures limited the supply of assimilates for grain growth. Thus potentially large losses of grain weight accumulation could follow high temperatures during GS3. Eastin (1976) observed reductions of duration of GS3 varying from 7 to 20% caused by temperatures 5℃ above optimum and corresponding reductions of grain filling rates were 28 and 5%. respectively.

Seetharama (1977) recorded GS3 durations varying from 31 to 56 days in 48 lines. Again, there is a contrast with the uniformity of at least earlier U.S. hybrid material, Eastin (1972) reporting a range of only 38 to 44 days for five hybrids and the six parents used in their production. This same author does however report a range of 31 - 56 days (identical with Seetharama's range) in a random mating population, and in such populations he found ranges with the much lower limit of 20 days. A comparison of 25 commercial hybrids in S.E. Queensland during the 1980/1981 season showed that GS3 varied between 33 and 44 days. J.D. Eastin (unpublished) reported a range among hybrids of 38.5 to 49.7 days or a range of 261 to 314 growing degree units.

Photosynthesis, Respiration, and Dry Weight Increase

Dry weight production is. apart from the relatively small mineral component, the net result of photosynthetic gain and respiratory loss of carbon. Photosynthesis and its variation in relation to environmental factors is relatively well understood, but much less is known about respiration which probably accounts for the loss of between one quarter and one half of the carbon fixed.

The amount of photosynthesis in canopies depends on the amount of photosynthetically active radiation intercepted by the plant parts involved, its distribution over the surfaces—and hence levels of radiation per unit surface area —and photosynthetic capacity per unit of such surface. The latter may have components of genetic variability, and certainly does have those arising from a great multiplicity of influences, such as age, acclimation, persistent effects of unfavorable conditions, water status and temperature. Sorghum, as a C_4 plant, does not have photorespiration in its leaves, and hence photosynthesis and net photosynthesis of leaves during daylight are the same.

Sorghum leaves have the high photosynthetic capacity of the C, grasses, rates in excess of 200 ng CO, cm^2 s ' being recorded in the field for horizontally exposed leaves in chambers (Eastin 1968, Rawson et al. 1978). In their natural orientation, which on average over whole leaf length can practically never be normal to the direction of illumination, rates will be lower. Thus Fischer and Wilson (1976) recorded, on the basis of dosing whole canopies with '"CO,, average rates of 122 ng CO_2 cm^2 s^{-1} for flag leaves in a plant stand. Although these leaves are the best illuminated in the canopy, they are substantially shaded by the heads.

Genetically based variation in photosynthetic capacity is of obvious interest. Although differences have often been measured in a number of the cereals, it is never clear that they cannot be attributed to other factors. It does not appear that any serious search for variation has been undertaken in sorghum, and it will not be useful to do so until more satisfactory criteria can be established. One of the confounding influences is possible feedback control; that is, an influence of the rate of utilization of products on the rate of their production. Clear examples of occurrence and nonoccurrence have been reported for cereals, but the issue has apparently never been examined carefully in any situation for sorghum.

The C_4 species generally have higher rates of photosynthesis than do C_3 species at high temperatures and high light. There has been some disagreement amongst workers on the extent to which this difference is maintained at lower temperatures and light. The comparison is of no importance here, but it might be observed that the efficiency of photosynthetic conversion by the leaves of C_4 plants is unlikely to be inferior at the lower temperatures at which they are usually grown and at the lower light levels within canopies. Ludlow (1981) presents data relevant to this question. Norcio (1976) found temperature optima for sorghum growing in the field to lie in the range 35°-42°C with more pronounced genetic differences at the high end, beyond which rates fell off sharply. Likewise, Gerik (1979) recorded genetic differences in the optimum. Sumayao et al. (1977) found a fall in rate of photosynthesis for a crop stand above 33℃. This is however a different situation, where leaf is on average exposed to low levels of illuminance. The temperature response of a leaf depends on illuminance, and it may be that optima are affected.

Photosynthetic rates are affected by leaf water status which may be adversely affected by both soil water supply and rates of transpiration. The effects are largely those of lowered stomatal conductance. Although there are reports of interrelationships between water status of the environment, stomatal conductance and photosynthetic rates (e.g., Sullivan and Blum 1970; Henzell et al. 1976), particular quantitative relationships may have limited value, because of the capacity of leaves to acclimate to reduced water status. This is considered later.

It is probable that widespread loss of photosynthetic efficiency occurs, especially during GS3, in consequence of leaf pathogens which would by usual criteria, be considered minor, and evidence of such losses is apparent to workers carrying out careful field studies of grain production. A. A. Done (personal communication) notes wide genetic diversity in sorghum in resistance to leaf disease, so much so that the more susceptible lines have no prospect of yielding satisfactorily in the wet season of the monsoon tropics; and he considers that resistance is a major requirement for cultivars adapted to such climates.

As in many cereals, photosynthesis in the head makes a significant contribution to dry matter production and grain yield. Unlike photosynthetic products synthesized in the leaves which may move to all parts of the plant, those of the head remain there and are an important part of grain yield. Fischer and Wilson (1971b) found that 18% of grain yield was derived from photosynthesis in the head, about half of this being attributable to fixation of carbon respired there. Fischer and Wilson (1976) described profiles of photosynthesis at noon in sorghum stands in the field. Over a period of some 3 weeks after anthesis, an average of about 15% of total canopy photosynthesis occurred in the heads, reaching a peak of approximately 20%, thereafter falling rapidly. The experimental method would not detect internal refixation of respired carbon and therefore the importance of photosynthesis in the head was probably greater. To the extent that inflorescences intercept an important fraction of solar radiation Fischer et al (1976) recorded 13% in a high population density stand of Texas 610,* but Eastin (1968) reported up to 40% at noon and even greater values at lower solar elevation, then high efficiencies of conversion are desirable and genetic variation should be examined. However, higher head photosynthesis achieved simply by higher interception may be counterproductive because, for the latter half of GS3, photosynthetic. efficiency in the head is low and radiation is intercepted which could be more efficiently used by leaves (Eastin and Sullivan (1969). Pasternak and Wilson (1976) observed that net photosynthesis was maintained in the panicle under relatively severe plant water stress, while that of leaves more or less ceased.

Rate of photosynthesis in leaves is expressed on a leaf area basis but photosynthesis of canopies is based on land area occupied by the crop. Maximum rates for leaves are not the important factor in determining high rates for canopies. The maximum rates in a canopy will come from the full interception of radiation and its distribution over the whole leaf surface in such a way that this surface is photosynthesizing at maximum efficiency of conversion, which is at quite low levels of illuminance and low rates of photosynthesis (Ludlow and Wilson 1971).

Clearly the ideal canopy cannot exist, or at the best, only temporarily. The canopy structure is fixed (on a short term basis), but solar angle changes during the day, radiation level changes throughout one day and between successive days, and amount of cloud changes the proportions of direct and diffuse radiation. These characteristics of radiation are factors which determine its distribution within the canopy. In practice then, an ideal canopy is one which gives the best average output over a number of days.

Canopy structural features and radiation penetration have been described by Loomis and Williams (1969) and Montieth (1969). Theoretically there are advantages in canopies with leaves which are more erect, narrow, widely separated vertically and randomly spaced horizontally. Fischer and Wilson (1976) have shown all of these to be present in the more efficient canopies of sorghum at higher population densities, although the relative importance of each was not determined. Trenbath and Angus (1975) argue that leaf angle is of little importance in the C_4 species and to be of value requires high solar angles. Hadley (1957). Maunder and Weddige (1966). Graham and Lessman (1968) and Hoshino et al. (1978) provide evidence of the advantage of height. U.

*Texas 610 is a smut-resistant form of RS610.

Jayasuriya (personal communication) has recorded genetically based differences in canopy structures and associated differences in productivity. Fischer and Wilson's (1975c) observation of large population density effects on structure within a genotype should be noted when searching for genetic differences; it may be necessary to examine those latter in relation to populations, although some of the superior characters may be expressed independently of population. Light distribution in sorghum stands has been discussed in relation to population densities, spatial arrangements and row orientation by Witt et al. (1972), Kanemasu and Arkin (1974), Kanemasu and Owonubi (1978). Kanemasu and Owonubi (1978) suggest that where hand harvesting is carried out. it might be desirable to mix short and tall genotypes to improve light interception. Higher population and more uniform spacing are generally shown to be favorable as expressed in dry matter production and grain yield, but there is less agreement that north-south rows are advantageous. These conclusions are reached where soil water supply is not limiting; where it is, there are other considerations which will be dealt with later.

Very high crop growth rates have been recorded for C_4 crops, close to the potential maximum of 71 g m^{-2} d^{-1} estimated by Loomis and Williams (1963). The highest rate observed for sorghum is 44 g m^{-2} d^{-1} (Fischer and Wilson 1975c). High rates will not occur except at high solar radiation, and comparisons between species, or within a species, mean nothing unless made under the same conditions.

Respiratory losses are high and therefore the extent to which they vary may be very important in dry weight production. This is a complex and not well understood subject. Evans and Wardlaw (1976) reviewed what was known for cereals, and provide a general background. It is usual to distinguish between growth and maintenance respiration, the former representing the energy (and corresponding dry weight) loss required in production of new tissues, whereas the latter is involved in maintenance at a subcellular level. Growth respiration is closely linked to dry weight production, and variability as a proportion of dry weight may be small.

Rawson et al. (1978) found that respiration in the panicle is strongly temperature dependent, and calculations from their data suggest that high temperatures would be deleterious to grain weight accumulation. Chowdhury and Wardlaw (1978) however examined temperature effects on grain filling in some detail and could not be sure that reductions associated with high temperature could be attributed to excessive respiration.

Grain Yield

There are two sources of material for grain filling. The major one under normal circumstances is that concurrently provided by photosynthesis. The other is the product of earlier photosynthesis, which has been temporarily stored elsewhere.

The usual patterns of total dry weight accumulation and grain growth determine significant temporary storage. In a period from at least two weeks before anthesis until several weeks after, weight accumulates linearly. In contrast, for about 2 or 3 days either side of anthesis, there is no significant expansion of nonreproductive parts and negligible increase in grain weight occurs for some 2 or 3 days after anthesis (Dickinson 1976); therefore, currently assimilated material must be stored in nonreproductive structures. Chamberlin (1978) showed that this occurs mainly in upper leaves and stem intemodes, although at the peak of such storage roots may also be involved. Fischer and Wilson (1971a) and Chamberlin (1978) estimated that 10-12% of grain yield is derived from carbon assimilated before anthesis.

The grain dry weight is usually about equal to the total plant weight increase during GS3 (e.g., Muchow and Wilson 1976). The ratio of grain weight to total dry weight increase after anthesis is referred to as the Distribution Index. Because the Distribution Index is approximately one, and some of the grain material arises from preanthesis assimilation, it follows that some of the GS3 photosynthesis goes elsewhere in the plant. Eastin (1972) and Chamberlin (1978) have described such a movement. This behavior is relevant to the earlier discussed problem of reaching conclusions about sink-source limitation to grain filling. If photosynthesis during GS3 is reduced, and this can happen from various causes, the amount of preanthesis contribution is perhaps little affected but becomes relatively more important; and the Distribution Index increases.

The failure of all current assimilates to go to grain derives substantially from the perennial habit of sorghum. Following the beginning of rapid grain filling and the transfer of stored material, the weight of nongrain parts declines, but later this increases again. This increase could be seen as the inability of the grain to store further material, that is, a late stage sink limitation, but it also represents the renewal of vegetative growth. It might be argued that a sorghum with more annual characteristics and therefore lacking competing sinks for assimilate would be desirable, but this would have to be associated with capacity for increased rate or effective duration of grain growth.

The importance of stored material may not be so much the amount which eventually becomes grain as that it is an additional supply which can offset inadequacies of concurrent photosynthesis during early grain growth stages. Chamberlin (1978) showed rates of grain weight increase exceeding rates of total weight increase under favorable conditions. U. Jayasuriya, (personal communication) observed, in a number of trials, far more uniform and usually higher rates of increase in grain than in total plant weight, which is possible only if a storage pool is available. As discussed earlier, eventual limitations to grain storage capacity and hence perhaps to yield, might be imposed by inadequacies of earlier stages of grain growth.

Because the major limitation to grain yield normally appears to be the supply of currently produced assimilates during grain filling, and as also noted, grain yield approximates to total dry weight production during that period, the main objective in obtaining yield is the maximization of net photosynthesis during GS3. The requirements of high rates have already been discussed, although there are difficulties of maintaining throughout GS3 capabilities which exist at the beginning. The influence of temperature, acting via respiration rate, has been discussed earlier.

Water deficits might be expected to lead to stomatal closure and hence reduction of photosynthesis, but reports that stomata remain open during this growth stage will be noted later. Nevertheless severe reductions of dry weight accumulation and grain yield in sorghum which is draughted during grain filling, is well known. Drought induced loss of leaf area will directly affect photosynthesis. High temperature may also cause loss of effective leaf area whereas in other areas of cultivation, suboptimal temperatures for photosynthesis may exist at this stage. Mineral nutrient status of the plant is likely to be declining because of decreasing soil moisture supply, cessation of root extension and perhaps reduction of root activity. The nutrient—and especially nitrogen—status of leaves will be reduced by remobilization and transfer to grain (Myers and Asher 1982). Increasing age will reduce the photosynthetic capacity of at least the older leaves in the canopy. Loss of effective leaf surface caused by pathogen and insect attack may increase with time.

Some other aspects of the development of grain yield have been sufficiently introduced earlier under Reproductive Growth, but reference to the seeming importance of the two is made here. The source-sink question needs clarification. If indeed the size of sink—the grain storage capacity—is not a serious limitation, then increases need not be sought. However, as explained before, a careful reappraisal of some conclusions which have been reached is required. The other is effective duration of grain filling. Under many cultivation situations a continuing source of grain filling material is not utilized because of the maturation of the grain.

High yields are associated with high plant populations, the importance of which in rates of dry weight production has been discussed. There is much disagreement in the literature concerning yield responsiveness to increasing population. An important factor in discrepancies is probably the degree of uniformity within plant stands. In a number of trials in S.E.Queensland (Australia, latitude 28°S) yields in excess of 13 t/ha (l4%moisture) have been measured. Muchow and Wilson (1976) recorded 14.81 and Fischer and Wilson (1975c) 14.5 t. M.R. Heslehurst and G.L. Wilson (unpublished) measured yields from 13.2 to 18.0 t/ha in six hybrids. In all of these, populations were 400 000 plants/ha or higher, and there was a very high degree of interplant uniformity. In a trial (unpublished), the hybrid Texas 610 was grown at populations up to 500 000 plants/ha and at three levels of uniformity of plant spacing. Responsiveness in grain yield up to the highest population was achieved only in the most uniform stand. In less uniform stands, there was a reduction in harvest index of some plants, caused by reductions in grain number to the point that sink limitations had been introduced. Yield decline in maize in consequence of non-uniformity has been described by Glenn and Daynard (1974).

It should be noted that the high yields referred to above were achieved in seasons of particularly high solar radiation. The higher yielding hybrids have relatively uniform durations of grain filling, and yield variation depends largely on rates of filling, which corresponds closely to rates of total dry weight production in crop stands; these in turn being closely dependent on intercepted radiation.

This leads to the question of scope for improvement in maximum yields beyond those presently being obtained. High yields are associated with hybrids, although whether this should necessarily be so is a question which is not addressed here. One of the earlier of these hybrids is Texas 610, which is still widely cultivated. In Queensland (Australia) it is used as a standard against which the yields of other cultivars are expressed in the annual yield trials conducted by the Department of Primary Industries. In a recent 6-year period, trials using the leading commercial hybrids gave average yields just below that of RS 610 in each of the four main areas of production.

The most promising avenue appears to be increased duration of grain filling, provided that this is accompanied by increased grain storage capacity. Such extension of GS3 could be based on either genetic characteristics or cultivation at lower temperatures than are usually experienced at this stage. It will in turn be restricted to climates which permit a longer growing season, or alternatively must be achieved by a reduction in time to anthesis. The latter does not however appear to be particularly promising in view of the widespread experience that this reduces yield. If this is simply a problem of inadequate leaf canopy for full interception of radiation, increased populations might largely compensate. There is however the possibility that further reduction of GS2 might not allow adequate development of the panicle, a requirement for an increase in its size having meanwhile been suggested. Moreover small plants might have root systems which less effectively exploit soil depth.

This brief reference to maximum yields should perhaps conclude with the reminder that most of the world's sorghum is grown where there is little likelihood of attaining 20% of such maxima, and other aspects of the physiology of yield become more important.

Water

Of the major cereals, sorghum is one of those better adapted to cultivation in climates where the probability of water deficits at some stages of growth is high. Therefore its water use and reactions to water deficits attract particular research attention.

General reviews on water relations are numerous, e.g., Begg and Turner (1976), Fischer and Turner (1978), and Turner and Kramer (1980). Cereal crops are dealt with by Boyer and McPherson (1975), while general reviews of the physiology of cereals, referred to earlier, have sections on water relations. Jordan and Sullivan (1982) cover aspects relevant to this paper.

The features of particular interest here are uptake and loss. Loss occurs mainly via stomata which are able to exercise a control over the rate of outward diffusion of water vapor by varying their resistance. The immediate control of stomatal behavior commonly lies in leaf water status, and much research has been directed to examining the relationship between them, with a particular interest in the possibility of genetically based variation (e.g., Henzell et al. 1975, 1976; Blum 1974a). Such variability is observed. There are some reports that the range of stomatal aperture, from closed to fully open, occurs over a very narrow range of leaf water potential (e.g., Blum 1974b; Turner 1974) although the particular value of potential varies widely between different reports. However. Jones and Rawson (1979), who followed a careful examination of stomatal behavior in sorghum, concluded that responses of that kind probably arose from the experimental methods used, and that opening not only occurs over a wide range of leaf water potential, but the particular range depends on the rate of fall of potential. Taking into account also that most studies of stomatal behavior in relation to leaf water status have been based on leaves which are undergoing rapid changes of water content, and that in the field stress develops much more slowly thus permitting physiological adjustment, doubt arises about the validity or usefulness of much of the work which has been reported in this area. This adjustment is the subject of much current study, not merely in terms of its physiology, which includes substantial osmotic adjustment (e.g., Jones and Turner 1978) but also in an attempt to identify genetic variation in the capacity. There is in fact little evidence so far of such variation. Jones and Turner found no difference between the two cultivars which they examined. Ackerson et al. (1980) report differences in osmotic adjustment in leaf water potential required to initiate stomatal control of transpiration before flowering.

Notwithstanding the view that stomatal variation is of major importance in controlling water use, there are reports that it plays a more limited role. Ackerson and Krieg (1977) and Ackerson et al. (1980) state that after heading, stomata are not sensitive to teaf water potential, down to -27 bars, while Sullivan and Blum (1970) reported that stomata of sorghum remain slightly open all day, even during severe drought. Insensitivity after anthesis has also been recorded by Hultquist (1973), Bennet (1979), and Garrity (1980). Ackerson and Krieg (1977) and Aho (1980) have observed control of water use other than by way of leaf water potential and its effect on leaf resistance. Stomata response to leaf-air vapor pressure deficit (VPD) was seen to have some influence, while a variable internal flow resistance existed, increasing as soil water potential decreased.

Recovery of stomata occurs fairly rapidly after relief of stress (Sullivan and Blum 1970), but to what extent there is genetic variation is not known; and again there may be acclimation effects involved.

There is significant water loss via the panicle. Pasternak and Wilson (1976) and Rawson et al. (1978) recorded losses of approximately 50 g per panicle per day. The former observed that with increasing water stress, transpiration from the head was little affected whereas that from the rest of the plant fell greatly.

Ritchie and Burnett (1971) report that with adequate soil moisture, an LAI of 2.7 is sufficient to result in evapotranspiration of 90% of potential, and Ritchie and Jordan (1972) recorded leaf water potentials of -6 to -9 bars in this situation. Likewise, Ritchie (1971) found that when canpies exceeded 45% ground cover and transpiration was not limited by water supply, daily net radiation was approximately equivalent to daily evaporation from the crop. At lower values of LAI, evaporation from the soil surface becomes important. In view of what has been said earlier about canopy structure and productivity, it would follow that water use efficiency should rise substantially at higher LAI. Olsen (1971) presented data which support this.

Ritchie and Jordan (1972), in modeling water loss, view soil water movement to the roots as the limiting factor when soil water level declines. Ritchie et al. (1972) add root distribution as another limitation. It is interesting to note that these workers can model water loss without calling on stomatal behavior as an input. It may be that a simpler system might have been operating because stomata remained open in spite of water deficits, reports of which have already been noted, or perhaps there was a stomatal response sufficiently closely linked to soil water supply to permit its being ignored in the model. A similar explanation would have to apply to the variable flow resistance referred to earlier.

Kanemasu et al.'s (1976) model of evapotranspiration does not take account of stomatal resistance except that it may be incorporated in the crop constant which they use, and the relatively high levels of soil water availability at which they worked may not have led to significant closure. In explaining differences between sorghum and soybean, they fall back on observed differences in stomatal resistances.

Sumayao et al. (1977) have also observed that transpiration from well watered sorghum is energy dependent and little affected by stomata, but as the supply declines they ascribe declining transpiration to stomatal closure. The work of Ackerson et al. (1980) has already been mentioned. They found stomatal response associated with leaf water potential as soil water declined and reported genotypic differences which only appeared when leaf potential fell. They also noted the large ontogenetic change in which stomatal control was lost after flowering. Again, it is difficult to reconcile this with some of the simpler models of water loss referred to above. Because sorghum is a C_4 plant, a higher water use efficiency is to be expected and has been shown by Rawson et al. (1978).

Water uptake depends on root growth, which has already been discussed. Bhan et al. (1973) state that drought resistant cultivars are superior in numbers and weights of roots, although one must beware of cause and effect components of such relationships. Thus Teare et al. (1973) observed that sorghum had about twice the weight of roots per unit volume of soil compared with soybean, but in fact used less water because of better stomatal control. Likewise Sullivan and Blum (1970) have reported cultivar differences in patterns of extraction, but they point out that root distribution is not the only factor involved in drought resistance. Jordan and Miller (1980) have drawn attention to the insufficiency of root density at depth to allow adequate use of soil moisture which may be available there. They have evidence of genetically based variation. Blum (1974a) observed differences among numerous genotypes in amount of water extracted from the soil, and varying associations with leaf water potentials, leaf resistance and drought suceptibility.

Making the best use of a limited supply of stored soil moisture is a problem of widespread concern. At the beginning of grain filling there is a balance of grain storage capacity and photosynthetic potential to fill it. The latter can be exercised only if there is sufficient soil moisture to meet transpirational demand while photosynthesis continues until grain maturity. A crop stand which maximizes the development of biomass up to flowering may deplete moisture storage so that little of the high grain potential can be realized. One approach is to use low plant populations, although there can be substantial compensation for numbers by sizes, especially if extensive tillering occurs.

Blum (1974 a) drew attention to advantages in slow rates of water extraction. Passioura (1972) made the same observation with wheat, where restriction of the roots to the seminal only, slowed down water use before anthesis so that with limited supply, enough remained for the completion of grain filling.

A procedure has been devised by Blum and Naveh (1976) in which a crop is established at a relatively high density within widely spaced double rows. The early competition not only reduces leaf area development and hence water use, but also restricts root growth so that the full soil volume is not occupied until late in the crop cycle, thereby extending water supply in time. Thomas et al. (1981) carried out extensive trials to test the value of wide rows, and concluded that there was an advantage only in very dry seasons and at low yield. They argued that the gain in such years did not compensate for loss of yield caused by inadequate populations in good years. The difference between the points of view seems to be that Blum and Naveh's system is designed for use with known, relatively large amounts of stored soil water, but with no expectation of effective rainfall during the growing season. On the other hand, Thomas et al. were working within a cropping system where soil water storage is relatively low at planting, insufficient to produce useful yields, and rain is hoped for at some point in the season.

Various workers refer to desirable strategies of transpiration control and soil water extraction (e.g.. Henzell et al. 1976; Blum 1974; Sullivan and Blum 1970). Obviously there is no one effective strategy, and the requirement is to match genotype and agronomic practice to the facts and probabilities of water supply in a particular location.

References

ACKERSON, R. C. and KRIEG, D Ft. 1977. Stomatal and nonstomatal regulation of water use in cotton, corn and sorghum Plant Physiology 60:850-853.

ACKERSON, R C. KRIEG, D. R., and SUNG, F. J M 1980 Leaf conductance and osmoregulation of field-grown sorghum genotypes. Crop Science 20:10-14.

AHO, N. 1980. (Effect of air dryness on net photosynthesis of two C, species: sorghum and maize) Comptes Rendus Hebdomardaires des Seances de I' Academic des Sciences D 290:543-546

ANGUS, J. F.. CUNNINGHAM, R. B., MONCUR, M. W., and MACKENZIE, D. H. 1980. Phasic development in field crops. I. Thermal response in the seedling phase Field Crops Research 3:365-378

ARKIN, G. F., VANDERLIP, R L, and RITCHIE, J. T. 1976. A dynamic grain sorghum growth model. Transactions of the American Society of Agricultural Engineers 19 : 622 -630.

BEGG. J. E.. and TURNER. N. C. 1976. Crop water deficits. Advances in Agronomy 28:161-217

BENNET, J. M. 1979. Responses of grain sorghum *[Sorghum bicolor* (L) Moench] to osmotic stresses imposed at various growth stages. PhD Thesis, University of Nebraska, Lincoln, Nebraska, USA.

BHAN, S.. SINGH, H. G., and SINGH. A 1973. Notes on root development as an index of drought resistance in sorghum *[Sorghum bicolor (L.)* Moench). Indian Journal of Agricultural Science 43 : 828-830.

BLUM, A. 1974(a). Genotypic responses in sorghum to drought stress. I. Response to soil moisture stress. Crop Science 14:361-364.

BLUM, A. 1974(b). Genotypic responses in sorghum to drought stress. II. Leaf tissue water relations. Crop Science 14:691-692.

BLUM, A., and NAVEH, M. 1976. Improved water-use efficiency in dryland grain sorghum by promoted plant competition. Agronomy Journal 68:111-116.

BOYER, J. S. 1970. Leaf enlargement and metabolic rates in corn, soybean, and sunflower at various leaf water potentials. Plant Physiology 46: 233 - 235.

BOYER, J. S., and MCPHERSON, H. G. 1975 Physiology of water deficits in cereals. Advances in Agronomy 27:1-23.

BROWN, R F. 1978. Environmental effects on panicle development in grain sorghum {*Sorghum bicolor* L. Moench). Ph.D Thesis, University of Queensland, St Lucia, Queensland, Australia.

CADDEL. J. L, and WEIBEL. D E 1971 Effect of photoperiod and temperature on the development of sorghum. Agronomy Journal 63:799-803

CADDELL. J. L., and WEIBEL, D. E. 1972 Photoperiodism in sorghum. Agronomy Journal 64:473-476

CASTLEBERRY, R. M 1973. Effects of thinning at different growth stages on morphology and yield of grain sorghum [*Sorghum bicolor* (L.) Moench] Ph D Thesis, University of Nebraska, Lincoln, Nebraska, USA

CHAMBERLIN, R. C 1978. The Physiology of lodging of grain sorghum [*Sorghum bicolor* (L) Moenchl PhD Thesis. University of Queensland, Australia

CHOWDHURY. S I. and WARDLAW, I. F. 1978 The effect of temperature on kernel development in cereals. Australian Journal of Agricultural Research 29:205 223

DICKINSON, T. E 1976 Caryopsis development and the effect of induced high temperatures in *Sorghum bicolor* (L.) Moench MS Thesis, University of Nebraska. Lincoln, Nebraska. USA

DOGGETT, H 1970 Sorghum London and Harlow, UK: Longmans Green and Company Limited 403 pp.

DOWNES, R W 1968. The effect of temperature on tillering of grain sorghum seedlings Australian Journal of Agricultural Research 19:59-64

EASTIN, J D 1968 Physiology of yield in grain sorghum Pages 129-137. *In* Proceedings. 23rd Annual Corn and Sorghum Research Conference of the American Seed Trade Association, eds. J. I. Sutherland and R. J. Falasca. American Seed Trade Association

EASTIN, J. D 1972 Photosynthesis and translocation in relation to plant development. *In* Sorghum in seventies, eds. N. G P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co. 638 pp.

EASTIN, J. D 1976. Temperature influence on sorghum yield. Pages 19 - 23 *in* Proceedings of the 31st Annual Corn and Sorghum Research Conference, eds. Harold P. Loden and Dolores Wilkinson. American Seed Trade Association.

EASTIN, J. D. 1981. Sorghum development and yield. *In* Proceedings of the Symposium on the Potential Productivity of Field Crops Under Different Environments, Sept 1980, ed. S Yoshida. Los Baros, Laguna, Philippines: IRRI.

EASTIN, J. D.. and SULLIVAN, C Y 1969 Carbon dioxide exchange in compact and semi-open sorghum inflorescences. Crop Science 9: 165-166.

EASTIN, J. D, BROOKING, I., and TAYLOR. S. O. 1976. Influence of temperature on sorghum respiration and yield. Agronomy Abstracts p. 71 American Society of Agronomy.

EASTIN, J. D.. DICKINSON, T., KRIEG, D., and MAUNDER, A. B. 1981. Crop physiology. *In* Dryland agriculture, eds. HE. Dregne and Wayne O Willis Madison, Wisconsin, USA: American Society of Agronomy

EASTIN, J. D., HULTQUIST, J. H., and SULLIVAN C. Y. 1973. Physiologic maturity in grain sorghum Crop Science 13: 175-178.

EVANS, W. F., and STICKLER, F. C 1961 Grain sorghum seed germination under moisture and temperature stresses. Agronomy Journal 53:369-372

EVANS, L. T., and WARDLAW. I. F. 1976. Aspects of the comparative physiology of grain yield in cereals. Advances in Agronomy 28 301-359

FISCHER, R A , and TURNER, N C. 1978. Plant productivity in the arid and semi-arid zones Annual Review of Plant Physiology 29:277-317

FISCHER, K.S., and WILSON. G.L. 1971(a) Studies of grain production in *Sorghum vulgare* I The contribution of pre-flowering photosynthesis to grain yield Australian Journal of Agricultural Research 22:33-37

FISCHER. K S .and WILSON. G. L. 1971(b). Studies of grain production in *Sorghum vulgare.* II Sites responsible for grain dry matter production during the post-anthesis period Australian Journal of Agricultural Research 22:39-47.

FISCHER, K S. and WILSON, G L 1975(a). Studies of grain production in *Sorghum bicolor* (L.) Moench. III. The relative importance of assimilate supply, grain growth capacity and transport system. Australian Journal of Agricultural Research 26:11-23.

FISCHER. K. S„ and WILSON, G. L. 1975(b). Studies of grain production in *Sorghum bicolor* (L.) Moench. IV. Some effects of increasing and decreasing photosynthesis at different stages of the plant's development on the storage capacity of the inflorescence. Australian Journal of Agricultural Research 26:25-30.

FISCHER, K. S., and WILSON, G. L. 1975(c). Studies of grain production in *Sorghum bicolor* (L.) Moench. V. Effect of planting density on growth and yield. Australian Journal of Agricultural Research 26:31-41.

FISCHER, K. S., and WILSON, G. L. 1976. Studies of grain production in *Sorghum bicolor* (L.) Moench. VI. Profiles of photosynthesis, illuminance and foliage arrangement. Australian Journal of Agricultural Research 27 : 35-44.

FISCHER, K. S., WILSON. G. L. and DUTHIE, 1.1976. Studies of grain production in *Sorghum bicolor* (L.) Moench. VII. Contribution of plant parts to canopy photosynthesis and grain yield in field situations. Australian Journal of Agricultural Research 27 :235-242.

FREEMAN, J. E. 1970. Development and structure of the sorghum plant and its fruit, Pages 28-72 *in* Sorghum production and utilization, eds. J. S. Wall and W. M. Ross. Westport. Connecticut, USA: The AVI Publishing Company, Inc. 702 pp.

FRYER, H. C, PAULI, A. W., and STICKLER. F C. 1966. Temperature influence on anthesis date in grain sorghum. *Sorghum vulgare* Pers. Agronomy Journal 58:9 -12.

GARRITY. D. P. 1980. Moisture deficits and grain sorghum performance. Ph.D. Thesis. University of Nebraska. Lincoln. Nebraska. USA.

GERIK, T. J. 1979. The relationship of photosynthesis and dark respiration in grain sorghum *[Sorghum bicolor* (L.) Moenchl to yield, yield components and temperature. Ph.D. Thesis. University of Nebraska, Lincoln, Nebraska, USA.

GILES. K. L., BASSETT, H. C. M., and EASTIN, J. D. 1975. The structure and ontogeny of the hilum region in *Sorghum bicolor.* Australian Journal of Botany 23:795 -802

GLENN, F. B., and DAYNARD, J. B. 1974. Effect of genotype, planting pattern and plant density on plant-to-plant variability of grain yield of corn. Canadian Journal of Plant Science 54:323-330.

GRAHAM. D.. and LESSMAN, K. J. 1968. Effect of height on yield and yield components of sorghum. Agronomy Abstracts. Madison, Wisconsin, USA: American Society of Agronomy.

HADLEY, H. H. 1957. An analysis of variation in height in sorghum. Agronomy Journal 49:144-147.

HEINRICH, G. M. 1981. Morphological and physiological mechanisms of yield stability in grain sorghum *[Sorghum bicolor* (L.) Moenchl across diverse environments. Ph.D. Thesis, University of Nebraska, Lincoln, Nebraska, USA.

HEMSATH, D. L., and MAZURAK, A. P. 1974. Seedling growth of sorghum in clay-sand mixtures at various compactions and water contents Proceedings of the Soil Science Society of America 38:387-390

HENZELL, R. G., MCCREE, K. J., VAN BAVEL. C. H. M , and SCHERTZ, K. F. 1975. Method for screening sorghum genotypes for stomatal sensitivity to water deficits Crop Science 15:516-518.

HENZELL, R. G.. MCCREE. K. J., VAN BAVEL. C. H. M., and SCHERTZ, K. F. 1976. Sorghum genotype variation in stomatal sensitivity to leaf water deficit. Crop Science 16:660-662.

HEYDECKER, W 1974. Germination of an idea: priming of seeds. University of Nottingham School of Agriculture Report (Part III) 1973/1974.

HORROCKS. R. D, and CLONINGER, F. D. 1974. Model for predicting emergence of grain sorghum Crop Science 14:365-367.

HOSHINO, T., UZIHARA. K., and SHIKOTA, S. I. 1978. Effects of-tall and short isogenic lines among grain sorghum varieties on dry matter production and yield performance at different plant densities. Japanese Journal of Crop Science 47:541-546.

HOUSE, L. R. 1980. A guide to sorghum breeding Patancheru, A.P., India: ICRISAT.

HULTQUIST, J. H. 1973. Physiologic and morphologic investigation of sorghum *[Sorghum bicolor* (L.) Moench]. I. Vascularisation. II. Response to internal drought stress. Ph.D. Thesis, University of Nebraska. Lincoln, Nebraska, USA.

JONES. M. M., and RAWSON, H. M. 1979. Influence of rate of development of leaf water deficits upon photosynthesis, leaf conductance, water use efficiency and osmotic potential of sorghum. Physiologia Plantarum 45:103-111.

JONES, M. M., and TURNER, N. C. 1978. Osmotic adjustment in leaves of sorghum in response to water deficits. Plant Physiology 61:122-126.

JORDAN. W. R., MCCRARY, M., and MILLER, F. R. 1979.

Compensatory growth in the crown root system of sorghum. Agronomy Journal 71 :803-806.

JORDAN, W. R„ and MILLER, F. R. 1980. Genetic variability in sorghum root systems: implications for drought tolerance. Pages 383-399 *in* Adaptation of plants to water and high temperature stress, eds. N. C Turner and P. J. Kramer, New York, USA: Wiley Interscience.

JORDAN, W. R., and SULLIVAN, C. Y. 1982 Reaction and resistance of grain sorghum to heat and drought These Proceedings: ICRISAT.

JORDAN, W. R.. MILLER, F. R., and MORRIS, D. E. 1979. Genetic variation in root and shoot growth of sorghum in hydroponics. Crop Science 19:468-472.

KAIGAMA, B. K., TEARE, I. D., STONE, L. R.. and POWERS, W. L. 1977. Root and top growth of irrigated and nonirrigated grain sorghum. Crop Science 17.555-559.

KANEMASU. E. T., and ARKIN, G. F. 1974. Radiant energy and light environment of crops. Agricultural Meteorology 14:211-225.

KANEMASU, E. T., and OWONUBI. J. L. 1978., Light distribution in three isolines of grain sorghum. American Meteorological Society Bulletin 59:1513.

KANEMASU, E. T., STONE, L. R., and POWERS, W. L. 1976. Evapotranspiration model tested for soybean and sorghum. Agronomy Journal 68:569-572

KASSAM, A. H., and ANDREWS, D. J 1975. Effects of sowing date on growth, development and yield of photosensitive sorghum at Samaru, Northern Nigeria. Experimental Agriculture 11 : 227-240.

KIESSELBACH, T. A., and WALKER, E. R. 1952. Structure of certain specialized tissues in the kernel of corn American Journal of Botany 39 : 561 -569.

LANE, H. C. 1963 Effect of light quality on maturity in the milo groups of sorghum. Crop Science 3:396-399.

LAVY, T. L, and EASTIN, J. D. 1969. Effect of soil depth and plant age on ^{32}phosphorus uptake by corn and sorghum. Agronomy Journal 61 :677-680

LEE, K., LOMMASSON, R C, and EASTIN, J. D. 1974. Developmental studies on the panicle initiation in sorghum. Crop Science 14:80-84.

LEWIS, B. R., HILLER, E. A., and JORDAN, W. R. 1974. Susceptibility of grain sorghum to water deficit at three growth stages. Agronomy Journal 66:589-591

LOOMIS, R. G., and WILLIAMS, W. A. 1963. Maximum crop productivity: an estimate. Crop Science 3:67-72.

LOOMIS, R. G., and WILLIAMS, W. A. 1969. Productivity and the morphology of crop stands: pattern of leaves. Pages 28-47 *in* Physiological aspects of crop yields, eds. J. D. Eastin, F. A. Hoskins, C. Y. Sullivan, and C. H. M. Van Bavel. Madison, Wisconsin, USA: American Society of Agronomy and Crop Science Society of America.

LUDLOW, M. M. 1981. Effect of temperature on light utilization efficiency of leaves in C_3 legumes and C_4 grasses. Photosynthesis Research 1:243-249.

LUDLOW, M. M.. and WILSON, G. L. 1971. Photosynthesis of tropical pasture plants I Illuminance, carbon dioxide concentration, leaf temperature, and leaf-air vapour pressure deficit. Australian Journal of Biological Science 24:449-470

MCCLURE. J. W and HARVEY, C. 1962. Use of radiophosphorus in measuring root growth of sorghums. Agronomy Journal 54:457-459.

MAHALAKSHMI, V. 1978. Temperature influence on respiration and starch synthetase in *Sorghum bicolor* (L.) Moench. PhD Thesis. University of Nebraska, Lincoln, Nebraska, USA.

MALI. C. V., MUSANDE, V. G., and VARADE, S B. 1977. Influence of soil bulk density on seedling emergence of sorghum. Journal of Maharashtra Agricultural Universities 2:193-195.

MALI, C. V., VARADE, S. B„ and MUSANDE, V. G. 1979. Water absorption by germinating seeds of sorghum varieties at different moisture potentials. Indian Journal of Agricultural Science 49:22-25

MAUNDER, A. B.. and WEDDIGE, L. A. 1966. Influence of the DW_2 locus on yield in sorghum. Sorghum Newsletter 9:10.

MAYAKI, W. C, STONE, L. R., and TEARE, I. D. 1976. Irrigated and nonirrigated soybean, corn, and grain sorghum root systems. Agronomy Journal 68:532 -534.

MERRILL, S. D., and RAWLINS, S. L. 1979. Distribution and growth of sorghum roots in response to irrigation frequency. Agronomy Journal 71 :738-745.

MICHAEL, G., and SEILER-KELBITSCH, H. 1972. Cytokinin content and kernel size of barley grain as affected by environmental and genetic factors. Crop Science 12 : 162-165

MILLER, F. R. 1982. Genetic and environmental response characteristics of sorghum. These Proceedings: ICRISAT.

MILLER, F. R., BARNES. D. K., and CRUZADO. H. J. 1968. Effect of tropical photoperiods on the growth of sorghum when grown in 12 monthly plantings. Crop Science 8:499-502.

MINISTRY OF AGRICULTURE. FISHERIES AND FOOD. 1980. Crop seed and soil environment. *In* Proceedings of a Conference organized by the Agricultural Development and Advisory Service. Malverr, 16-17 May 1979 London: Her Majesty's Stationery Office.

MONTEITH, J. L. 1969. Light interception and radiative exchange in crop stands. Pages 89-111 *in* Physiological aspects of crop yield, eds. J. D. Eastin. F. A. Haskins, C. Y. Sullivan, and C. H. M. Bavel. Madison, Wisconsin, USA: American Society of Agronomy and Crop Science Society of America.

MUCHOW. R. C. and WILSON, G. L. 1976. Photosynthetic and storage limitations to yield in *Sorghum bicolor (L.)* Moench. Australian Journal of Agricultural Research 27:489-500

MYERS, R. J. K. 1980. The root system of a grain sorghum crop. Field Crops Research 3 : 53-64.

MYERS, R. J. K., and ASHER, C. J. 1982 Mineral nutrition of grain sorghum: Macronutrients. These Proceedings: ICRISAT.

NORCIO, N. V. 1976. The effects of high temperature and moisture stress on photosynthetic and respiration rates of grain sorghum. Ph.D. Thesis, University of Nebraska, Lincoln, Nebraska, USA.

NUTILE, G. E. 1964. Effect of desiccation on viability of seeds. Crop Science 4:325-328.

OGUNLELA, V. B. 1979. Physiological and agronomic response of a grain sorghum *[Sorghum bicolor* (L.) Moench] hybrid to elevated night temperatures. Ph.D. Thesis. University of Nebraska, Lincoln, Nebraska. USA.

OLSON, T. C. 1971. Yield and water use by different populations of dryland corn, grain sorghum and forage sorghum in the western com belt. Agronomy Journal 63:104-106.

PASTERNAK. D., and WILSON, G. L. 1972. After-effects of night temperatures on stomatal behaviour and photosynthesis of sorghum. New Phytologist 71 :683-689.

PASTERNAK, D.. and WILSON, G. L. 1976. Photosynthesis and transpiration in the heads of draughted grain sorghum. Australian Journal of Experimental Agriculture and Animal Husbandry 16:272-275.

PASSIOURA. J. B. 1972. The effect of root geometry on the yield of wheat growing on stored water. Australian Journal of Agricultural Research 23:745-752.

PAULSON, I. W. 1962. Embryology and seedling development to floral transition of *Sorghum vulgare* Pers. Ph.D. Thesis, Iowa State University, Iowa, USA

PEACOCK, J. M. 1982. Response and tolerance of sorghum to temperature stress. These Proceedings: ICRISAT.

PHILLIPS, J. C, and YOUNGMAN, V.E. 1971. Effect of seed moisture content on emergence and yield of grain sorghum Crop Science 11 : 354-357.

PURSEGLOVE, J W. 1972. Tropical crops I Monocotyledons. London. Longman. 334 pp.

QUINBY. J. R. 1972. The genetic control of plant growth in sorghum. *In* Sorghum in seventies, eds. N. G. P. Rao and L R. House. New Delhi: Oxford and IBH Publishing Co. 638 pp.

QUINBY, J. R.. HESKETH, J D., and VOIGT, R. L. 1973. Influence of temperature and photoperiod on floral initiation and leaf number in sorghum. Crop Science 13:243-246.

RAO, N.G.P., and HOUSE, L R. (eds.) 1972 Sorghum in seventies. New Delhi: Oxford and IBH Publishing Co. 638 pp.

RAWSON. H. M., TURNER, N. C, and BEGG, J. E. 1978. Agronomic and physiological response of soybean and sorghum crops to water deficits. IV. Photosynthesis, transpiration and water use efficiency of leaves. Australian Journal of Plant Physiology 5:195-209.

RICE, J.R 1979. Physiological investigations of grain sorghum *[Sorghum bicolor* (L.) Moenchl subjected to water stress conditions. Ph.D. Thesis, University of Nebraska, Lincoln. Nebraska. USA.

RITCHIE, J. T. 1971. Dryland evaporative flux in a subhumid climate: I. Micrometeorological influences. Agronomy Journal 63:51-55.

RITCHIE, J. T. and BURNETT, E. 1971. Dryland evaporative flux in a subhumid climate: II. Plant influences. Agronomy Journal 63:56-62.

RITCHIE, J. T., BURNETT. E., and HENDERSON, R. C. 1972. Dryland evaporative flux in a subhumid climate: III. Soil water influence. Agronomy Journal 64:168-173.

RITCHIE, J. T., and JORDAN, W. R. 1972. Dryland evaporative flux in a subhumid climate: IV. Relation to plant water status. Agronomy Journal 64:173-176.

ROBERTS. E. H. (ed.) 1972. Viability of seeds. London: Chapman and Hall. 448 pp.

Ross, W. M. and WEBSTER, 0. J. 1970. Culture and use of grain sorghum. Agricultural Research Service, USDA Handbook No. 385. Washington, D. C. U.S. Government Printing Office.

SEETHARAMA, N. 1977. Variability in sorghum growth stages. Presented at International Sorghum Workshop, ICRISAT, 6-12 May. Hyderabad. India.

SRIVASTAVA, D. P., and PINNELL, E. L. 1963. Germination studies in grain sorghum. Missouri Agricultural Experimental Station Research Bulletin no. 828.

STOUT, D. G„ SIMPSON, G. M., and FLOTRE, D. M. 1980. Drought resistance of *Sorghum bicolor* (L.) Moench. 3. Seed germination under osmotic stress. Canadian Journal of Plant Science 60:13-24.

SUH, H. W., CASADY, A. J., and VANDERLIP, R. L. 1974. Influence of sorghum seed weight on the performance of the resulting crop. Crop Science 14:835-836.

SULLIVAN, C. Y„ and BLUM, A. 1970. Pages 55-66 *in* the Proceedings of the 25th Corn and Sorghum Research Conference. American Seed Trade Association.

SUMAYAO, C.R, KANEMASU, E. T., and HODGES, T. 1977. Soil moisture effects on transpiration and net carbon dioxide exchange of sorghum. Agricultural Meteorology 18:401-408.

TEARE, I. D., KANEMASU. E. T„ POWERS, W. L., and JACOBS, H S. 1973. Water-use efficiency and its relation to crop canopy area, stomatal regulation, and root distribution. Agronomy Journal 65:207-211.

THOMAS, G. A., MYERS, R. J. K., FOALE, M. A., FRENCH, A. V., HALL. B., LADEWIG. J H., DONE, A.A., TAYLOR, G. K., LEFROY, E.. WYUE, P., and STIRLING, G. D. 1981. Evaluation' of row spacing and population density effects on grain sorghum yield over a range of northern Australian environments. Australian Journal of Experimental Agriculture and Animal Husbandry 21 :210-217.

TRENBATH, B. R., and ANGUS, J. 1975. Leaf inclination and crop production. Field Crop Abstracts 28:231-244.

TURNER, N. C. 1974. Stomatal response to light and water under field conditions. The Royal Society of New Zealand Bulletin 12:423-432

TURNER, N. C, and KRAMER. P. J (eds.) 1980. Adaptation of plants to water and high temperature stress. New York, USA: Wiley Interscience. 482 pp.

WHITEMAN, P. C, and WILSON, G. L. 1965. Effects of water stress on the reproductive development of *Sorghum vulgare* Pers. University of Queensland Papers, IV(14).

WITT, M.D.. VANDERLIP, R. L. and BARK, L. D. 1972. Effect of row width and orientation on light intercepted by grain sorghum. Transactions. Kansas Academy of Science 75:29-40

WOODSTOCK, L. W. 1973. Physiological and biochemical tests for seed vigor. Seed Science and Technology 1 :127-157.

YAYCOCK, J. Y.. JAN, H.. and VANDERLIP. R. L. 1975. Temperature, time, and NH_4Cl concentration in vigour testing of sorghum seed. Agronomy Journal 67:241-242

Session 2 Sorghum and its Environment

S. K. Sinha* Discussant—1

As a discussant, my concern should be to comment upon the two papers that have just been presented. The topic of this session, sorghum and its environment, has been discussed by almost all the speakers. I shall therefore dwell upon the biological aspects of the sorghum environment.

The following main points were made by the preceding speakers:

1. In India, sorghum is grown as a rainy-season *(kharif)* and as a postrainy season *(rabi)* crop. During the rainy season, the total rainfall is generally adequate, but due to poor distribution, it can cause agricultural drought. The postrainy season crop is grown mostly on black soils on stored soil moisture, after the cessation of the monsoon rains in central and south India.
2. In the rainy season, the maximum and minimum temperatures range between 35°C and 15°C respectively in different parts of the country. The temperatures normally decline at the time of grain development. In the postrainy season higher temperatures generally prevail during planting and grain fill.
3. The phenology of the crop is important in relation to productivity. Matching of critical stages, such as grain development, with adequate water availability and suitable temperatures would be desirable objectives.

Some mention was made about partitioning of dry matter after anthesis, effects of temperature on grain development, respiration, population density and modeling.

Sorghum Yields in India

The average yield of sorghum, in India, is 675 kg ha ' though yields up to 7200 kg ha ' or more have been obtained at different research centers (Table 1). It is interesting to note that the average yields in the districts where research centers are located are relatively poor. This suggests **that** although the technology for improved sorghum production is available, it has not yet been accepted by the farmer. Since high yielding hybrids and varieties are already components of this technology, there has to be therefore **a** greater emphasis placed on improved management in this decade. This requires a better physiological understanding of the crop in order to plan a suitable management strategy.

Table 1. Experimental farm yields and the average yield of sorghum in some districts.

Research Stn	Yield Kg/ha⁻¹	District	Yield Kg/ha-
ICRISAT	7200	Medak	410
Rahuri	5920	Ahmednagar	410
Amravati	5750	Amravati	1230
Dharwar	6900	Dharwar	1491
Coimbatore	5780	Coimbatore	863
Akola	4040	Akola	673
Parbhani	4120	Parbhani	681

Physiological Aspects of Yield

Wilson and Eastin (1982) have given a detailed account of the various growth processes from germination to grain fill, which could influence grain yield in sorghum. However, it is important to know the capacity of available cultivars to produce dry matter and their ability to partition it for grain production. It is the complementation of these components which determines grain yield (Sinha and Khanna 1975).

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International Crops Research Institute for the Semi-Arid Tropics 1982 Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru, A.P.. India Patancheru, A P India: ICRISAT

We have grown hybrid CSH-6 at Delhi from 1979 to 1981 with and without irrigation (Chaturvedi, Kailasanathan, Rajagopal and Sinha, unpublished). Dry matter accumulation up to 22 tonnes ha^{-1} was obtained in this hybrid in 92 days. This gives an average rate of 23.9 g m^{2} day^{-1} for the entire period of growth. The interception of light is almost complete after 40 days of growth when the maximum leaf area is reached. In the last 50 days a crop growth rate of 40 g m$^{!}$ day ' was recorded. If we select the peak period of dry matter accumulation, then a rate of 50 g m^{2} day' was observed.

Despite 22 tonnes ha^{-}' of dry matter production, the grain yield was only 4.5 or 5.1 tonnes ha'. This means that under field conditions, a relatively poor harvest index is achieved despite the fact that on an individual plant basis the harvest index is sufficiently high in hybrids (Sinha and Khanna 1975). Accordingly studies on panicle development, its potential and characteristics become important areas for investigation under field conditions where interplant competition is important.

Sink Potential

In most of the hybrids released in India including CSH - 6, panicle differentiation starts between 25 and 30 days after sowing. Anthesis occurred between 55 and 57 days and maturity was obtained between 85 and 91 days (Table 2). The analysis of panicle characters shows that there are on an average 90 or more secondary branches and each secondary has up to 50 kernels or more. The kernel weight is 30-35 g per 1000 grains. Therefore, the average weight of a panicle is about 175 g. At a relatively lower population such as 2 or 4 plants m"$^{!}$ a grain weight of up to 250 g per panicle can be obtained. All this suggests that the 'sink' potential of the existing hybrids, particularly CSH-6. is considerably high, but is not realized in spite of sufficient dry matter being produced.

The following questions become relevant in this respect:

1. Why under field conditions is only 20% or less of the potential panicle weight achieved, despite the availability of dry matter?
2. What is the form in which dry matter is stored in the stem and leaves?
3. Is it possible that limitation of some nutrients, such as nitrogen (applied say at the rate of 40-60 kg N ha') restricts the development of grains in the panicle?
4. What is the effect of senescence of leaves on the mobilization of nitrogen from leaves to grains?
5. What percentage of dry matter produced after anthesis, is utilized for grain development?

Answers to the above questions would provide a better understanding for achieving higher yields under favorable conditions.

Effect of Water Availability and Population Density

The pattern of dry matter accumulation for 1979, 1980 and 1981 is given in Figure 1 in relation to rainfall. In the last 2 years, the crop was irrigated at the time of anthesis, therefore for about 40-60 days from sowing, there was

Table 2. Effect of location on the number of days to differentiation, anthesis, and maturity in the sorghum hybrid CSH-6.

Location	Latitude (°N)	Days from sowing: Initiation	Flag leaf emergence	Anthesis	Maturity
ICRISAT	1727	18	41	55	85
Rahuri	19.24			55	86
Delhi	28.35	25	41	55	86
Hissar	29.10		48	57	91

(**Based** on collaborative modeling experiment with ICRISAT Agroclimatology program, unpublished!

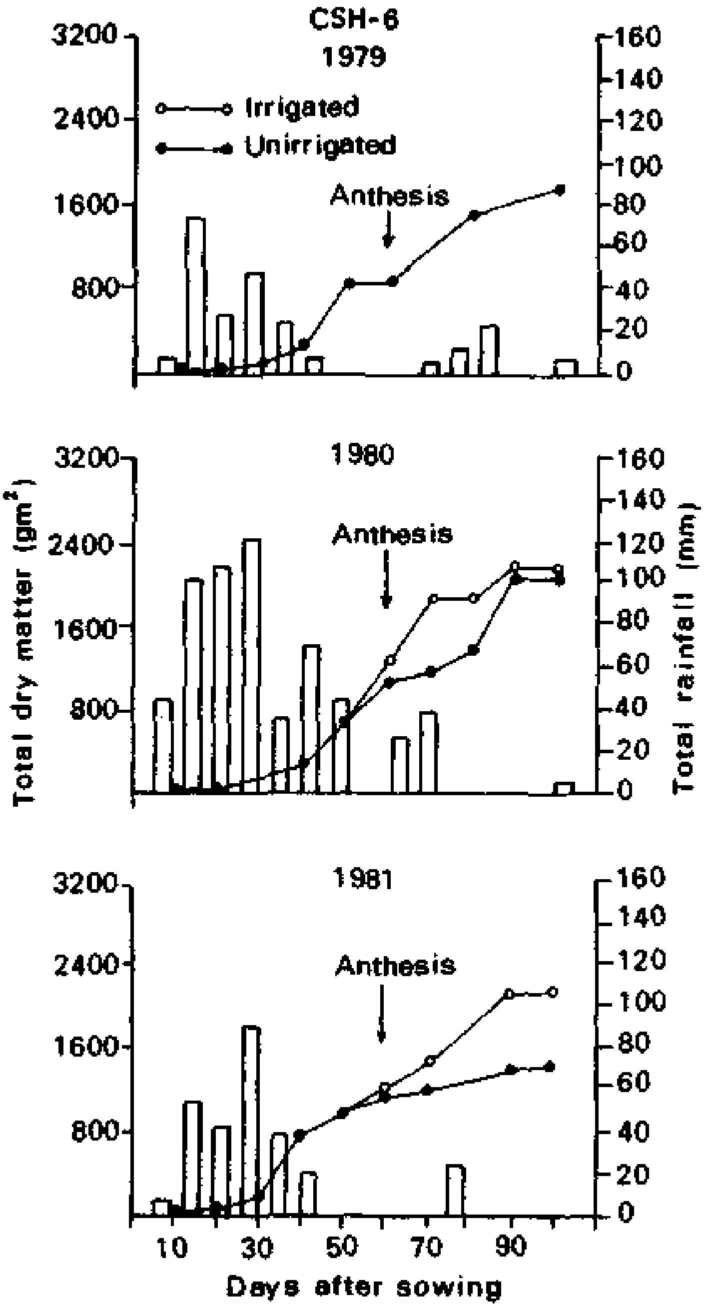

Figure 1. Pattern of dry-matter accumulation in relation to rainfall in 1979, 1980, and 1981. in hybrid CSH-6 (Chaturvedi, Kailasnathan. Rajagopal. and Sinha. unpublished).

adequate water to support growth. However because of the failure of rains in 1979 and 1981. a water deficit developed from 60 days onward, at anthesis. Irrigation at this stage increased total dry matter by 70% and resulted in an increase of grain yield by 89% (Table 3). Therefore, it is essential that there is adequate moisture available in the soil profile after anthesis.

Passioura (1973) reported that grain yield in wheat correlated linearly with water availability after anthesis. This is possibly because most of the photosynthate produced after anthesis is utilized for grain development. In sorghum, the increase in dry matter production after anthesis was 192% in 1981 (Table 4). but the increase in grain yield was only 89%. This suggests that post-anthesis photosynthates are not utilized for grain development in sorghum as effectively as in wheat. This aspect requires detailed investigation under Indian conditions.

One of the methods for ensuring adequate moisture after anthesis could be by manipulating population density. In the All India Coordinated Dryland Agriculture Research Project, a population of 180 000 plants ha^{-1} is recommended. This population was not found suitable in a year of deficient rainfall but was satisfactory when the rainfall was adequate. Therefore, it appears that a number of studies at different locations are required to determine the suitable population for a given water regime at different stages of growth.

Considering the fact that in the semi-arid regions of India where sorghum is grown, the rainfall ranges from 700 to 1400 mm (Sivakumar and Virmani 1982) the possibilities of collecting runoff water are very promising. A single irrigation with the stored water could considerably increase yields and would alleviate the period of drought.

Table 3. Biological and grain yield in CSH--6 at Delhi.

Year	Biological yield (q/ha)*		% increase over I_0	Grain yield (q/ha)	I_1	% increase over I_0
1979	169+16			34±3		
1980	153±2	173±2	13	39±9	45±6	15
1981	117±3	160±7	37	27±2	51+2	89

*q = quintal (1q = 100 kg). I_0 = No irrigation; 1, = Irrigation at anthesis. (Same in Table 4)

4. TotTableal dry matter distribution in CSH-6 at and attar anthasis.

Year	At anthesis		% increase over I_0	Post-anthesis (gm^{-2})		over I
	I_0	I_1		I_0	I_1	
1979	585±29			1104±45		
1980	682 ±43	682±43		851 ±43	1050±24	23
1981	893+94	893 ±94		437 ±68	1276±111	192

Rabi Sorghum

Sivakumar and Virmani (1982) in their paper stated the conditions under which *rabi* sorghum is grown. The main problem is that in black soils cracks appear from the time of panicle emergence to harvest. A rise in mean temperature then adds to the problem of drought, leading to poor yields. The following questions are relevant to this situation:

1. What is the initial available soil moisture and how long does it take for the soils to develop cracks?
2. How much cumulative evaporation leads to cracking?
3. Can the time of panicle emergence be adjusted to occur before the appearance of soil cracks?
4. Would photoperiod sensitive varieties be more desirable? (In fact M35-1, which is adaptable to these regions, is a photosensitive variety. Will early differentiation in this variety be more advantageous?)
5. What is the optimum population which a given soil moisture profile could support up to grain development?

To my understanding, the above questions have not been addressed in depth in the *rabi* sorghum growing areas. Answers to many of these questions would be necessary to develop a suitable strategy for improving yields.

Conclusions

In India, considerable progress has been made in breeding for yield. Consequently very high yielding cultivars are available. However in my opinion, the average yield of sorghum will increase only through improvement in management, based on a detailed understanding of agrometeorological factors, crop growth, and development. This is where the emphasis in the eighties should be placed. Breeding for stability components, such as diseases, may be a better objective than breeding for yield.

References

PASSIOURA, J B. 1976 Physiology of grain yield in wheat growing on stored water Australian Journal of Plant Physiology 3: 559-65

SINHA. S K. and KHANNA, R 1975. Physiological, biochemical and genetic basis heterosis Advances in Agronomy 27: 123-170

SIVAKUMAR. M. V. K.. and VIRMANI. S. M. 1982. The physical environment These Proceedings: ICRISAT

WILSON. G L. and EASTIN, J. D 1982 The plant and its environment These Proceedings: ICRISAT

Session 2 Sorghum and its Environment

P. R. Goldsworthy* Discussant—2

The papers of Sessions 1 and 2 have referred to two situations in which the aims of sorghum improvement are likely to differ. The first concerns favorable environments, where the aim of improvement is often to achieve maximum potential production; the second is in adverse environments where the aim is usually to prevent or limit yield loss. Though the aims may differ, an understanding of the development of yield in terms of the phenology of the crop, in the manner described here by Professors Wilson and Eastin, is a necessary step towards crop improvement in both situations.

The phenology of the crop places the development and production of yield in time. How this is done is likely to have an important influence on yield in any given environment. The recognition of different stages of development of a crop plant and measurement of the rate and duration of the changes that take place during each stage provide the basis on which to examine how the time available is used to produce yield, and whether it can be used better.

In favorable environments the aim is towards the highest potential production and for sorghum, improvements are designed to exploit the high growth rates attainable by C_4 crops. There may be scope for manipulation of the duration of the growth phases to make better use of time and avoid undue competition between the developing grains and other demands for assimilates. The duration from anthesis to maturity has not been found to vary greatly, but within its span a longer effective duration of grain growth offers the prospect of improved yields. Even so it is pointed out that feedback, by which the rate of utilization of the products of photosynthesis influences the rate of their production, often confounds studies of source-sink balance and little more progress may be possible until better techniques of measurement are available to us. Yields of 14 t/ha or more have been attained, and it is probable that this is near to the maximum production with the prospect of only comparatively small additional gains in the future.

Adverse environments present a different challenge. Dr. Leng has shown us how progress to increase production and yield of cereal crops has differed between crops and regions over the past three decades. However, part of this contrast in rates of progress may be a consequence of differences between environments. Much of the increase in yield and production of wheat and rice in Asia has come from irrigated crops; the corresponding increase in yields of maize in the United States and Europe, and of sorghum in the United States and Mexico, has been accomplished in favorable environments. In contrast, where the environment is less favorable and there is less control over it, gains have been smaller. Dr. Leng provides a notable example with wheat in the United States, where management of the crop is extensive rather than intensive, and yield increases have been small. Similarly there has been much less progress to improve yields of rice in Africa or of maize and sorghum in Africa and Asia, where these crops are grown without irrigation, with uncertain rainfall and on marginal land. Yields of sorghum in these environments are around 700 kg/ha and the near maximum yields of 14 t/ha attained in favorable environments are of little relevance. The principal aim in less favored environments is to limit yield loss, from pests and disease, or from adverse variations in environment, particularly in the amount and distribution of water.

Pests and diseases often cause serious losses when control of the environment is limited. In small-scale agriculture, host plant resistance is often the only practical means available to control

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damage. Recent advances in food legumes illustrate how new sources of genetic diversity can be used successfully to develop resistant varieties and so limit loss. This may be the only practical way to control pests and diseases of sorghum also, particularly downy mildew.

To minimize the adverse effects on crop yield of variation in climate, we must first recognize distinct climatic zones as described here by Drs. Sivakumar and Virmani. The next step is to define the expected variation within these zones so that we can estimate the risk posed to a crop. Seasonal variations in temperature and radiation at a given site are comparatively predictable; the amount and duration of rainfall is usually much less predictable. The variation in depth and physical characteristics of the soil also influences directly, the amount of water available. These variables can be defined to estimate the expected duration of the growing season when water is available, and the probability of the occurrence of periods when water will be limiting, in the manner described by Drs. Sivakumar and Virmani. The agronomist or breeder has then to select a genotype with the phenology and physiological responses that will place the production of grain at the most favorable time, when there is neither too much nor too little water.

Because of the geographic spread of their responsibility, the crop improvement programs at international agricultural research centers have usually adopted a recurrent selection procedure based on the performance of breeder's lines at several locations, in different environments. This leads to the development of improved varieties that are less sensitive than traditional, local cultivars to the features of a particular environment, but it has the advantage that the improved varieties can be widely distributed. However, in some regions, notably West Africa, photoperiod sensitivity in local cultivars is a necessary part of the adaptation of sorghum to growing seasons that differ in length with latitude, and introduced cultivars that lack similar adaptation are therefore unlikely to be widely adopted. This suggests much more work may be required with photoperiod sensitive genotypes adapted to specific environments.

Genotypes which by virtue of their phenology avoid drought can help to diminish losses. This is not a new concept. May and Milthorpe (1962) argued that it was likely to be a more rewarding approach than the search for tolerance to internal water deficits, which until then had attracted more attention and continues to do so.

Root distribution also has a direct bearing on the amount of water available to a crop and Professors Wilson and Eastin note that there is genetic diversity in root morphology in sorghum that should be explored.

The accumulation in the stem of labile carbohydrate which can later be mobilized to fill grain is a feature of many eld, traditional cultivars of cereals, and is usually associated with low yield. It is not a feature of new modern varieties. Even so, it may represent a useful mechanism of survival, buffering grain yield against circumstances which may adversely affect photosynthesis during grain filling. In developing varieties for adverse environments we may not wish to discard this character entirely.

The two papers by Drs. Sivakumar and Virmani, and Professors Wilson and Eastin illustrate the variation in the crop and its environment, and the complexity of the relationships between the two. One conclusion is the need for perhaps fewer experiments, at selected locations, with better environmental data, so that more general and useful conclusions can be drawn from them.

Two other topics warrant special note, i.e., seedling emergence, and hybrid vigor. Dr. Peacock notes the first as an important problem in many SAT regions, yet if progress is to be made there is a need for a better definition and then measurement of the characters that determine seedling vigor. Similarly, if hybrid sorghum is consistently better than varieties there is need to explain this in terms of rates and durations of the measurable processes that determine yield in the two types of sorghum.

Reference

MAY. L.H., and MILTHORPE, F.L 1962. Drought resistance of crop plants. Field Crop Abstracts 15: 171 -179.

Session 2 Sorghum and its Environment

Discussion

Nicou

I wish to make the following three comments on the physical environments of West Africa: (1) A number of sorghum zones exist in West Africa where the average rainfall of between 500 and 800 mm comes in a very erratic pattern. This makes sorghum breeding more difficult. If too short, the sorghum plants might wither, if too long, the grains might become moldy. (2) The soils of this region are mostly sandy and sandy-clay and the water reserve is approximately 8 cm. Moreover the soil depth is of great importance; and the presence of a laterite crust at 30 - 60 cm makes it more difficult to study the plant response. (3) In attempting to improve crop yields, agronomic research should not be ignored. The studies conducted over the last 20 years in Upper Volta suggest that a little extra water applied in time has a profound effect on increase in grain yield.

Scheuring

I would like to elaborate on Mr. Nicou's comments concerning sorghum plant growth in West Africa. The West African farmer recognizes the sudden disruption of regular rains in September. He adjusts the planting date of his local sorghums so that they will flower during the latter fortnight of September. In many years the plants flower and fill grain under extreme drought. The soil moisture and fertility levels are extremely low during postfloral drought since the soil clay content and CEC are so low in West Africa. Local sorghums have evolved over centuries under those austere conditions. The local sorghums, particularly the guineenses are able to fill sound vitreous grain under postfloral drought stress, while under identical conditions, introduced varieties and hybrids seem to physiologically collapse after flowering. They set floury grain with low test weight which is useless as food. We must be careful not to overstate the potential performance of HYVs and introduced hybrids under the severe conditions in West Africa. If new varieties and hybrids are ever to make an impact in West Africa, they must be able to handle the boom and bust situation of vigorous growth under high moisture during the month preceding anthesis followed by the filling of hard vitreous grain under extreme moisture and fertility depletion during the month following anthesis.

Sivakumar

Your comment is very pertinent and important. I should mention that the work of Drs. Kassam and Andrews, from the Institute of Agricultural Research at Samaru, on short Kaura, a photosensitive Nigerian sorghum showed that when sown after 26 May, the total dry weight and grain yield decreased at the rate of 1700 kg/ha per week and 360 kg/ha per week respectively. Dr. Curtis and Professor Bunting also showed that the date of heading of local sorghum is closely related to the average date of the end of local rains, by means of photoperiodism.

Parvatikar

Winter sorghum grows on stored, limited, and depleting soil moisture conditions. The temperature increases as the crop matures. Under these conditions which of the growth stages—GS1, GS2 or GS3—should have longer duration?

Wilson

I do not know if a long GS1 has any value; a long GS2 may lead to increased numbers of florets and hence numbers of grains and a long GS3 should, if potential grain sizes are adequate to accommodate the additional material available, lead to larger grains. Overall therefore yield should increase. However the field situation is commonly one in which long crop durations are undesirable for a number of reasons, most of which result in yield reductions.

Eastin

Not much information is available on this point. However, growth room tests suggest that a 10% reduction in length of the panicle development period can reduce seed number per unit land area by a fourth to a third which corresponds closely to the percent grain yield reduction. Generating a high leaf area during GS1 (long duration) may not be desirable in severe stress areas.

Parvatikar

Just by improving crop stand (ear bearing plants/ unit land area) and harvest index in M35-1, a significant improvement in yield can be achieved in the *rabi* (postrainy season). Breeders should cooperate with physiologists in this venture.

Wilson

An increase of harvest index achieved by increasing, and storing as grain, the amount of material produced after anthesis, relative to that produced earlier, should generally be satisfactory. If, however, it results from maximizing the movement to grain of both stored photosynthate and that produced during GS3, there are two problems. One is increased risk of lodging. The other is reduced fodder value of the stover, a very important component of yield in some countries like India.

Rana

(1) Dr. N.G.P. Rao has shown this morning that the total biomass production of tropical varieties is much higher but they are low in productivity due to low harvest index and poor population performance. Therefore, the first correction to be made in the tropical tails is to modify the dry matter distribution so that the major part of dry matter produced is translocated to the earhead as shown by the high harvest index of CSH-1 or CSV-1.

The second step to increase the productivity is to increase the total biomass production maintaining the high harvest index (around 40-50%), and the maturity. It amounts to the simultaneous selection for high rate of growth and high harvest index. CSH-5 and CSH-9 are examples. These hybrids have an average yield of 4 t/ha or more under rainfed agriculture. Their potential yield is 8-9 t/ha. Now the question is what is next? We have two alternatives at this stage—either to continue the selection for a higher rate of growth and high harvest index, or to select for a longer grain filling stage without changing the maturity period and the population response.

(2) The temperate early dwarfs show wider adaptability across the continent but not the long duration dwarfs. We do not know the physiological basis for the wider adaptability of temperate dwarfs.

Sinha

Many Indian hybrids have high yield potential (seed number). It will be difficult to increase this potential further without changing the length of GS2. Under Indian conditions further increase in GS2 is not desirable.

Blum

There is a higher root density per unit leaf area (cm root/cm^3 soil/cm^2 leaf area) in early genotypes, as compared with late genotypes. Hence early genotypes are also more dehydration avoidant than late ones.

Session 3

Factors Reducing Sorghum Yields
Environmental Stress

Chairman: H. G. Jones

Co-Chairman: S. Fukai

Rapporteurs: B. V. S. Reddy

N. Seetharama

Reaction and Resistance of Grain Sorghum to Heat and Drought

W. R. Jordan and C. Y. Sullivan*

Most of the world's grain sorghum production occurs in arid or semi-arid climates without the aid of irrigation. Droughts of variable duration and intensity are commonplace in these regions and are often associated with above average temperatures. The economic and moral implications of serious crop losses from recent droughts have focused new research efforts on the management of limited water resources to maintain high yields. In the following sections we examine the response of grain sorghum to low soil water availability and high temperatures and discuss means to ameliorate deleterious effects of these stresses.

Potentially, the problem of crop performance in water-limited situations resolves into two basic components. A genetic component sets broad limits on the mechanism(s) through which the plant copes with a specific stress, while a management component influences both pattern and total amount of water available to the crop. Even though each component may be viewed as distinct from the other, the expression of genetically-controlled mechanisms often represents a form of adaptation which depends on the nature of the drought. Because the components do interact, efficient use of water must be based on a thorough understanding of the entire production system including climate, management, and genotype.

Yield and Water Use

Results from recent field studies shown in Figure 1 (Garrity 1980; Sullivan et al. 1980; Garrity et al. 1981) illustrate the linear relation between grain yield and total water use (evapotranspiration, ET) reported by others (Hanks et al. 1969; Inuyama et al. 1976; Gerard et al. 1980). This general relation is expected and results from the central roles played by photosynthetic tissues in light interception and by stomata in regulation of water vapor and CO_2 exchange.

In Garrity's studies, ET was varied with a line source sprinkler irrigation system where water applications decreased linearly with distance perpendicular to the source line (Hanks et al. 1976). By using two parallel source lines spaced at appropriate distances, and by operating the lines singly or simultaneously, water may be applied in a gradient (G) or uniform (I) fashion. Data presented in Figure 1 were obtained by operating the system in the gradient mode during all three growth stages (GGG treatment) which allowed gradual development of water stress throughout the season. Figure 2 illustrates results from other treatments where gradient or uniform irrigations were applied in combinations with different growth stages. In this manner, the effect of water deficit at specific growth stages was determined. For example, the GGI treatment was irrigated in the gradient mode allowing stress to develop during growth stages 1 and 2 (GS1 = 5-leaf stage to panicle initiation; GS2 = panicle initiation to end of anthesis), with a uniform irrigation (no stress) applied during growth stage 3 (end of anthesis to physiological maturity).

The relationships presented in Figures 1 and 2 illustrate several points. Harvest index (grain yield/total above-ground dry matter) was not affected by water stress suggesting that all three hybrids possessed mechanisms which allowed maintenance of the balance between vegetative and reproductive growth. However, the slopes of the regression lines differed among hybrids and

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patanehetu. A.P., India. Patancharu. AP India: ICRISAT.

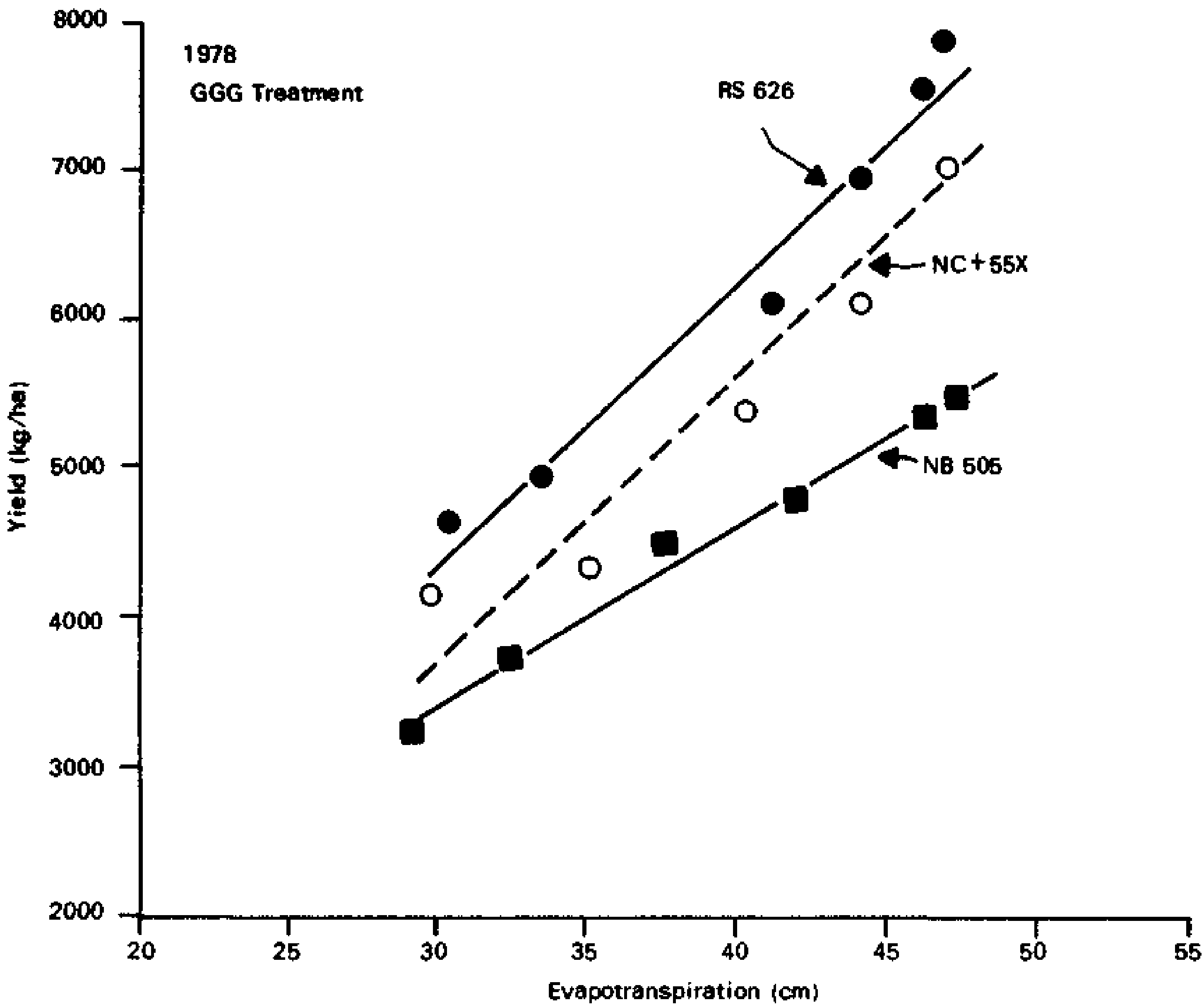

Figure 1. The relationship between evapotranspiration and grain yield for three sorghum hybrids grown on a sandy soil in western Nebraska in 1978. Evapotranspiration was modified by regulation of soil water availability with a line-source sprinkler irrigation system. See text for details of the treatment (from Garrity 1980).

irrigation treatments suggesting differences in water use efficiency (WUE, defined as grain yield/total ET). The effects of water stress (reduced ET) on relative yields did not vary among hybrids, further Suggesting that differences in yield potential with adequate irrigation was primarily responsible for differences among hybrid yields under water-limiting conditions. Because of the difficulty in separating soil evaporation from transpiration, the genotypic variation in apparent WUE may not translate into real biological differences in grain yield per unit water transpired.

The response of 'RS 626' to soil water availability during each of the three growth stages (Fig. 2) provides evidence that the history of water availability to the crop may significantly alter the apparent WUE. For example, the apparent WUE of the GGI treatment was lower (greater yield loss per unit ET reduction below maximum) than GGG even though there was no stress during the grain filling period. These results suggest that the yield potential for the crop was already set and high soil water availability during grain filling contributed more to ET than to grain yield. Results from the IIG treatment suggest a greater loss of water occurred as soil evaporation during early growth before complete canopy cover (a leaf *area* index approximately equal to 3) was achieved. Additional water losses via soil evaporation contribute to ET but not grain yield accounting for the lower

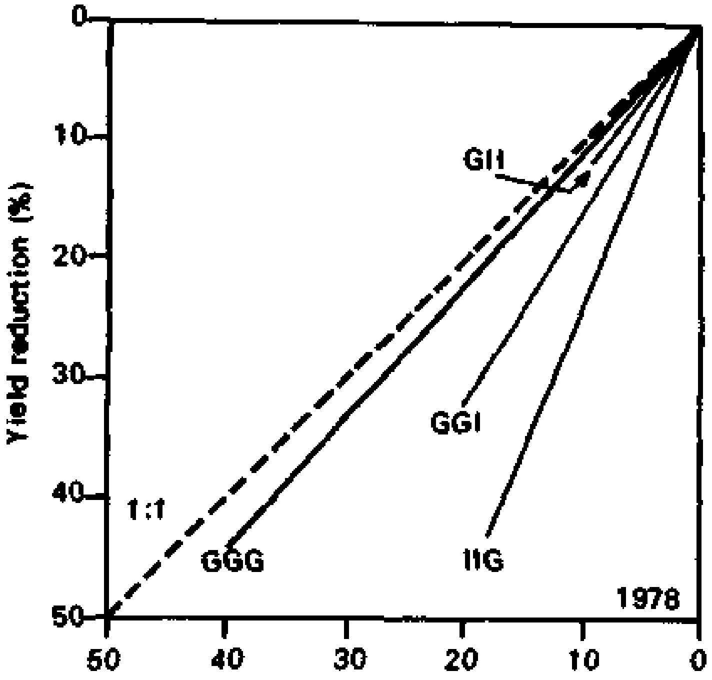

Figure 2. The relationship of evapotranspiration deficit to grain yield reduction for "RS 626" hybrid grain sorghum. Refer to text for treatment definitions (from Garrity et al. 1982).

WUE compared with the GGG treatment. Harvest index was unaffected by ET deficit (water stress) in all treatments. This is consistent with the report of Boyer and McPherson (1975) that the harvest index of maize was not altered by soil water deficits sufficient to reduce grain yields by 50% or more. Some genotypic variability for maintenance of harvest index during drought is suggested, however, from data presented by Hsiao et al. (1976b). They found grain yield of sorghum cultivar 'Ryer 15' fell as irrigations were reduced, but the harvest index remained relatively constant. In contrast, 'DD38' maintained grain yield at the expense of dry matter in vegetative parts (higher harvest index).

In the examples of Garrity et al. (1981) and Hsiao et al. (1976b) discussed above, soil water availability was adjusted so yield reductions were generally less than 50% of maximum and actual grain yields were above 3000 kg/ha. Since even the low yields achieved in these studies represent excellent yields in some sorghum producing regions, additional mechansims for drought resistance would likely be required for crops grown with severe water limitations. Developmental plasticity could contribute greatly to yield maintenance in situations where extensive 'head blasting' results from severe heat and drought stress during the boot stage as illustrated by the response of 'RS 610' (Hsiao et al. 1976b). Severe stress at head emergence resulted in lower seed numbers per head, but enhanced tillering resulted in more heads per plant. In spite of serious head blast, final yields were still 78% of the fully watered controls. Genotypic variability in head blast in response to drought has been observed and will be discussed in a later section.

Situation and Risk Analysis

Crop improvement for enhanced drought resistance must be based, first of all, on a quantitative understanding of the production climate with regard to soil water availability. Detailed soil and weather information are available for many locations, but, until recently, interpretation of this information in terms of plant response has relied strongly on extensive yield testing. Considering the cost, time requirement and environmental variability encountered from year to year, it is a small wonder that breeding of truly drought resistant cultivars has been a difficult goal to attain.

Powerful new tools in the form of Crop Simulation Models (CSMs) are now available to assist in the development of drought resistant cultivars. Such models are driven by climatic inputs, usually in the form of temperature, solar radiation and rainfall, and thereby provide a rapid, inexpensive means to test specific hypotheses related to weather sequence effects on growth, development and yield. When coupled with a soil water balance subroutine, plant response to any degree or pattern of available soil water may be evaluated. While this approach will obviously not provide a panacea for all problems, we propose that accurate, validated CSMs be used to evaluate the potential benefit of specific mechanisms related to drought resistance. This approach, with crop maturity as a test variable, is illustrated in Figure 3.

In this example, the CSM entitled SORGF (Arkin et al. 1976; Maas and Arkin 1978), was run on 31 years of weather data from Temple, Texas; Lubbock, Texas; and Manhattan, Kansas. Because of model construction, anthesis date was varied by specifying that the crop formed either 15 (early maturity) or 17 (later maturity) leaves. This

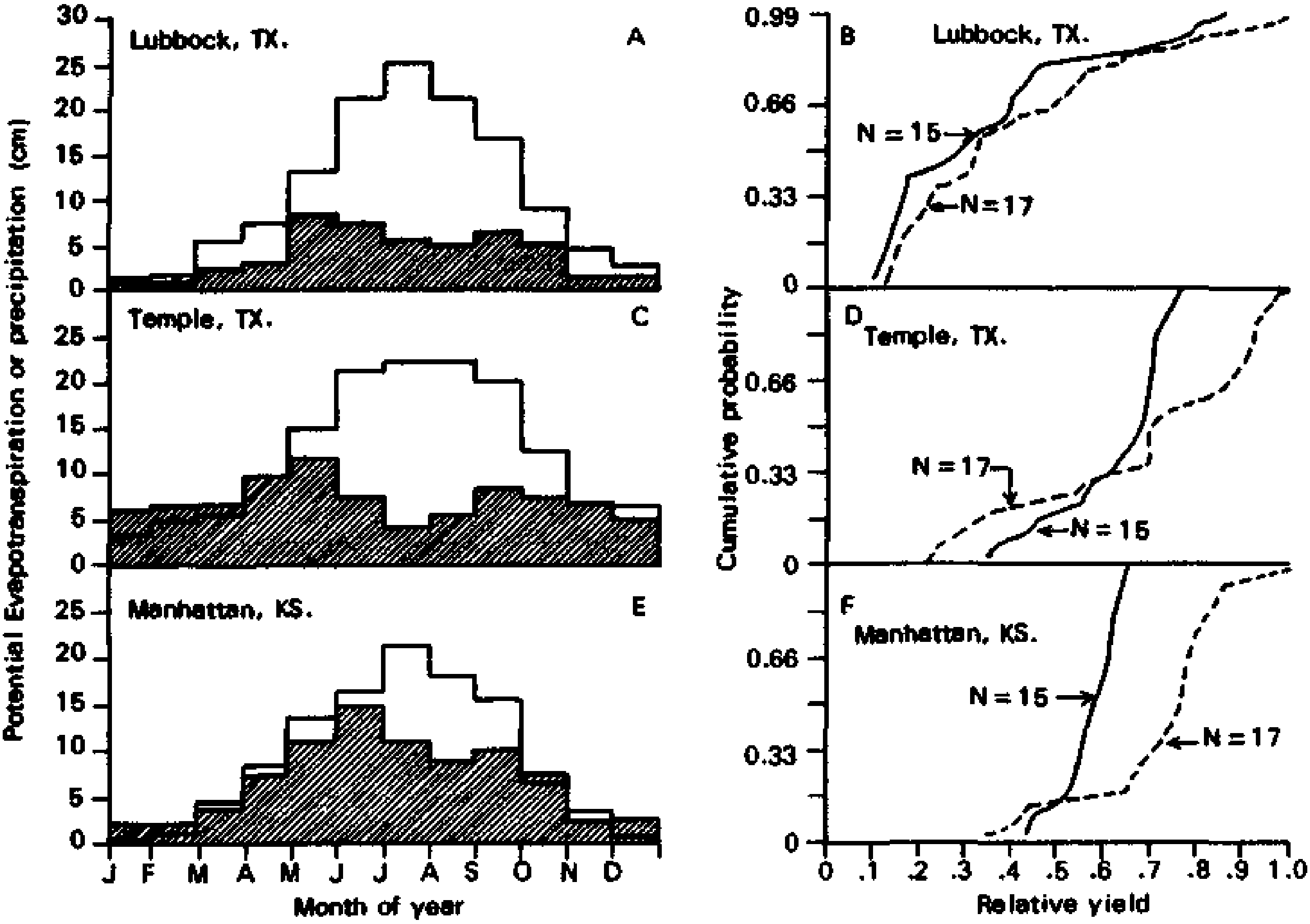

Figure 3. A, C, and E represent a 31-year average distribution of precipitation (shaded bars) and potential evapotranspiration by months for three locations. B. D. and F represent the probability for a given yield at those locations for an early (N = 15) and a late (N = 17) maturity genotype. Yields are from simulations with SORGF using actual daily weather data for each location. See text for details.

choice produced anthesis dates which differed by about 10 days at each location. The soils at each location were assumed to hold a maximum of 180 mm plant available water within the profile. The profiles were assumed to be completely filled at planting time at Temple and Manhattan, but only 50% filled at Lubbock because of low winter rainfall (Fig. 3A, C, and E). Planting dates were those commonly used in each region. Yields are expressed as a fraction of the highest simulated yield during the 31 seasons.

Several points may be made from this analysis. First, in this situation the later maturity genotype is always preferred at Lubbock (Fig. 3B) since the yield is slightly higher at any probability level. However, this is not the case at Temple and Manhattan (Figs. 3D and F) since the probability curves crossed at relative yields near 0.6 and 0.5, respectively. At these two locations early maturity is associated with greater yields in about 33 and 15% of the years, respectively. Since producers will be penalized in terms of yield in only a relatively few years at Temple and Manhattan, and rarely at Lubbock, the risk associated with using the later maturity genotype is more than offset by its higher yield potential (compare early vs late at high probability levels). The power of CSMs in preliminary analyses of this type is evident in the wide choice of possible initial conditions, and a quantitative estimation of the effects of many proposed modifications of crop response may be obtained.

A basic requirement for using CSMs such as SORGF is that each potential mechanism for drought resistance must be quantified in terms of changes in plant morphology, phenology, or physiological activity. Herein lies the most serious limitation to the use of CSMs to evaluate potential mechanisms for avoidance or tolerance of drought. For the most part, individual mechanisms have not been studied in sufficient detail to quantify their effects in terms of specific plant responses. Concentrated research efforts in this area are badly needed. Mechanisms of potential benefit to survival and yield maintenance of sorghum grown under drought conditions are considered in more detail in the following sections.

Mechanisms for Avoidance or Tolerance of Drought and Heat

The literature abounds with examples of metabolic and growth disturbances induced by water stress. Few of these disturbances have been critically examined to determine their potential roles as contributing factors in overall drought resistance. Jordan and Monk (1980) summarized reports for sorghum related to various mechanisms for avoidance or tolerance of drought and concluded that avoidance mechanisms provided the greatest opportunities for yield maintenance since tolerance mechanisms were often associated with substantial yield losses. Some selected examples are discussed below, and a subjective evaluation of their potential usefulness in crop improvement is made.

Maturity

The potential for matching crop maturity to specific, water-limited environments was illustrated in Figure 3. The yield advantage associated with early maturity for a dryland sorghum grown in a mediterranean climate has been documented by Blum (1970). Early maturity would be expected to be of greater potential benefit in situations where growth is achieved solely on stored water. Since genetic manipulation and selection for maturity is relatively simple (Quinby 1972), the potential of this mechanism can be quickly exploited. The underlying problem associated with this approach appears to be an incomplete understanding of the environment with regard to water supply and a quantitative expression of an acceptable level of risk associated with choice of a specific maturity genotype. Since weather data bases are generally available throughout much of the world's sorghum production area, the basic problem reduces to one of producer education and information availability.

Root System Diversity

Diurnal development of internal water deficit (low plant water potential) is a well documented phenomenon resulting from the time lag in water uptake from the soil to replace that lost in transpiration. For soghum, water uptake appears to be rapid enough to prevent development of low leaf water potential so long as plant available water in the rooting zone is not reduced below about 30% (Ritchie 1974). The plant root system plays a central role in determining the rate and final amount of soil water actually available to the crop. Modification of the root system to extract greater quantities of soil water or to regulate the rate of depletion may constitute an important drought avoidance mechanism (Blum 1974a).

Genetic improvement of a trait requires the existence of both genetic variability for the character and a means to quantitatively assess the character on large numbers of plants. The existence of genetic variability for root characteristics in sorghum is demonstrated by several recent reports (Jordan et al. 1979; Blum et al. 1977a, b; Wright 1978; Bower 1972; Nour and Weibel 1978; Bhan et al. 1973; Jordan and Monk 1980). The genetic variability is generally expressed in the distribution of growth (dry matter) between the shoot and root, or in the distribution of growth between root axes and lateral branches. As with other characters, little work has been devoted to the examination of benefits to plant performance which may be derived from specific root variants. High root to shoot ratios of young plants have been correlated with superior drought resistance of a few lines (Nour and Weibel 1978; Bhan et al. 1973), but work thus far does not constitute a rigorous test of the value of specific root characteristics to drought resistance. The development of specific root variant isolines would provide a badly needed source of genetic material to test the value of specific root traits.

As in the case with maturity, a choice of the root "ideotype" must be based on a thorough understanding of the seasonal pattern of water availability for the soil of interest. While little evidence exists that cultivars of sorghum differ in their capacity to extract more or less water from a soil layer permeated by roots, a case may exist for proposing that increased rooting depth will increase the total water available to the plant. Such an illustration is provided by Jordan and Miller (1980) for sorghum growing on a deep clay soil. In this instance, an adapted hybrid does not normally remove all available water below a soil depth of about 75 cm. Increased rooting density in the lower portion of the soil profile allows the timely extraction of greater quantities of soil water, as illustrated in Figure 4. The net result is a delay in the time required to deplete the profile to the extent where serious water deficits occur. If these deficits normally occur near anthesis, a particularly sensitive growth phase, then deep rooting may contribute to yield maintenance. Also, a delay in the onset of serious water deficits may allow the crop to avoid damaging water deficits provided this delay is associated with higher probabilities of rainfall needed to complete grain development. Deep rooting is a potentially useful mechanism for crops grown on soils where deep profile recharge occurs during the off season.

As an alternative to root system modification to increase the total available soil water, Passioura (1972) proposed root modifications which act to regulate the rate of water use. His research with wheat provided strong evidence that grain yield was highly correlated with soil water remaining at anthesis. Provided the probability for significant rainfall during the growing season was low, varieties which used a smaller fraction of the total water during vegetative growth produced higher grain yields. Since dryland wheat often exists on only a few seminal roots, he proposed to increase the root resistance to water flow by selection for small xylem vessel diameter. High root resistance acts to slow vegetative growth (water potentials are lowered) and thus reduces leaf area index and the water use before anthesis. While Richards and Passioura (1981a,b) have successfully identified genetic variability for xylem vessel diameter in wheat roots, no such comparable effort appears to have been undertaken with sorghum.

Thus, while genetic variability in a few root characteristics has been demonstrated, prognosis for increasing drought resistance by breeding for these traits is not good. Methods to study root systems are relatively primitive and are not suitable for evaluating the large numbers of plants required in breeding programs. Furthermore, the plasticity exhibited in rooting patterns of plants growing in a natural field environment prevents genotypic expression of deep rooting except during seasons with extended periods of drought (Jordan and Monk, Agronomy Abstracts 1980).

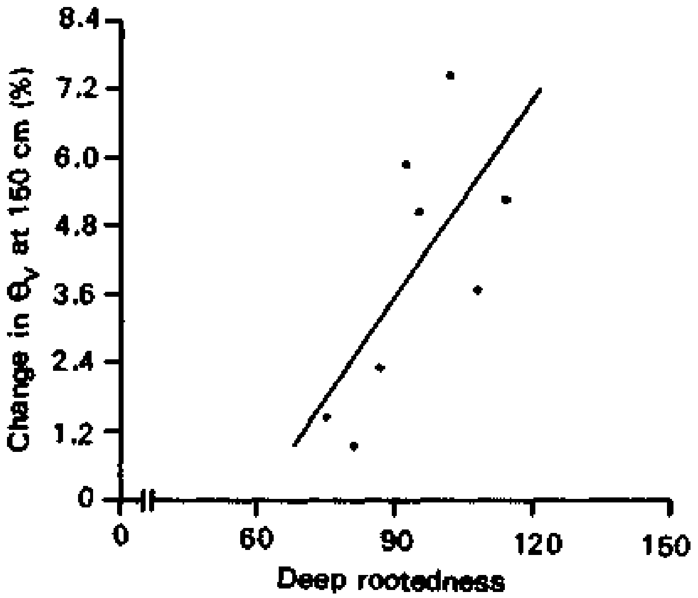

Figure 4. The relationship between deep rootedness of sorghum at anthesis and change in volumetric soil water content at the 150-cm soil depth during a 12-day period near anthesis. Deep rootedness is the soil depth above which 80% of the roots were observed.

Epicuticular Wax Loads

The aerial portions of most sorghums are covered with a thick, amorphous layer of wax. In addition, the normal or "bloom" types are characterized by the presence of wax filaments on the peduncle, leaf sheaths and the basal portion of the abaxial leaf surfaces giving these tissues a fluffy, white appearance. The presence of the waxy bloom is controlled by a single, dominant gene (BmBm), but several bloomless (bmbm) and sparse bloom (hh) variants are known (Ayyangar and Ponnaiya 1941; Ayyangar et al. 1937; Peterson et al. 1979).

Epicuticular wax (EW) has been implicated as a feature of sorghum which enhances its drought resistance. Comparisons between pairs of BmBm and bmbm isolines demonstrate a consistent yield advantage in favor of the BmBm type which is accentuated in water-limited environments (Ross 1972; Webster 1977; Webster and Schmalzel 1979). These results suggest the BmBm character may permit more efficient use of limited soil water and support the finding that the transpiration ratio is higher for BmBm isolines (Chatterton et al. 1975). Presumably, heavier wax loads associated with the BmBm character lowers net radiation by increasing reflectance and thickens the boundary layer thereby retarding transpiration (Blum 1979). EW loads on leaves of normal (BmBm) sorghums were reported to range between 1.14 and 2.19 mg dm^{2} (Ebercon et al. 1977; Powell et al. 1977), but environment is known to modify the EW load of many plants. An example of environmental effects on EW loads on 14 genotypes grown under dryland conditions at Temple, Texas (USA), is shown in Figure 5 (Jordan et al. 1981). Mean EW loads over all genotypes ranged from a low of 0.91 mg dm^{2} in 1979 (wet year) to a high of 1.51 mg dm^{2} in 1977 (dry year). The range among genotypes averaged over all years was 0.97 to 1.63 mg dm^{2}. Genotype response across environments (years) was variable with some cultivars maintaining EW loads consistently above the mean (M35-1 and RTx430) or below the mean (RTx7078 and IS1598C), while the reaction of others was inconsistent across years. In 1980, an evaluation of 138 normal (BmBm) lines released from the sorghum conversion program demonstrated that a wide range of genetic variability exists for EW loads

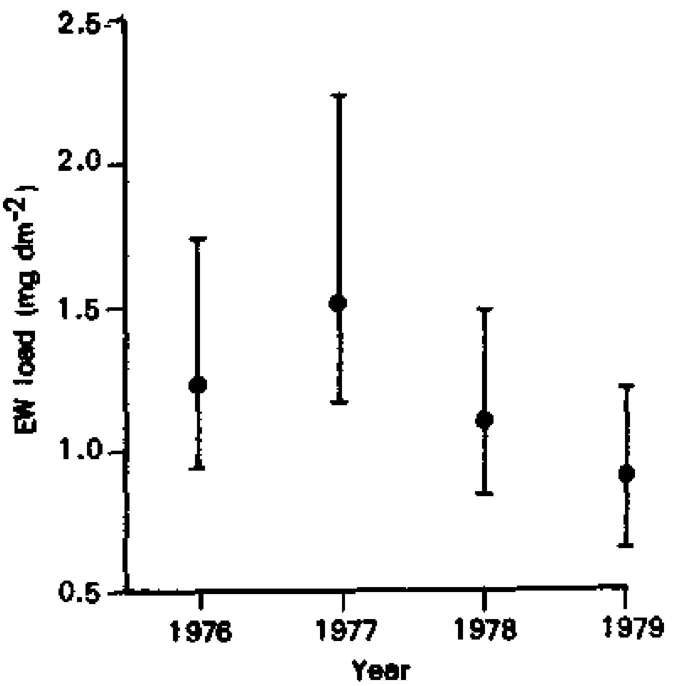

Figure 5. Epicuticular wax load on leaves of 14 sorghum genotypes grown in unirrigated plots at Temple, Texas IUSA) from 1976 to 1979. Means of all genotypes are indicated by the dot. and the range is designated by the vertical bars.

(1.13 to 3.41 mg dm^{2}) which may be of potential use in breeding programs.

Crop improvement for higher EW loads does appear possible, and techniques are available for the rapid screening of large numbers of samples (Ebercon et al. 1977). However, the value of higher EW loads within the range of BmBm genotypes remains to be demonstrated. The role of high EW loads appears to be important to leaf survival rather than to maintenance of high productivity since its principal effect is to retard water loss via the cuticular pathway. As such, variations in EW loads would be expected to be important only when stomata are closed by severe water deficits. If high EW loads act to preserve green leaf area by prevention of lethal desiccation, it may be an important character that allows rapid responses to rehydration if water becomes available later in the growing season.

Osmoregulation

Osmotic adjustment by cells through synthesis and accumulation of solutes in response to water deficits has been termed osmoregulation. Accumulated solutes are often a complex mixture of organic acids, amino acids and sugars. It is believed that osmoregulation serves as a mechanism to maintain turgor as tissue water potentials fall, thereby maintaining growth (Hsiao et al. 1976a). Genetic variability for osmoregulation has been reported for wheat (Morgan 1980) and rice (Steponkus et al. 1980), but not for sorghum. One comparison of 'RS 610' and 'Shallu' failed to demonstrate differences in osmoregulatory capacity even though the two cultivars are known to differ in drought resistance (Jones and Turner 1978; Turner and Jones 1980). Blum and Ebercon et al. (1977) reported cultivar differences in the capacity to accumulate proline in response to water stress, but it is not known if osmoregulation parallels proline accumulation. Blum (1979) suggested that proline may be important as an energy source during recovery from water stress.

If osmoregulation is to be considered an important mechanism in drought resistance with potential application in a breeding program, much basic work remains. First, genetic variability in the rate or final extent of osmotic adjustment must be demonstrated. Then, simple, rapid techniques must be developed to evaluate the character. Finally, the value of osmoregulation to performance under water-limiting conditions must be demonstrated. It therefore appears unlikely that rapid advances in improving the general osmoregulatory capacity of sorghums will be forthcoming in the near future.

While the prognosis for timely incorporation of general osmoregulatory capacity into sorghums is poor, a case may be made for genetic manipulation of stomatal response to water deficit, one specific consequence of osmoregulation. When exposed to water deficits, sorghum plants adapt in many ways. One form of adaptation is a general lowering of the leaf water potential at which stomatal closure occurs. If this phenomenon is assumed to be a consequence of osmoregulation, rather than a result of changes in cell size or cellular elasticity, then the maintenance of low stomatal resistance may be taken as a measure of osmoregulation. Henzell et al. (1975) reported cultivar differences in stomatal sensitivity to water deficit, but no large-scale screening activity has been undertaken. Ackerson et al. (1980) also reported osmotic adjustment of lines and hybrids subjected to drought in the field, but their results may have been confounded by changes in cell size. Among the six cultivars they tested, the predicted point of zero turgor ranged between -21.0 and -25.5 bars leaf water potential. Whether differences in net photosynthesis were also maintained at low water potentials is not known. Genotypic differences in fractional water loss per unit decrease in leaf water potential, possibly due to osmoregulation, were also demonstrated in one test with ten diverse sorghum types (Blum 1974b).

Heat and Desiccation Tolerance

When plants can no longer maintain turgor through combinations of mechanisms regulating water uptake and loss, cellular desiccation results. During the symposium "Sorghum in the Seventies," Sullivan (1972) described a simple method for the evaluation of heat and desiccation tolerance based on loss of membrane integrity of leaf tissue following stress under controlled conditions. Not only does the heat tolerance of leaf discs accurately predict whole-plant response to high temperatures, but heat tolerance has been positively correlated with yield when crops are exposed to heat and drought stress (Sullivan and Ross 1979). Taken as a whole, this body of work represents one of the few examples where results from a basic laboratory test have been extended to field situations with positive results. It seems appropriate to review current progress related to heat and desiccation tolerance tests.

Genotypic variability exists within sorghums for both heat and desiccation tolerance (Sullivan and Blum 1970; Sullivan 1972; Blum and Ebercon 1976; Sullivan et al. 1977; Sullivan and Ross 1979), but parallel cultivar rankings between the two tests are often not obtained (Sullivan and Ross 1979). Both heat and desiccation tolerances change with stage of plant development and with environment as shown in Figure 6. Therefore, the appropriate time to evaluate genotypes from field nurseries should reflect normal patterns of stress occurrence. The 1980 season at Temple, TX provided a near-ideal test situation because of a long midseason drought. Since water deficits rarely develop early in the season, cultivars were sampled near anthesis when differences in drought response were visible. Results from a test involving 136 lines from the sorghum conver-

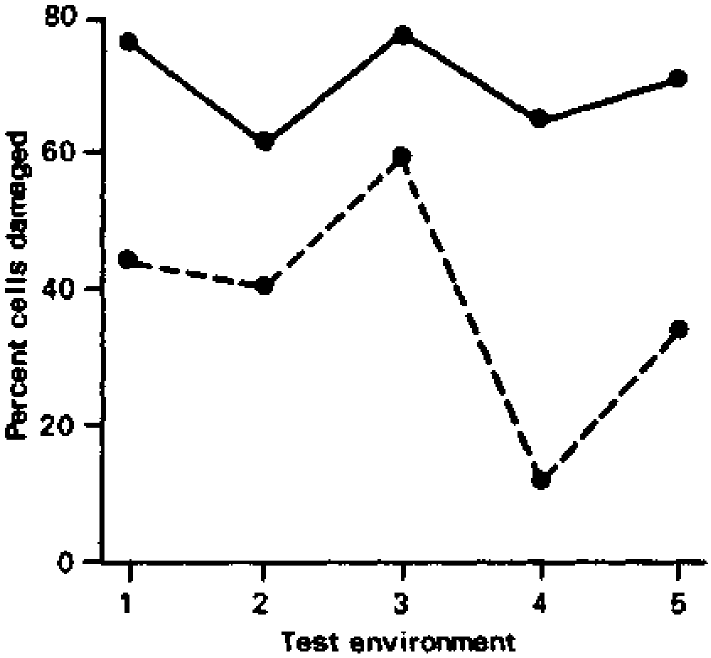

Figure 6. Mean heat {—) or desiccation (——) tolerance of 49 sorghum genotypes grown in five environments in 1980. Evaluations were made at one time when half the genotypes had reached anthesis. Environments: 1 = Temple, Texas (USA), dryland, 1980; 2 = Big Spring, Texas, 1980; 3 = Lubbock, Texas, irrigated, 1980; 4 = Lubbock, Texas, dryland, 1980; 5 = Temple, Texas, dryland, 1981.

sion program are illustrated in Figure 7. The heat tolerances of several lines, were significantly greater than those of the two standard lines, RTx430 and BTx378 (61 and 64% damage, respectively). These results provide further evidence that parental lines with high heat tolerance can be identified for incorporation into breeding programs. Similar conclusions resulted from evaluation of desiccation tolerance of these same lines, but heat and desiccation tolerances of genotypes were not significantly correlated.

Results from a second test, also conducted in 1980, illustrate the feasibility of genetic manipulation based on these tests. The response of 30 F, hybrids to a stress induced by a Carbowax 3000

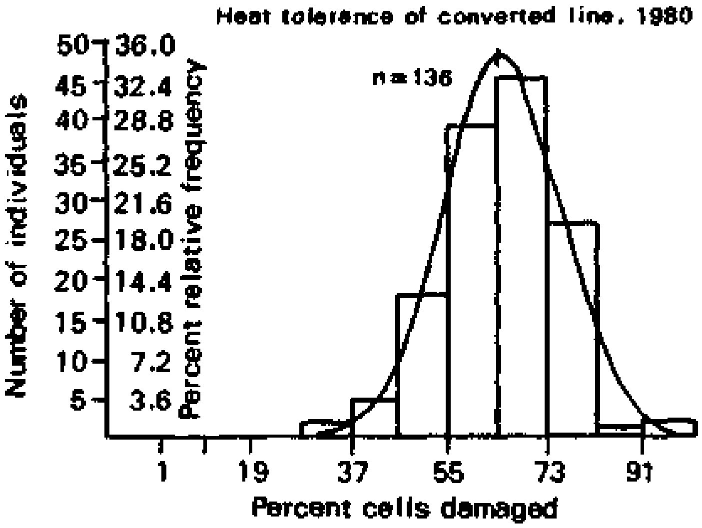

Figure 7. Frequency distribution of heat tolerance for 136 diverse sorghum lines grown at Temple, Texas (USA), in 1980.

solution with a water potential of -33 bars is illustrated in Table 1 (Jordan and Monk 1980). Of the females tested, 'A35-6' promoted greatest desiccation tolerance, while hybrids with 'ATAM618' were most susceptible. Among the pollinators, 'GPR148' promoted greatest desiccation tolerance, while '1790E' and Tx7000' hybrids were most susceptible.

Since the parental lines used in the hybrid test were not selected solely on known differences in heat or desiccation tolerance, the relatively small range in cellular damage (Table 1) is not unexpected. The relatively consistent performance of some parents in hybrid combination suggest selection for high or low heat or desiccation tolerance is an attainable goal in a breeding program. However, neither of these tests appear to be in general use in major breeding programs today.

Photosynthesis

Water stress reduces the photosynthetic capacity of a crop in many ways ranging from inhibition of leaf area development to reduced photochemical and biochemical activities of chloroplasts (Boyer 1976). Parallel reductions in net photosynthesis and stomatal conductance are well documented consequences of plant water deficits. Since drought stress is frequently accompanied by high temperatures, substantial heat stress may develop as transpiration rates fall and leaf temperatures rise (Gates 1968; Peacock 1982).

Data of Norcio (1976), cited in Sullivan et al. (1977), suggests that substantial variability in the

Table 1. Desiccation tolerance of 30 F, sorghum hybrids grown at Temple, Texas in 1980. Hybrids are ranked from low (1) to high (6) tolerance within each column. Mean cellular damage (X) for hybrids with each male and female are given at the side and bottom of the table. All evaluations were made near anthesis (Jordan and Monk 1980).

Male parent	Female parent					
	A35-6	A4R	ATAM618	ATx623	ATx5405	X, %
1790E	1	1	1	2	3	50.4
Tx430	4	2	5	5	1	45.0
SC0170-6-17	5	5	4	4	4	40.7
Tx7078	3	3	3	3	5	43.9
Tx7000	2	4	2	1	2	48.9
GPR148	6	6	6	6	6	34.1
X, %	39.6	42.7	51.1	44.0	41.8	43.8

temperature optimum for photosynthesis may exist among sorghum genotypes. Maximum photosynthetic rates for 'RS 626' were observed near 35°C, while the maximum for 'NB9040' occurred near 42°C. The extinction temperature for both genotypes was near 45°C. Further tests demonstrated a positive correlation between the ability to maintain photosynthesis at high temperatures and cellular heat tolerance determined by the leaf-disc method (see preceding section). Since yield in a high-stress year was highly correlated with cellular heat tolerance for these same genotypes, a causal relation between heat tolerance of the photosynthetic process and yield is suggested.

Visual Reactions to Drought

Only recently have sorghum breeders reported attempts to quantify and determine the genetic mechanisms underlying visible symptoms of drought stress. In the Texas sorghum breeding program, cultivars are ranked and selection made on the basis of leaf rolling, excessive leaf erectness, leaf bleaching, leaf tip and margin burn, delayed anthesis and head blast (Clark et a!.. 1979; Woodfin et al. 1979). The presence of these symptoms is considered an undesirable drought response. Evaluations before anthesis and again during late grain filling has provided a means to separate genotypes based on "early" or "late" drought reaction. Cultivar differences have been observed for early or late drought tolerance, but, thus far, no genotypes have been found with high tolerance at both growth stages. It is significant that visible stress symptoms were not correlated with heat nor desiccation tolerance evaluations in 1980 involving 49 genotypes in four environments. There also appears to be some question as to whether all symptoms currently included in the visible stress rating should be considered as undesirable. Leaf rolling, for example, does reduce canopy photosynthesis, but reduced interception of radiation may be more important in terms of avoidance of heat and desiccation stresses (Begg 1980).

Because of their relatively short existence, the success of breeding programs based on selection for visible drought symptoms cannot be evaluated. Visual screening does, however, overcome the limitations inherent in screening for physiological characters and may provide near-term opportunities for crop improvement.

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References

ACKERSON, R. C, KRIEG, D. R., and SUNG, F. J. M. 1980. Leaf conductance and osmoregulation of field-grown sorghum genotypes. Crop Science 20:10 -14.

ARKIN, G. F., VANDERLIP, R. L, and RITCHIE, J. T. 1976. A dynamic grain sorghum growth model. Transactions of the American Society of Agricultural Engineers 19: 622 -630

AYYANGAR, G. N. R., RAO, V. P., NAMBIAR, A. K., and PONNAIYA, B. W. X. 1937. The occurrence and inheritance of waxy bloom on sorghum. Pages 4-15, Volume 5B, *in* Proceedings of the Indian Academy of Science.

AYYANGAR. G. N. R . and PONNAIYA, B. W. X 1941. The occurrence and inheritance of a bloomless sorghum Current Science 10:408-409

BEGG. J. E. 1980 Morphological adaptations of leaves to water stress. Pages 33-42 *in* Adaptation of plants to water and high temperatures stress, eds. N. C. Turner and P. J Kramer. New York. USA: Wiley-Interscience

BHAN, S., SINGH, H G., and SINGH, A. 1973. Note on root development as an index of drought resistance in sorghum *[Sorghum bicolord)* Moench) Indian Journal of Agricultural Science 43:828-830.

BLUM, A. 1970. Effect of plant density and growth duration on grain sorghum yield under limited water supply. Agronomy Journal 62:333-336.

BLUM, A. 1974a. Genotypic responses in sorghum to drought stress. I. Response to soil moisture stress. Crop Science 14:361-364.

BLUM, A. 1974b. Genotypic responses in sorghum to drought stress. II. Leaf tissue water relations. Crop Science 14:691-692.

BLUM. A., and EBERCON, A. 1976. Genotypic responses in sorghum to drought stress. III. Free proline accumulation and drought resistance. Crop Science 16:428 -431.

BLUM, A., ARKIN, G. F., and JORDAN, W. R. 1977a. Sorghum root morphogenesis and growth. I. Effect of maturity genes. Crop Science 17:149-153.

BLUM. A., JORDAN. W. R., and ARKIN, G. F. 1977b. Sorghum root morphogenesis and growth. II. Manifestation of heterosis. Crop Science 17:153-157.

BLUM, A. 1979, Genetic improvement of drought resistance in crop plants: A case for sorghum. Pages 429-445 *in* Stress physiology in crop plants, eds. H. Mussell and R. C. Staples. New York, USA: Wiley-Interscience.

BOWER, J. T. 1972. A comparison of root systems of two isogenic height lines of hybrid grain sorghum. M. S. Thesis, University of Nebraska, Lincoln, Nebraska, USA.

BOYER. J. S. 1976. Water deficits and photosynthesis. Pages 153-190. Volume IV, *in* Water deficits and plant growth, ed. T. T. Kozlowski. New York, USA: Academic Press.

BOYER, J. S., and MCPHERSON. H. G. 1975. Physiology of water deficits in cereal crops. Advances in Agronomy 27:1-23.

CHATTERTON, J. N., HANNA, W. W.. POWELL, J. B., and LEE, D. R. 1975 Photosynthesis and transpiration of bloom and bloomless sorghum. Canadian Journal of Plant Science 55:641-643.

CLARK, L. E., ROSENOW. D. T„ and HAMBURGER, A. J. 1979. Screening for stress tolerance in sorghum. Page 52 *in* Proceedings of the 11th Biennial Grain Sorghum Research and Utility Conference, Grain Sorghum Producers Association, Wichita, Kansas, USA.

EBERCON, A., BLUM, A., and JORDAN, W. R. 1977. A rapid colorimetric method for epicuticular wax content of sorghum leaves. Crop Science 17:179-180.

GARRITY, D. P. 1980. Moisture deficits and grain sorghum performance. Ph.D. Dissertation, University of Nebraska, Lincoln, Nebraska, USA.

GARRITY, D. P., WATTS, D. G., SULLIVAN. C. Y., and GILLEY, J. R. 1981. (Submitted for publication) Moisture deficits and grain sorghum performance: crop evapotranspiration relationships. Agronomy Journal.

GATES, D. M. 1968. Transpiration and leaf temperatures. Annual Review of Plant Physiology 19:211-238

GERARD, C. J., BORDOVSKY, D. G., and CLARK, L. E. 1980. Water management studies in the Rolling Plains. Texas, Agricultural Experiment Station, Bulletin Number 1321.

HANKS, R. J., GARDNER. H. R„ and FLORIAN, R. L. 1969. Plant growth-evapotranspiration relations for several crops in the central Great Plains. Agronomy Journal 61: 30-34

HANKS, R. J., KELLER, J., RASMUSSEN, V. P., and WILSON, G. D. 1976. Line source sprinkler for continuous variable irrigation—crop production studies. Soil Science Society of America Journal 40 : 426-429.

HENZELL, R. G , MCCREE, K. J., VAN BAVEL, C. H. M., and SCHERTZ. K. F. 1975. Method for screening sorghum genotypes for stomatal sensitivity to water deficits. Crop Science 15:516-518.

HSIAO. T. C, ACEVEDO, E., FERERES, E., and HENDERSON, D. W. 1976a. Water stress, growth, and osmotic adjustment. Philosophical Transactions of the Royal Society of London, B 273:479-500.

HSIAO, T. C, FERERES, E. ACEVEDO, E., and HENDERSON, D. W. 1976b. Water stress and dynamics of growth and yield of crop plant. Pages 281 -305 *in* Water and plant life: problems and modern approaches, eds. O. L. Lange, L. Kappen and E. D. Schulze. New York, USA: Springer-Verlag.

INUYAMA, S., MUSICK, J. T., and DUSEK, D. A. 1976. Effect of plant water deficits at various growth stages on growth, grain yield and leaf water potential of irrigated grain sorghum. Proceedings of the Crop Science Society of Japan 45 : 298-307.

JONES, M. M., and TURNER, N. C. 1978. Osmotic adjustment in leaves of sorghum in response to water deficits. Plant Physiology 61 :122-126.

JORDAN. W. R., MILLER, F. R., and MORRIS, D. E. 1979. Genetic variation in root and shoot growth of sorghum in hydroponics. Crop Science 19:468-472.

JORDAN, W. R., and MILLER, F. R. 1980. Genetic variability in sorghum root systems: Implications for drought tolerance. Pages 383-399 *in* Adaptation of plants to water and high temperature stress, eds. N. C. Turner and P. J. Kramer. New York, USA: Wiley-Interscience.

JORDAN, W. R„ and MONK, R. L. 1980. Enhancement of drought resistance of sorghum: progress and limitations. Pages 185-204 *in* Proceedings of the 35th Annual Corn and Sorghum Research Conference. Grain Sorghum Producers Association, Wichita, Kansas, USA.

JORDAN, W. R., MONK, R. L, MILLER, F. R., ROSENOW, D. T., and CLARK, L . E. 1981. (Submitted for publication). Environmental physiology of sorghum. I. Environmental and genetic control of epicuticular wax load. Crop Science.

MASS, S. J., and ARKIN, G. F, 1978. User's guide to SORGF: A dynamic grain sorghum model with feedback capacity. Research Center Program and Model Documentation Number 78-1. Texas Agricultural Experiment Station, Temple, Texas, USA.

MORGAN, J. M. 1980. Differences in adaptations to water stress within crop species. Pages 369-382 *in* Adaptation of plants to water and high temperature stress, eds. N. C. Turner and P. J. Kramer New York. USA: Wiley-Interscience.

NORCIO, N. V 1976 Effect of high temperature and water stress on photosynthesis and respiration rates of grain sorghum. Ph.D. Dissertation, University of Nebraska, Lincoln, Nebraska, USA.

NOUR, A. E. M., and WEIBEL, D. E. 1978. Evaluation of root characteristics in grain sorghum. Agronomy Journal 70:217-218.

PASSIOURA, J B. 1972. The effect of root geometry on the yield of wheat growing on stored water. Australian Journal of Agricultural Research 3:745-752.

PEACOCK, J. M. 1982 Responses and tolerance of sorghum to temperature stress. These Proceedings: ICRISAT

PETERSON, G. C, SUKSAYRETRUP, K, and WEIBEL, D E. 1979. Inheritance and interrelationships of bloomless and sparse-bloom mutants in sorghum Sorghum Newsletter 22:30

POWELL, P., WEIBEL, D., SOTOMAYER, A., and ALAMEDA, M. 1977. Increased susceptibility of bloomless sorghum to foliar fungal pathogens. Sorghum Newsletter 20 : 76 -77.

QUINBY, J. R. 1972. The genetic control of plant growth in sorghum. Pages 161-172 in Sorghum in seventies, eds. N. G. P. Rao and L. R. House, New Delhi, India: Oxford and IBH Publishing Co.

RICHARDS, R. A., and PASSIOURA, J. B. 1981a. Seminal root morphology and water use of wheat I. Environmental effects. Crop Science 21 .249-252.

RICHARDS, R. A., and PASSIOURA, J. B. 1981b. Seminal root morphology and water use of wheat. II. Genetic variation. Crop Science 21 .253-255

RITCHIE, J. T. 1974. Atmospheric and soil water influences on plant water balance. Agricultural Meteorology 14:183-198.

Ross, W. M. 1972. Effect of bloomless (blbl) on yield in Combine Kafir-60. Sorghum Newsletter 15:121.

STEPONKUS, P. L, CUTLER, J. M . and O' TOOLE, J. C. 1980. Adaptation to water stress in rice. Pages 401-418 *in* Adaptation of plants to water and high temperatures stress, eds N. C Turner and P. J Kramer. New York, USA: Wiley-Interscience.

SULLIVAN, C. Y., and BLUM. A. 1970. Drought and heat resistance of sorghum and corn. Pages 55-66 *in* Proceedings of the 25th Annual Corn and Sorghum Research Conference of the American Seed Trade Association, Wichita, Kansas, USA.

SULLIVAN, C. Y. 1972. Mechanisms of heat and drought resistance in grain sorghum and methods of measurement. Pages 247-263 *in* Sorghum in seventies, eds N G. P. Rao and L R. House. New Delhi, India: Oxford and IBH Publishing Co.

SULLIVAN, C. Y., NORCIO, N. V., and EASTIN, J. D. 1977. Plant responses to high temperatures. Pages 301 -307 *in* Genetic diversity in plants, eds. A. Muhammed, R. Askel and R. C. Von Borstel New York, USA: Plenum Publishing Corp.

SULLIVAN, C. Y„ and Ross, W. M. 1979. Selecting for drought and heat resistance in grain sorghum Pages 263-281 *in* Stress physiology in crop plants, eds. H. Mussell and R. C. Staples, New York, USA: Wiley-Interscience.

SULLIVAN, C Y., WATTS, D. G., GARRITY, D. P., and MAURER, R. E. 1980. Responses of sorghum and corn to limited irrigation. Pages 205-218 *in* Proceedings of the 35th Annual Corn and Sorghum Research Conference, Grain Sorghum Producers Association, Wichita, Kansas. USA.

TURNER, N. C, and JONES, M. M. 1980. Turgor maintenance by osmotic adjustment: A review and evaluation. Pages 87-103 *in* Adaptation of plants to water and high temperature stress, eds. N. C. Turner and P J. Kramer. New York, USA: Wiley-Interscience.

WEBSTER, 0. J.. 1977. Sorghum studies in Arizona. Sorghum Newsletter 20:81.

WEBSTER, O. J., and SCHMALZEL, C. 1979. Yield trials of isogenic lines, normal vs. bloomless. Sorghum Newsletter 22:24

WOODFIN. C. A.. ROSENOW, D. T., CLARK, L. E.. and JOHNSON, J. W. 1979. Differential response of sorghum cultivars to drought stress. Page 82 *in* Agronomy Abstracts.

WRIGHT, S. A. 1978. The effect of height genes and gibberellic acid on root and shoot development of *Sorghum bicolor(L)* Moench. M.S. Thesis, Texas A&M University, College Station, Texas, USA.

Response and Tolerance of Sorghum to Temperature Stress

J.M. Peacock*

Before attempting to address this subject it is important to define what is understood by temperature stress. It is a complex subject which has recently been reviewed in three books (Lyons et al. 1979; Levitt 1980; Turner and Kramer 1980) therefore definitions and details of the physiological and biochemical processes associated with temperature stress will not be given here. In brief, however, a quantitative definition of temperature stress in sorghum, as in any crop, is difficult to provide since it will depend on a number of factors which will include the duration of exposure of either high or low temperature, the activity or stage of growth of the exposed tissue and finally the thermal adaptation of the particular sorghum cultivar.

The productivity and adaptation of a sorghum crop will be most affected when temperature stress coincides with *critical* stages of growth so it is proposed to examine the effects of temperature stress on each critical stage of development (Wilson and Eastin 1982), starting with the newly sown seed, to the grain on the panicle at the hard dough stage. Consideration will be given to what is currently understood about the plants' response and adaptation to low and high temperatures, but more emphasis will be given to describing current screening techniques and how our present understanding of the problem can enable sorghum scientists to develop more efficient screening procedures for the future.

In addition, because it has been suggested that acclimation and adaptation should be examined within distinct geographical regions (House 1981 a), I propose to deal with high and low temperature stress separately.

At the outset it is important to establish two points: (1) the need to obtain a clearer picture of the temperature conditions of the sorghum-growing areas of the world and the probabilities of lethal and stress inducing temperatures occurring at any time during the growing season. An example of this is given by Rosenthal and Hammer (1979) but, as discussed by Sivakumar and Virmani (1982), this is an area where an increased research thrust is required in the future. (2) that to interpret the effects of temperature per se on plant growth in the field is often difficult because temperatures in the crop canopy vary both with time and space (Fig. 1).

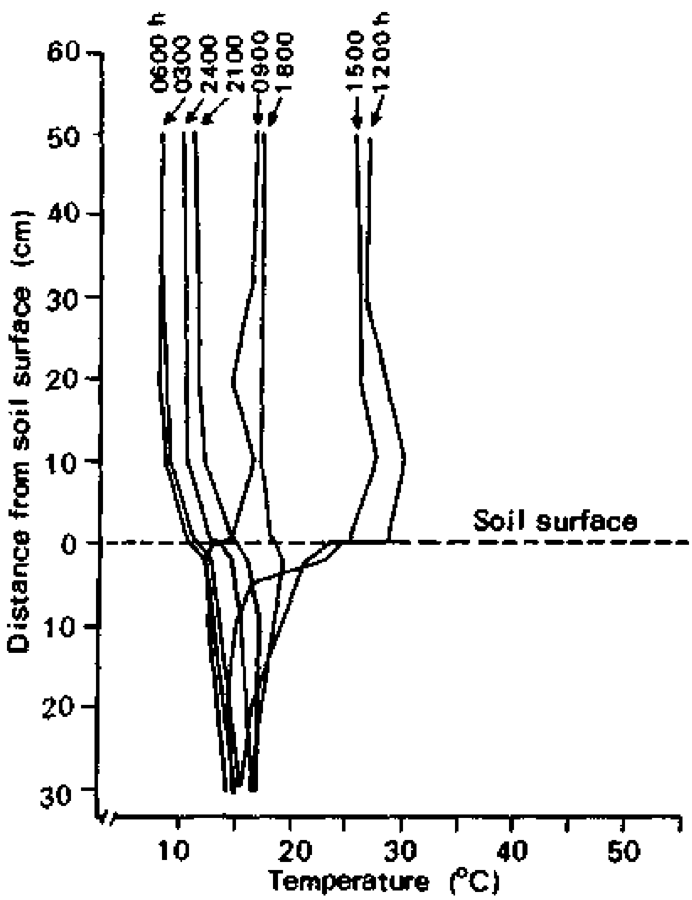

Figure 1. A series of soil and air temperature profiles measured during a 24-hr period (10 April 1976) in a sorghum crop cv 65 D, Sebele, Botswana.

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International Crops Research Institute for the Semi-Arid Tropics. 1982 Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru, A.P., India Patancheru. AP India: ICRISAT

High Temperature (Heat Stress)

Introduction

Heat stress is a major factor influencing the productivity and adaptation of many wild and cultivated plants and many crop species of tropical and subtropical origin are sensitive to high temperatures in the range 30 - 55°C.

In the semi-arid tropics where sorghum is grown, air temperatures often exceed 40°C and leaf temperatures of 55°C have been measured. At the soil surface even higher temperatures (>60°C) can be experienced by the emerging sorghum plumule (Peacock and Ntshole 1976) and temperatures as high as 68°C have been recorded (Peacock 1977). Under such conditions heat stress is often accompanied by drought stress and there are usually interactions within the plant to these two stresses (Sullivan et al. 1977). Despite this, it is argued (Sullivan and Ross 1979) that for plant breeding purposes it is desirable to measure and select for them separately. This has been done in Nebraska and currently is a major research area at ICRISAT (ICRISAT 1981). In addition, a number of scientists have used response to heat stress to select for drought resistance (Hunter et al. 1936; Heyne and Laude 1940; Heyne and Brunson 1940; Kaloyereas 1958; Kilen and Andrew 1969). Also heat stress is easier to induce experimentally than water stress.

It is for these reasons that in sorghum research at ICRISAT more emphasis is being placed on utilizing temperature stress as a means of selection for both heat and drought tolerance. Already it has been shown that there is sufficient variability to select for sorghum genotypes with high temperature tolerance (Sullivan and Blum 1970; Wilson et al. 1982).

High Temperature Effects on Processes and Growth Stages

Germination and Establishment

The ability of a sorghum seedling to emerge and establish rapidly is a vital prerequisite to the adoption of any new cultivar. However this has been largely ignored by crop improvement programs throughout the world. Although many promising sorghum cultivars may have resistance across geographic regions to local pests and diseases, what is their use if under farm or experimental conditions they fail to emerge and establish?

Martin et al. (1935) stated that sorghums are of tropical origin and have long been known to germinate and grow best at relatively high temperatures. The optimum soil temperature in Martin's experiment was between 30°C and 35°C but a review of the literature (Table 1) 46 years after that experiment was conducted shows that optimum germination can occur at soil temperatures ranging from 21°-35°C (Martin et al. 1935; Rosbaco 1958; Stoffer and Van Riper 1963; Bajay and Papp 1969; Kanemasu et al. 1975; Aisien and Ghosh 1978). It would also appear that the supposedly lethal temperature for germination ranges from 40°-48°C (Knapp 1966; Singh and Dhaliwal 1972; Kailasanathan et al. 1976). These two ranges in temperature suggest that there is genetic variation, not only in the optimum temperature for germination but in the temperature at which coleoptiles can survive.

Recent studies at ICRISAT (Wilson et al. 1982) have confirmed that there is genetic variation in the ability of sorghum to emerge at high soil temperatures and the results of this series of experiments will be discussed in the later section on selection for heat tolerance.

Leaf Area Development, Stem Growth, and Tillering

In sorghum, as in any crop plant, the rate of dry

Table 1. Summary of data on optimum and lathal germination temperatures in sorghum.

		Reference
Optimum temperature	30-•35	Martin et al, 1935
	30-•35	Rosbaco, 1958
	21	Stickler et al, 1962
	22	Bajay and Papp, 1969
	26	Pavlov, 1969
	23	Kanemasu et al, 1975
	22	Aisien and Ghosh, 1978
	22- 25	Kusewa, 1978
Lethal temperature	> 40	Singh and Dhaliwal, 1972
	40	Kailasanathan et al, 1976
	47	Kusewa, 1978
	48	Knapp, 1966

matter production is strongly affected by leaf area especially during GS1 when the canopy is developing (McCree and Davis 1974). The components affecting leaf area development include the time to panicle initiation, (through its influence on leaf number) the rates of leaf appearance, leaf expansion and leaf senescence, and the combined effects of canopy structure. In the Poaceae, in the absence of water and nutrient stress, these developmental rates have been shown to be largely governed by temperature (Watts 1974, for maize; Peacock 1975a, b, and 1976a, for temperate grasses; and Gallagher 1979, for temperate cereals). In sorghum, few quantitative data are available (Troughton et al. 1974; McCree and Davis 1974; Johnson 1967) about the effects of temperature on leaf area development although Johnson's (1967) data suggest that leaf extension closely parallels air temperature particularly at night. More recent data of Baker (1981 unpublished) show that final leaf number and leaf area were increased when temperatures were varied from 25°/20°C to 35°/25°C.

The effect of temperature on the rate of leaf appearance has been examined by Downes (1968) who showed that in sorghum, leaf appearance increased linearly with air temperature from 13° to 23°C.

Genetic variation in leaf growth in relation to temperature has been shown to be large (Quinby et al. 1973; Wade et al. unpublished). Some data from ICRISAT on the effects of temperature on leaf extension are shown in Figure 2. The continuous line represents the best fit of the data and it can be seen that the rate of leaf extension is markedly reduced above temperatures of 34°C. The dotted line, fitted by eye suggests that the base temperature (T_0) for leaf extension is around 15.5°C. In most field situations however, water stress, which usually accompanies high temperatures, will have had an earlier and more drastic effect on the rate of leaf extension.

Tillering will also affect the final leaf area and although it is affected by many environmental variables. Downes (1968) showed that the rate of tiller production in the cv Combine Kafir ceased if the average daily mean temperature exceeded a threshold value of about 18°C. However Escalada and Plucknett (1975) show that there is a considerable interaction between temperature and photoperiod; when temperatures were increased (from 23.9°/15.5°C to 32.2°/23.9°C) with a simultaneous increase in daylength (10-14h) increases in tiller number per plant resulted.

There is clearly a dearth of information on the effects of temperature on leaf area development and almost none on the effects of high temperature. Studies were initiated at ICRISAT in 1980 to examine the effects of temperature on leaf area development over a wide range of temperatures

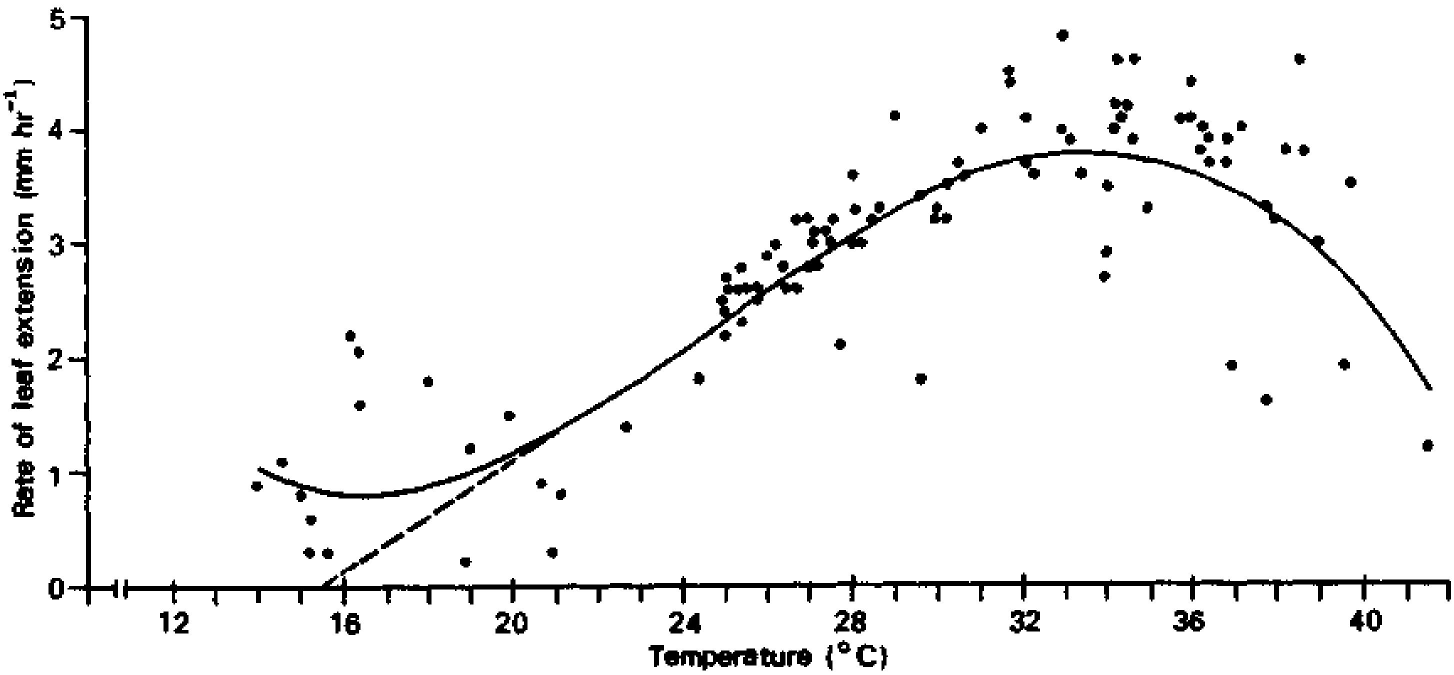

Figure 2. Relationship between leaf extension and temperature in sorghum cv CSH 8 (adapted from Wade et al. unpublished).

with emphasis on the summer season where the effects of high temperature in the absence of water and nutrient stress are being examined. Of particular interest is the effect of high temperature per se not on cell expansion, division or the resultant growth, but on cell and leaf tissue survival. (See later section on selection for heat tolerance.)

In my opinion, studies on the relationships between (high) temperature and the rates of leaf extension, appearance and senescence and the interactions with water and nutrient stress are vital both in the areas of improved crop establishment and drought resistance. This should be marked as an area for a major research thrust in the 80s.

Root Growth and Nutrient Uptake

There appears to be a complete dearth of information on the effects of high temperature on root development and nutrient uptake in sorghum. This is an important area and should perhaps be examined in the 80s.

Panicle Initiation and Development—The Components of Yield

The onset of the reproductive phase commences with the initiation of the panicle meristem marking the end of the vegetative growth phase. This usually occurs between 30 and 40 days after emergence but the timing which may vary from 19 to 70 days (House 1981 b) is largely controlled by photoperiod and temperature (Caddel and Weibel 1971; Downes 1972; Quinby et al. 1973). How temperature affects floral initiation is still not clear. Recent work by Baker (1981 unpublished) shows that increasing day/night temperatures from 25720° to 35°/25°C hastened floral initiation. However earlier work by Downes (1972) and Quinby et al. (1973) indicated that higher temperatures (day/night 32°/28° and 32729°C) delayed initiation. It is possible that the higher night temperatures are delaying initiation. The length of the reproductive phase (GS3) is also markedly reduced by temperature (Baker 1981 unpublished) and day temperatures were shown by Caddel and Weibel (1971) to be most important. There is no information about very high (45°-55°C) temperatures on either the onset or the length of the floral period.

Some information is available though on the effects of high temperature on floret development. Downes (1972) and Baker (1981 unpublished) showed that high temperature (day/night 33°/28° and 35°/28°C) late in panicle development induced floret abortion, a result which was, in general, consistent with the findings of Pasternak and Wilson (1969) using artificially produced heat waves (5 days at 42°/32°C. day/night) at the boot stage. However they showed that there was no floret damage if the panicle was fully emerged. In a study using 6 sorghum cultivars grown in 14 different environments, it was found that tolerance to high temperatures contributed more to yied stability than did tolerance of low moisture conditions. Specifically, where high temperatures occurred during panicle development, the capacity of a genotype to produce greater seed numbers per head (and hence greater yield) was important (Heinrich 1981).

It is now well documented that heat hardening occurs when plants are exposed to subinjurious high temperatures (Sullivan and Kinbacher 1967; Coffman 1957; Levitt 1980); however, as concluded from the above results the ability of genotypes to heat harden, varies. Some genotypes may fail to harden appreciably, while others harden very noticeably. Table 2 shows the heat tolerance of four sorghum lines before and after heat hardening in growth chambers at about 3 weeks of age. The relative ranking of heat tolerance changed when they were exposed to high temperatures. In this experiment (Sullivan et al. 1977), sorghum CK-60 did not heat-harden to the same extent as the others, and its relative tolerance was lower than the other sorghums after the high temperature treatment. However it was found that as the plants aged and neared the boot and bloom stage in the field, only the yellow

Table 2. Effect of heat hardening on the relative heat tolerance of four sorghum genotypes. *

Day/night .temperature (°C)	
31/27	42/27
CK60	9084
9084	RS610
RS610	C7078
C 7078	CK60

a. The sorghums are ranked from highest to lowest in heat tolerance (from Sullivan et al. 1977).

endosperm sorghum 9084 remained high in heat tolerance and that there were no evident differences in the heat tolerance of the remaining three. The effect of high temperatures at the time of panicle development may not be that critical but it is obviously an area which needs further research in an attempt to establish whether heat hardening carried out in the seedling stage can confer tolerance in the later stages.

The effects of temperature on the components of yield are well documented (Tateno and Ojima 1976; Eastin 1976; Chowdhury and Wardlaw 1978). Grain number per head itself was not significantly altered by temperatures over the range (day/night) 21°/16° to 36°/31°C and 30°/25° to 35°/25°C (Chowdhury and Wardlaw. 1978; Downes 1972; Baker 1981 unpublished); however, yields were markedly reduced at higher temperatures (30°/25°, 35°/25°C) due to a reduction in grain weight (Tateno and Ojima 1976; Baker 1981 unpublished). There is evidence that high temperatures during panicle development may reduce seed number per head, and yield, in some sorghum cultivars (Heinrich 1981; Ogunlela 1979).

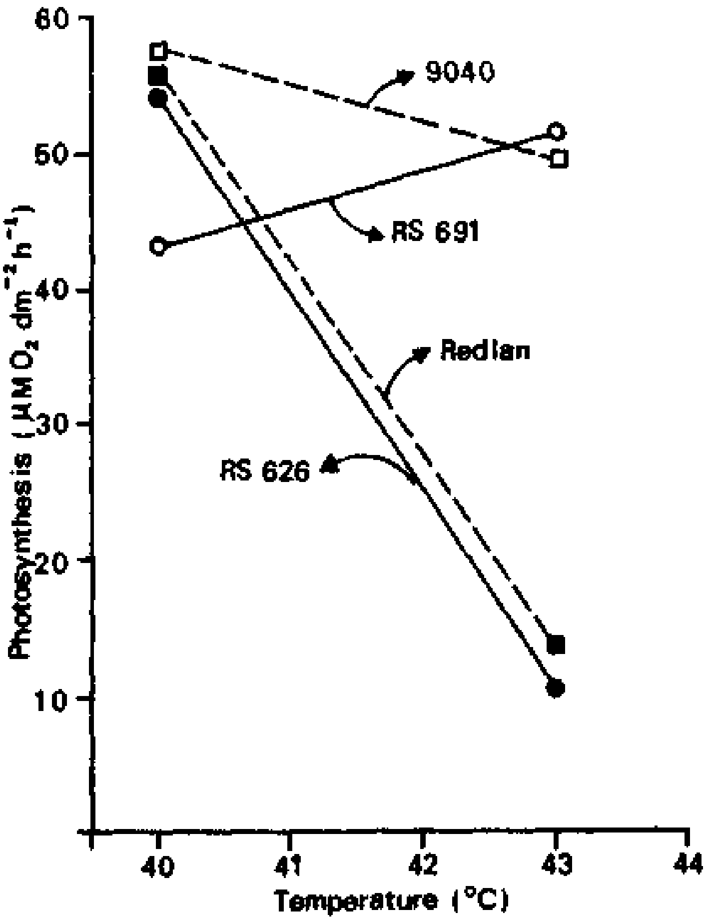

Figure 3. High temperature effects on photosynthesis of four sorghum cultivars (from Norcio 1976).

Photosynthesis and Respiration

Genetically based variation in photosynthetic capacity has always been of interest in crop plants. In C_4 species, like sorghum, high rates of photosynthesis occur only at high temperatures and at high light intensities. The optimum temperature has been shown to range from 30° to 42°C (Norcio 1976; Vong and Murata 1977). Sumayao et al. (1977) concluded however that photosynthetic rates declined when leaf temperatures exceeded 33°C. Chesnokov et al. (1974) found that photosynthesis was reduced by 70% at 44°C and 95% at 48°C. Genotype differences in the maintenance of photosynthesis at high temperatures (43°C) obviously occur (Norcio 1976). Figure 3 shows that the hybrid RS 691 and its male parent 9040 maintained high levels of photosynthesis compared with Redlan and RS 626. Norcio (1976) also found a positive correlation between high photosynthesis rates at high temperatures and cellular heat tolerance of sorghums determined by the "electro-conductivity" method (Sullivan 1972). However, selection for high photosynthetic rates per se in other crops has generally not been a productive approach to increasing yields. However when heat stress is involved, an ability to maintain relatively high rates of photosynthesis may very well contribute to yield. This should be examined further. The high correlation between heat tolerance and high photosynthesis as shown by Norcio (1976) is encouraging but it is unlikely that the measurement of photosynthesis per se will ever become a practical screening method.

That respiration rates in sorghum (like any crop) are influenced by temperature is well established (Norcio 1976; Vong and Murata 1977; McCree 1974; Eastin 1981). Wilson and Eastin (These Proceedings) have thoroughly reviewed this subject and concluded that there is a great deal of genetic variability in respiration response to temperature. Of particular interest is the recent work of Gerik (1979) and Mahalakshmi (1978); the former showing that whole plant dark respiration varied from 4 to 10 mg Co_2 g^{-1} hr' at 30°C. More recent work by Eastin (1981) shows that respiration in sorghum at panicle initiation increased 12-14% for every degree C over the range from 12°-27°C.

Selection Methods for Heat Tolerance

It has been established that genetic variation to

Table 3. Rank order off percent emergence for some genotypes of different surface treatments, showing (a) no interaction with temperature and (b) Interaction.

	Genotype serial number												
treatment	(a) 3	7	16	18	19	22	30	(b) 23	24	26	13	25
Bare soil	1	27	18	26	17	29	6	3	5	4	11	30
Light kaolin	4	25	18	27	16	30	1	5	8	14	15	23
Heavy kaolin	4	26	18	29	15	30	7	13	25	16	1	12

heat stress in sorghum exists. It is vital therefore that in the 80s breeders and physiologists concentrate on developing screening and breeding methods to generate heat tolerant material. It is equally important that the selection methods are simple, repeatable and inexpensive, and capable of screening a wide range of germplasm and breeders lines.

Improved Emergence and Establishment

A series of experiments were conducted, at ICRISAT, in the laboratory, glasshouse and field studying the emergence of a number of sorghum genotypes over a range of high temperatures. The work demonstrated that some lines have an ability to emerge even when soil surface temperatures were as high as 55°C. In the laboratory experiments, the temperature of the soil surface in pots was controlled using a band of heating elements positioned above a water bath (Soman 1981). The surface temperature could be varied between 35° and 65°C either by a thermostat or varying the height of the heat source above the soil. The significance of this technique is that the effect of heat stress can be examined in the absence of either water shortage or soil crusting. In the glasshouse similar experiments were conducted but different surface treatments were used to manipulate temperature. Charcoal dust (black) and kaolin (white) were used to modify surface temperatures (Wilson et al. 1982) with the bare soil surface (no surface cover) providing a medium treatment. In the field (in this case large brick chambers) (Wilson et al. 1982) the same surface covers were used to modify soil temperature independently of soil water and crusting. The results show that there is considerable genotypic variation and tolerance. Genotype x temperature interactions were also observed and this requires further investigation (Table 3).

The effect of temperature on the rate of plumule extension was also examined (Soman 1981, Fig. 4). It is argued that the quicker the plumule reaches the surface the more chance it has for emerging before a surface crust develops. The rates were shown to vary among genotypes (e.g., at 41°C the hybrid CSH 6, grew at a rate of less than 0.5 mm hr^{-1} while the variety SPV 354 grew at a rate of 1.3 mm hr').*

The development of the plumule in the soil is now being examined more closely. Visual observations indicate (Plate 1) that on reaching the surface (in many instances where there is no crust) the plumule bends over. In some instances the leaves curled around themselves and could not emerge. In collaboration with the production economists at ICRISAT, a survey into the specific problems relating to crop establishment in farmer's fields has been initiated together with on-farm experiments. The problems of crop establishment in sorghum cannot be overemphasized. Along with drought it is the major limiting factor to sorghum production in the SAT (Peacock 1980). Temperature clearly plays an important role and I regard this as one of the key areas for research in the 80s.

* It is worth noting that throughout this series of experiments on factors affecting crop establishment (temperature, water and crusting effects) the Indian varieties performed significantly better than the hybrids CSH 1, CSH 5, CSH 6. Only CSH 8 appeared to have the tolerance of the varieties (Soman 1981). This is perhaps important because numerous reports have been received this year about poor crop establishment of CSH 5 in farmers' fields in Central India and until now the dominance of sorghum hybrids in nonstress, and to some extent in stress conditions has gone unchallenged.

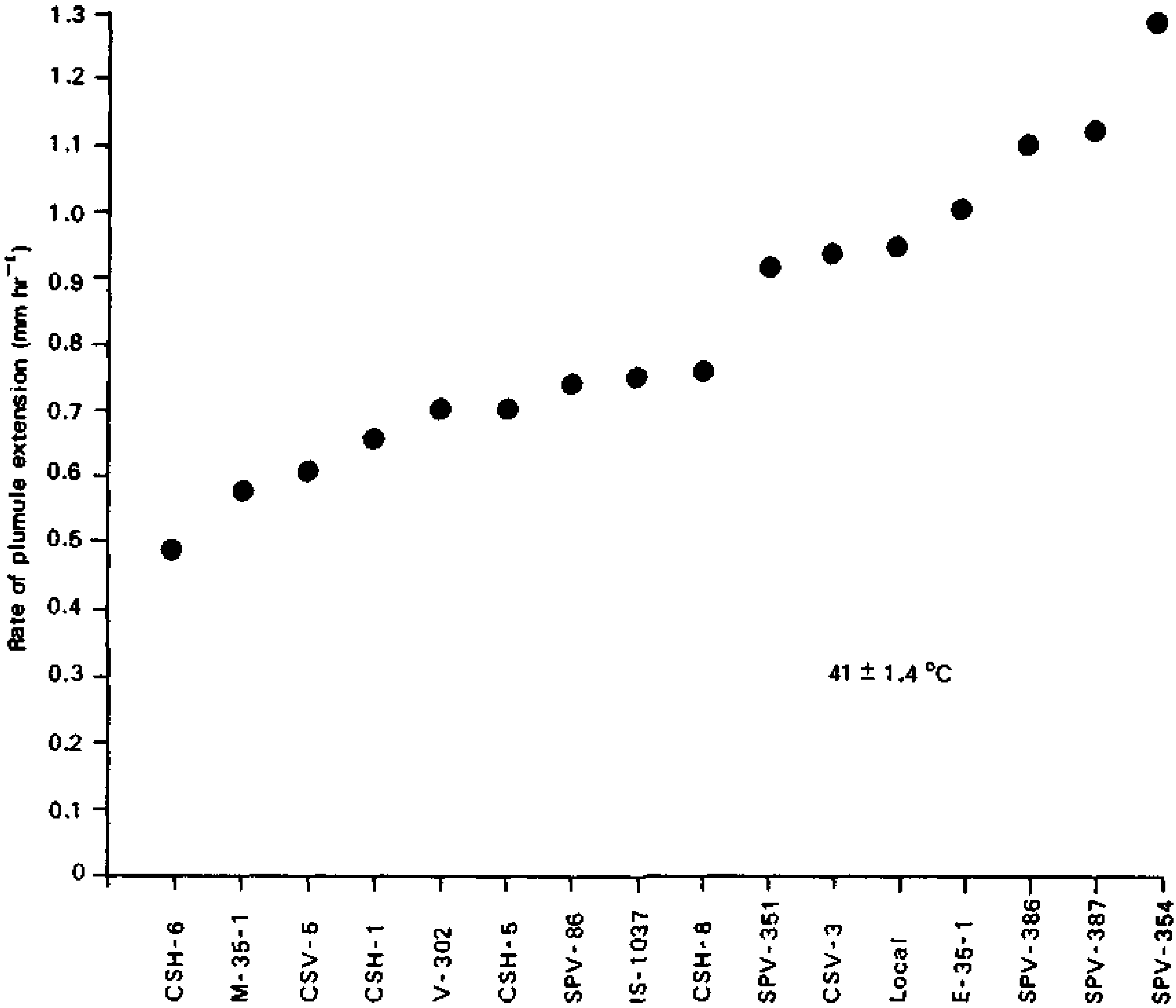

Figure 4. Genotypic differences in the effect of temperature on the rate of plumule extension in a range of sorghum cultivars (adapted from Soman 1981).

Leaf Tissue Survival

Earlier work (Sullivan and Blum 1970; Sullivan 1972; Blum and Ebercon 1976; Sullivan and Ross 1979) has shown that genetic variability for both heat and desiccation tolerance exists in sorghum. The inability to survive high temperature may give rise to the phenomena known as "leaf firing" (Sullivan et al. 1977; Peacock 1979; Jordan and Monk 1980). Research in Botswana (Peacock 1979) showed that leaf firing occurred in the hybrid RS 610 at a leaf temperature of 43°C. This relatively low leaf temperature suggests that it would be advantageous to select lines having a high critical leaf temperature or so-called heat tolerance.

At Nebraska the leaf disc method (which essentially estimates the electrolytic leakage from a leaf disc by measuring the electrical conductivity) has been extensively used to measure heat tolerance (Sullivan 1972). In addition Sullivan and Ross (1979) showed that in two populations (M35-1 conversion hybrids and NP9BR lines) heat tolerance was positively correlated with higher yields (Fig. 5).

At ICRISAT germplasm and breeders source material have been screened for heat and desiccation tolerance. Lines were sown at Sangareddy (26 km from ICRISAT Center) in April 1980 and established with irrigation. No further water was applied until the monsoon broke in early June. During the period air temperatures reached 43°C

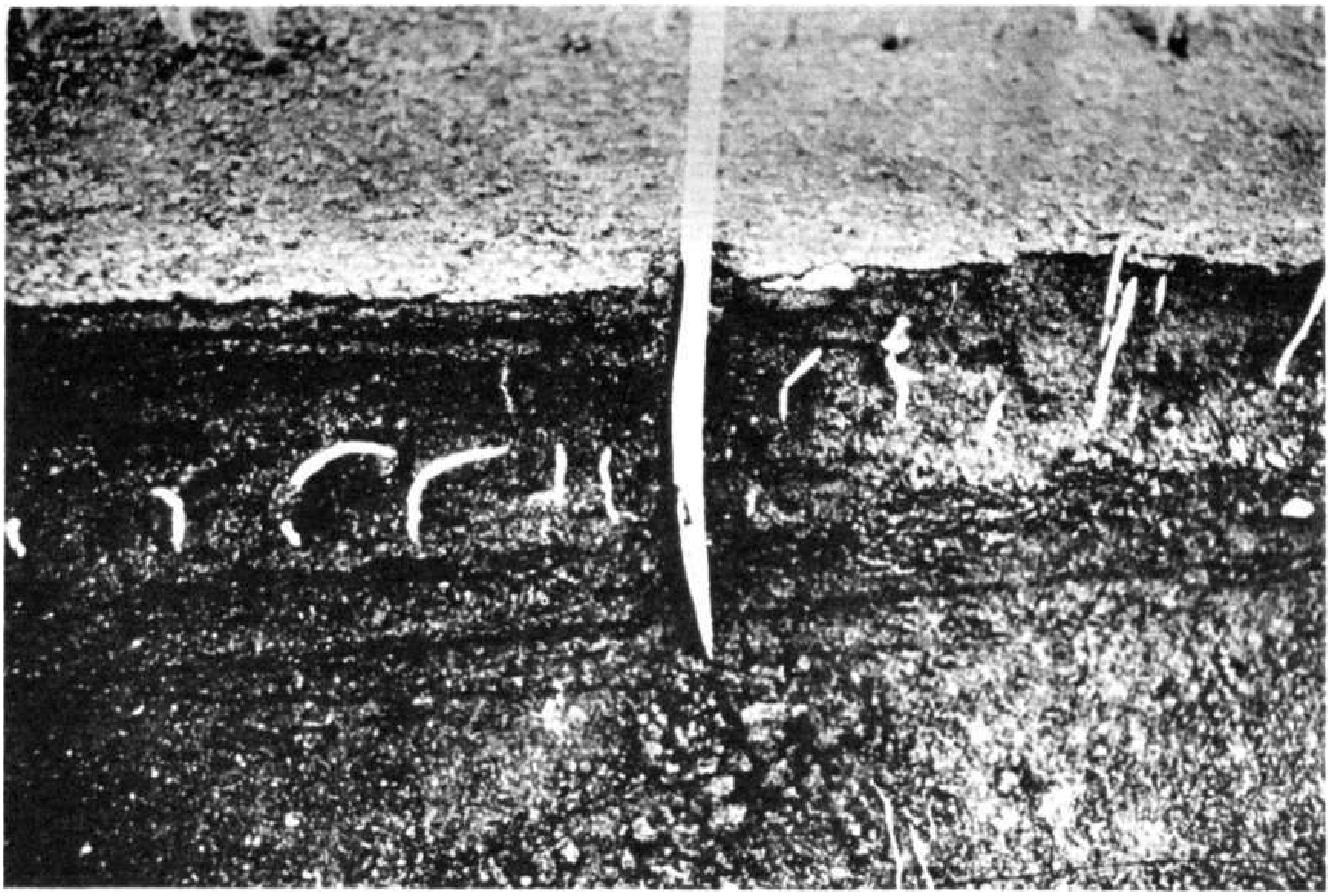

Plate 1. The effect of high soil surface temperature on plumule emergence in sorghum. Plumules ot the cultivar to the right of the steel blade are bent over and will not emerge; those of the cultivar to the left are unaffected.

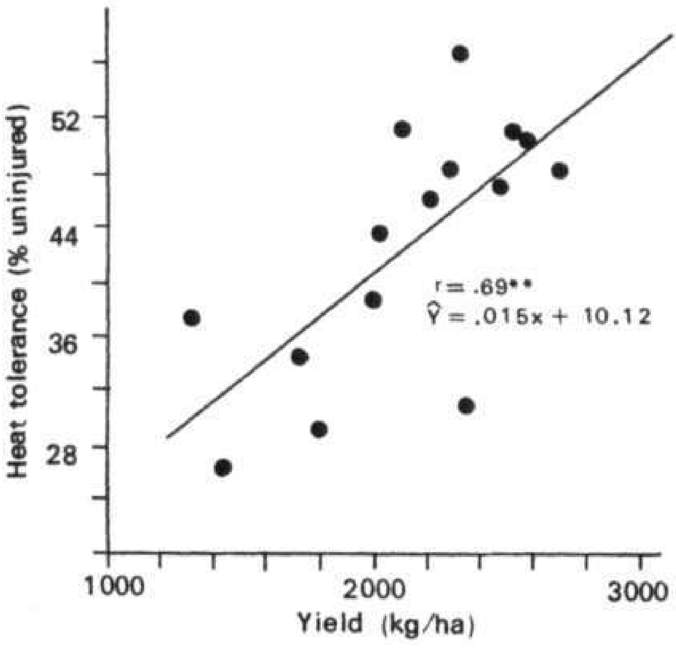

Figure 5 The relationship between heat tolerance and yield of. fifteen M35-1 conversion hybrids determined during a period of maximum stress in Nebraska (from Sullivan and Ross 1979).

and leaf temperature exceeded 55°C. Leaf desiccation (firing) occurred but the extent and variation did not become so apparent until 10 days or more after the rains had started. It was then obvious that some lines had been completely "fired", others partially fired, whilst some were unaffected. Despite having made the measurements of leaf temperature (which are many times easier to measure than either stomatal conductance or solute and water potentials) material was selected by visual scoring. Over a 1000 lines could be evaluated in a day. Good correspondence was also obtained when the same material was grown at Anantapur (India) and Gadambalia (Sudan) (Plate 2) under naturally occurring drought during the normal growing (rainy) season. It should be emphasized however that these were pilot experiments. Eventually the physiological basis of the visual scores should be known and this will be carried out on a limited number of susceptible and tolerant lines at a later stage.

Experiments conducted in 1981 using the line source irrigation technique (Hanks et al. 1976;

Plate 2. The effect of extreme heat and water stress on sorghum cultivars grown at Gadambalia, Sudan. The leaves of the cultivar in the row on the left are desiccated.

ICRISAT 1982) showed that two sister lines which had previously been shown to be desiccation susceptible (D71463). and desiccation tolerant (D71464), in the Sangareddy experiment were also drought susceptible and tolerant respectively. More recently at Temple, Texas (Jordan and Sullivan 1982) results from a screen involving 136 lines provide further evidence that parental lines with high heat tolerance can be identified and that breeding for tolerance is an attainable goal. As mentioned earlier it is known that under field conditions heat stress often accompanies drought stress and that plants with drought resistance also have higher heat resistance (Levitt 1980). Very early work (Hunter et al. 1936; Heyne and Laude 1940; Heyne and Brunson **1940)** classified drought resistance in maize seedlings based on resistance to high temperatures. Moreover they found that drought resistance at the seedling stage was highly correlated with that in **the** mature field plants grown in the hot dry summer, thus demonstrating a simple, inexpensive, but repeatable method for selecting for drought resistance.

Other techniques have been used to identify heat tolerance and in addition to the electrical conductivity method (Sullivan 1972), two laboratory techniques look promising, (a) the chlorophyll stability index (Kayloyereas 1958, as modified by Murty and Majumder 1962) and (b) the measurement of increased chlorophyll fluorescence (Smillie 1979a). In the latter, the temperature at which there is an increase in chlorophyll fluorescence yield can be correlated with the temperature of irreversible damage to the photosynthetic membranes.

All three methods may provide valuable screening tools to evaluate the inherent adaptability of sorghum lines to temperature extremes. However in the final analysis, if all these can be equated to a visual score (such as 'leaf firing') in the field, as described earlier, then it is the visual score approach that should be adopted in crop improvement programs. It is possible that the simple approach adopted by Heyne and his colleagues in the 1930s will provide the basis for our heat and drought screening techniques for sorghum in the 1980s.

Low Temperature (Chilling Stress)

Introduction

Many important crop species of tropical and subtropical origin are sensitive to low temperatures in the range of 20° down to about 0°C and suffer "chilling injury" when subjected to nonfreezing temperatures below about 10° to 15°C. The common symptoms of chilling injury include poor establishment, chlorosis of young seedlings, restricted growth and development and in the case of certain cereals, spikelet sterility and reduced grain yield. The extent and severity of chilling injury is a function of the temperature and duration of the chilling stress, the species and condition stage of plant development. As mentioned at the beginning of this paper, this is a subject which has recently been comprehensively reviewed (Lyons et al. 1979; Levitt 1980; Raper and Kramer 1981) and all three books should be referred to for details of the biochemical and physiological processes involved.

In sorghum a number of the relationships between temperature and growth have already been discussed in this paper so it is proposed to deal only with the specific effects of low temperature on sorghum and to cover those areas which will enable a crop improvement team to generate improved cold-tolerant lines from the sources of resistance identified. *Sorghum bicolor is* known to be particularly chilling sensitive (Bagnall 1979). However some grain sorghums are known to possess varying degrees of cold tolerance (Singh 1977) and a substantial amount of these have been grown in the highlands of Ethiopia. Uganda, Yemen Arab Republic and to a limited extent in the highlands of Kenya, Zaire, Cameroun and New Mexico. In some areas, for example Botswana, cold night temperatures are at present one of the major factors limiting sorghum production (Peacock and Ntshole 1976).

Low Temperature Effects on Processes and Growth Stages

Germination and Establishment

Large-scale screening of the germplasm at low temperature has not been carried out, but according to Quinby et al. (1958) the minimum temperature for germination is between 7.2°C and 10°C which is remarkably close to the range of 8° -10°C quoted by Pinthus and Rosenblum (1961). Both groups indicate that a higher temperature (15.6°C), was required for subsequent emergence. More recently Thomas and Miller (1979) have established that the minimum germination temperature may vary within species from 4.6°C to 16.5°C and the implication of these data are discussed further by Miller (1981). Singh and Dhaliwal (1972) obtained 55% emergence at 15°C reaching an optimum between 25° and 30°C. They obtained no emergence at all at 5° and 10°C. McWilliam et al. (1979) found that initial germination, seedling-respiration and mesocotyl extension in three sorghum species all declined as the temperature was reduced from 24° down to 8°C. The rate of decline, however, varied between species (S. *leiocladum, S. verticilliflourm, S. bicoloi).* especially in the lower part of the temperature range below about 12°C.Arrhenius plots of germination rate for two of the species, a commercial U.S. hybrid (S. *bicolor)* and a wild tropical species *(S. verticilliflorum)* are shown in Figure 6a. A characteristic of the responses is the sudden increase the Q_{10} values below a certain temperature range. In this case it was higher (14°- 16°C) for the more sensitive tropical species than for the commercial U.S. hybrid (11°-12°C). A similar response has been observed for the elongation of the mesocotyl of sorghum seedlings (Fig. 6b). McWilliam (1981) suggests that these high Q_{10} s below about 12°C indicate extremely high activation energies and may help explain the poor response at these temperatures. Genetic differences were also observed by Pinthus and Rosenblum (1961), and Stickler et al. (1962) found that Kaoliangs (sorghum originating in the mountainous regions of central and western China) germinated and emerged faster than standard grain sorghum varieties, particularly at low temperatures.

Sorghum seedlings are normally killed when temperatures drop below 0°C although some seedlings have been reported to withstand a slight frost (Martin 1941), Seed however will survive temperatures down to -12°C provided the seed moisture content is below 15% (Gritton and Atkins 1963; Rosenow et al. 1962; Bass and Stanwood 1978) However at higher moisture levels (30-35%) subsequent germination was markedly affected (Carlson and Atkins 1960; Rosenow et al. 1962; Kantor and Webster 1967).

Leaf Area Development, Stem Growth, and Tillering

There is a dearth of information on the effects of low temperature on leaf area development, stem growth, and tillering. Recent work by Major et al. (1981) in a controlled environment chamber showed that reductions in leaf number and plant height caused by chilling temperatures (13°C/8°C day/night) were only temporary but tiller number was increased from three to as many as eight per plant. Major's (1981) work however showed that exposure to-chilling temperatures (13°C/8°C day/night) did not affect grain growth, grain number per panicle or yield per panicle. The period of low temperature was in the dark and there is evidence that the growth of sorghum is much less sensitive to a period of low temperature given during the night period than under conditions of high irradiance during the day (Bagnall 1979). McWilliam

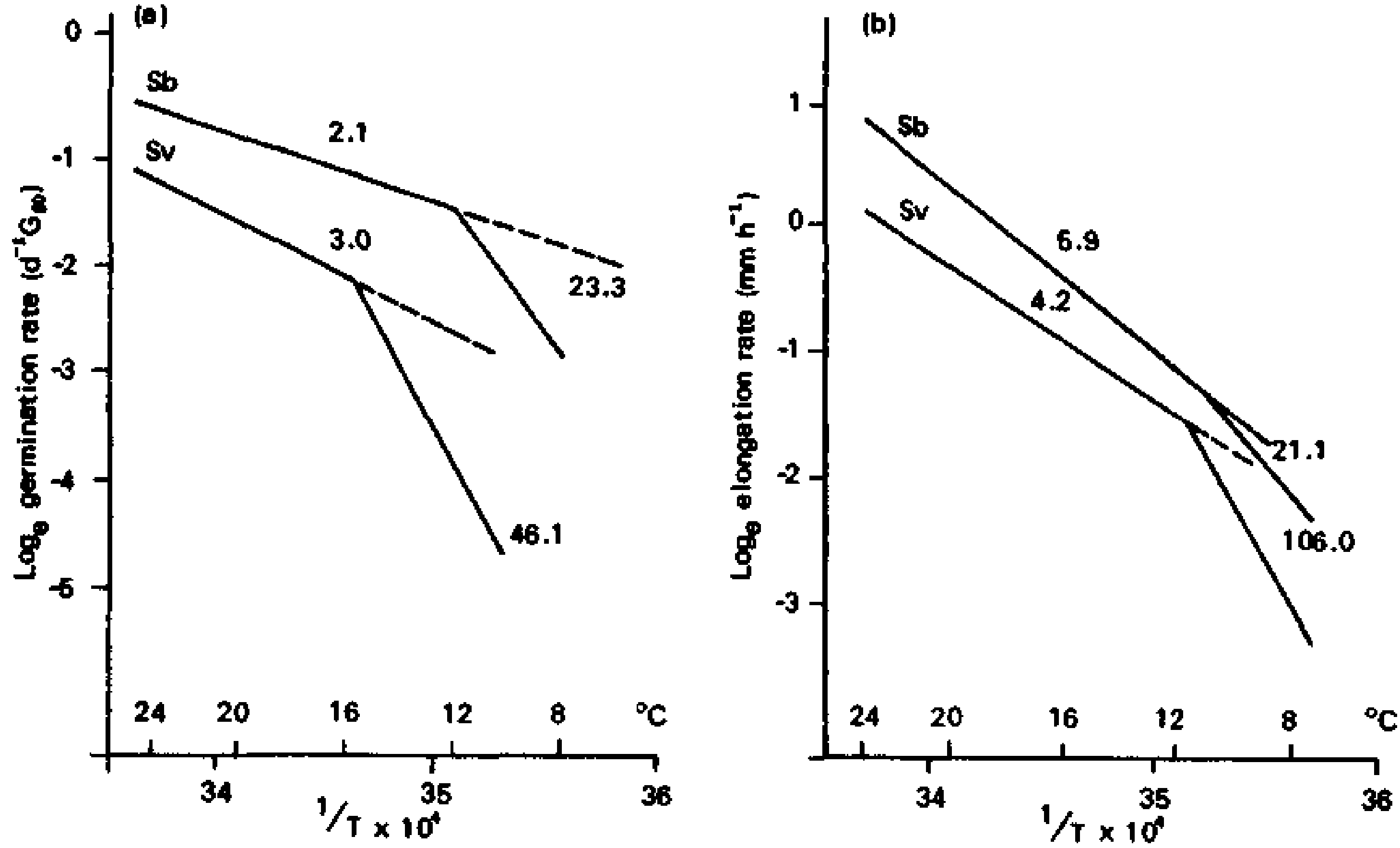

Figure 6. Arrhenius plots for (a) germination rate (reciprocal of days to 50% germination) and (b) mesocotyl elongation rate for two sorghum species (Sb.. S. bicolor, *commercial hybrid;* Sv. S. verticilliflorum, *tropical wild sorghum).* Q_{10} *values derived from regressions are indicated for each slope. (Adapted from McWilliam 1981.)*

(1981) claims that light accelerates and intensifies low temperature injury in chilling-sensitive tissue.

Another common symptom of chilling injury during early growth is chlorosis on the first formed leaves. Chlorophyll synthesis is severely depressed at low temperatures in many chilling sensitive species and Slack et al. (1974) observed irreversible chlorotic bands on sorghum leaves exposed to temperatures close to 0°C. Recent evidence (McWilliam et al. 1979) from electron micrographs of sorghum leaf tissue suggest that the failure to develop chlorophyll under these conditions is associated with the arrested development of the thylakoid membrane system of the developing plastids. Apart from this work, there is nothing to my knowledge and like the earlier work reported on leaf area development at high temperature it needs examining. Possible sites in countries of Eastern Africa, Mexico could be identified for detailed studies in the 1980s.

Root Growth and Nutrient Uptake

As with high temperature, there is apparently no information.

Panicle Initiation and Development—The Components of Yield

Unlike high temperature effects, there is apparently very little information on the effects of low temperature on panicle initiation and development, although Downes and Marshall (1971) demonstrated in glasshouse experiments that night temperatures of 13°C or less during meiosis can induce male sterility. Taylor (1973) speculated that poor grain sorghum yield in New Zealand may have been due to pollen sterility induced by low temperature. This was examined further by Brooking (1976) who was able to induce male sterility by exposure to low night temperatures. However, as yet, there is no unequivocal evidence for the occurrence of low temperature-induced pollen sterility in sorghum crops in New Zealand and further detailed field work is required to elucidate the potential importance of this type of sterility induction. Peacock (1977a) argued that the low yields of late planted sorghum in Botswana were almost certainly due to the low night temperature (4°-12°C) occurring during GS3. Indeed Eastin (1976) shows that with RS 610, night temperatures of 17°C (29°C/17°C) were too low to permit a high metabolic efficiency.

Photosynthesis

The effects of low temperature on photosynthesis have been examined (Pasternak and Wilson 1972; Bagnall 1979) and it is clear that photosynthetic rates drop rapidly on exposure to temperatures below 20°C. In addition to the direct effect on photosynthesis, the injury to the leaf incurred during chilling can affect the photosynthetic capacity of the leaf when returned to a higher temperature (McWilliam 1981). Considerable work has been carried out on the low temperature effects of photosynthetic reactions (Taylor et al. 1974; Slack et al. 1974). Bagnall (1979) showed that wild sorghum *S. leiocladum* had a higher photosynthetic rate over the range 3° to 20°C than *S. bicolor,* however it is unlikely that detailed measurements of leaf or canopy photosynthesis, as in the high temperature work, are going to provide practical screening methods.

Selection for Chilling Tolerance

In summary it is apparent that very little is known about sources of variation to chilling tolerance in sorghum. Variation however does exist (Bagnall 1979; Manokaran 1979) and therefore it is important that breeders and physiologists in the 1980s further develop practical strategies to generate improved cold tolerant material. Singh (1977)-in outlining a breeding program for cold tolerance at a Sorghum Workshop in Hyderabad indicated that any one of the followig reasons could be attributed to the failure of sorghum at low temperature: (i) poor or no germination, (ii) good germination and vegetative growth but no flowering, (iii) flowering, but no pollen and seed set, and (iv) partial or poor seed production. Clearly (i) and (ii) deal primarily with temperate zones where sowing occurs in a cold spring but there are warm summer temperatures at flowering, (iii) and (iv) are likely to be associated with the high elevation tropics where it can be cold at the time of flowering and where night temperatures are steadily dropping as the crop approaches physiological maturity. Both are important but there may be little correlation between the two types of material.

To identify and generate such material, screening methods have to be improved and adopted and a recent review (Paull et al. 1979) titled "Chilling injury assays for plant breeding" lists a number of rapid screening techniques to assist in selecting for greater chilling tolerance. Two methods appear promising. First, fluorescence monitoring of intact leaves has been used to screen a number of higher plants with positive results (Murata and Fork 1975; Melcarek and Brown 1977) and the technique can be adapted to measure detached leaf segments (Smillie 1979b). Second, leakage of cell contents has been successfully used to assay chilling injury (Creencia and Bramlage 1971; Patterson et al. 1976).

It is interesting to note that in screening for heat tolerance both the fluorescence method and the electrical conductivity method have been successfully used with sorghum and therefore attempts should now be made (if not already done so) to use the two methods for screening for chilling tolerance in sorghum.

In addition, inheritance studies (Paull et al. 1979) indicate that variation for chilling sensitivity within species is largely additive and under polygenic control. Increased chilling tolerance has been achieved by selection in com (Mock and Bakri 1976) and in tropical varieties of rice (IRRI 1978).

The transfer of genes for cold tolerance from wild species adapted to high altitudes in the tropics is being attempted with sorghum (van Arkel 1977) and Guiragossian, V. (personal communication) has made excellent progress in selecting for early flowering and good seed set in high altitude sorghums in Mexico.

This is obviously an important area and like the research on heat tolerance should be given increasing support during the 1980s. I believe that success will depend not only on developing simple screening techniques for chilling tolerance, but in locating suitable areas for field evaluation.

References

Aisien, A. O., and GHOSH, B. P. 1978. Preliminary studies of the germinating behaviour of Guinea corn *{Sorghum vulgare).* Journal of the Science of Food and Agriculture 29:850-852

BAGNALL, D. J. 1979. Low temperature responses of three sorghum species. Pages 67-80 *in* Low temperature stress in crop plants. The role of the membrane.

eds. J. M. Lyons, D. Graham and J. K. Raison. New York and London: Academic Press.

BAJAY, J., and PAPP, B. 1969. Relationship between germination of grain sorghum *(Sorghum vulgare var frumentaceum) and* temperature of soil. Acta agron. Hung. 18:238-241.

BASS, L. N. and STANWOOD, P. C. 1978. Long term preservation of sorghum seed as affected by seed moisture, temperature and atmospheric environment. Crop Science 18:575-577.

BLUM, A, and EBERCON. A. 1976. Genotypic responses in sorghum to drought stress. III. Free proline accumulation and drought resistance. Crop Science 16:428 -431.

BROOKING, I. R. 1976. Male sterility in *sorghum bicolor* (L.) Moench induced by low night temperature. 1. Timing of the stage of sensitivity. Australian journal of Plant Physiology 3:589-596.

CADDEL, J. H., and WEIBEL, D E 1971. Effect of photoperiod and temperature on the development of sorghum. Agronomy Journal 63 : 799-803.

CARLSON, G. E., and ATKINS, R. E. 1960. Effect of freezing temperatures on seed viability and seedling vigor of grain sorghum. Agronomy Journal 52 : 329-333.

CHESNOKOV, V. A., MIROSLAVOVA, S. A., and MOSHKANOVA, V. V. 1974. The effect of preliminary heating on the Co_2 gas exchange of leaves with C_3 and C„ pathway photosynthesis. Vestnik Leningrad Skogo Universiteta, Biologiya 2:108-115.

CHOWDHURY, S. I., and WARDLAW, I. F. 1978. The effect of temperature on kernel development in cereals. Australian Journal of Agricultural Research 29: 205-223.

COFFMAN, F. A. 1957. Factors influencing heat resistance in oats. Agronomy Journal 49: 368-373.

CREENCIA, R. P., and BRAMLAGE. W. J. 1971. Reversibility of chilling injury to corn seedlings. Plant Physiology 47:389-392.

DOWNES, R. W. 1968. The effect of temperature on tillering of grain sorghum seedlings. Australian Journal of Agricultural Research 19:59-64.

DOWNES, R. W. 1972. Effect of temperature on the phenology and grain yield of *Sorghum bicolor.* Australian Journal of Agricultual Research 23:585-594.

DOWNES, R. W., and MARSHALL, D. R. 1971. Low temperature induced male sterility in *Sorghum bicolor.* Australian Journal of Experimental Agriculture and Animal Husbandry 11 : 352-356.

EASTIN, J D. 1976. Temperature influence on sorghum yield. Pages 19-23 *in* Proceedings of the Thirty-first Annual Corn and Sorghum Research Conference, eds. H P. Loden and D. Wilkinson. American Seed Trade Association.

EASTIN, J. D. 1981. Sorghum development and yield. *In* Proceedings of the Symposium on Potential Productivity of Field Crops Under Different Environments. 22-26 Sept 1980. IRRI.

ESCALADA, R G., and PLUCKNETT, D. L. 1975. Ratoon cropping of sorghum. 2. Effect of daylength and temperature on tillering and plant development. Agronomy Journal 67:479-484.

GALLAGHER, J. N. 1979. Field studies of cereal growth. 1. Initiation and expansion in relation to temperature and ontogeny. Journal of Experimental Botany 30:625 -636.

GERIK, T. J. 1979. The relationship of photosynthesis and dark respiration in grain sorghum *[Sorghum* bicolor(L) Moench) to yield, yield components and temperature. Ph.D. Thesis, University of Nebraska. Lincoln, Nebraska. USA.

GRITTON, E. T., and ATKINS, R. E. 1963. Germination of grain sorghum as affected by freezing temperatures. Agronomy Journal 55:139-142.

HANKS, R. J.. KELLER, J., RASMUSSEN. V. P., and WILSON, G. D 1976. Line source sprinkler for continuous variable irrigation—crop production studies Soil Science Society of America Journal 40: 426-429.

HEINRICH, G. M. 1981. Morphological and physiological mechanisms of yield stability in grain sorghum *[Sorghum bicolor* (L.) Moench) across diverse environments. Ph.D. Thesis, University of Nebraska, Lincoln, Nebraska, USA.

HEYNE, E. G., and LAUDE, H. H. 1940 Resistance of corn seedlings to high temperatures in laboratory tests. Journal of American Society of Agronomy. 32:116 -126.

HEYNE, E. G., and BRUNSON, A. M. 1940 Genetic studies of heat and drought tolerance in maize Journal of American Society of Agronomy 32:803-814.

HOUSE, L. R. 1981a. ICRISAT in the 80s—A 10-Year Plan. Internal Report, ICRISAT.

HOUSE, L. R. 1981b. The sorghum plant. Growth stages and morphology. Pages 16-31 *in* A guide to sorghum breeding, ed. L. R. House. Patancheru, A.P., India: ICRISAT.

HUNTER. J. W.. LAUDE. H. H., and BRUNSON, A. M. 1936. A method for studying resistance to drought injury inbred lines in maize. Journal of American Society of Agronomy 28:694-698.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1981. Pages 30-31 *in* ICRISAT Annual Report 1981. Patancheru, A.P., India ICRISAT.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) 1982. ICRISAT Annual Report 1980 /81. Patancheru, A.P.. India: ICRISAT.

IRRI (International Rice Research Institute). 1978. Pages 138-142 *in* IRRI Annual Report 1978.

JOHNSON, W. C. 1967. Diurnal variation in growth rate of grain sorghum. Agronomy Journal 59:41-44.

JORDAN, W. R., and MONK, R. L. 1980. Enhancement of drought resistance of sorghum: progress and limitations. Pages 185-204 *in* Proceedings of the 35th Annual Com and Sorghum Research Conference, Grain Sorghum Producers Association, Wichita, Kansas.

JORDAN, W. R., and SULLIVAN, C. Y. 1982. Reaction and resistance of grain sorghum to heat and drought. These Proceedings: ICRISAT.

KAILASANATHAN. K.. RAO, G.G.S.N.. and SINHA S. K. 1976. Effect of temperature on the partitioning of seed reserves in cowpea and sorghum. Indian Journal of Plant Physiology 19:171-177.

KANEMASU, E. T., BARK, D. L. and CHIN CHOY. E. 1975. Effect of soil temperature on sorghum emergence. Plant and Soil 43:411-417.

KANTOR, D. J., and WEBSTER, 0. J. 1967. Effects of freezing and mechanical injury on viability of sorghum seed. Crop Science 7:196-199.

KAYLOYEREAS, S. A. 1958. A new method of determining drought resistance. Plant Physiology 33:232-233.

KILEN. T. C. and ANDREWS, R. H. 1969. Measurement of drought resistance in corn. Agronomy Journal 61:669 -672.

KNAPP, R. 1966. Effect of various temperatures on the germination of tropical and sub tropical plants. Angew Bot. 32:230-241.

KUSEWA, P. K. 1978. The influence of temperature on germination and early seedling growth of maize (*Zea mays)* and sorghum (*Sorghum bicolor).* M. Agr. Studies Thesis. University of Queensland, Australia.

LEVIIT, J. 1980. Responses of plants to environmental stresses Second Edition, Volume 1: chilling, freezing, and high temperature stresses. New York, USA: Academic Press. 497pp.

LYONS. J. M., GRAHAM, D., and RAISON. J. K. 1979. Low temperature stress in crop plants. The role of the membrane. New York, USA: Academic Press. 565pp.

MAHALAKSHMI, V. 1978. Temperature influence on respiration and starch synthetase in *Sorghum bicolor* (L) Moench. Ph.D. Thesis, University of Nebraska, Lincoln, Nebraska. USA.

MAJOR, D. J., HAMMAN. W. M., and ROOD, S. B. 1981. Effect of short-duration chilling temperature exposure on growth and development of sorghum. Field Crops Research 3.

MANOKARAN, W. 1979. Effect of chilling temperature on sorghum. M.Sc. Agr. Thesis. University of New England, Armidale, NSW. Australia.

MARTIN. J. H 1941. Climate and sorghum. USDA Agricultural Year Book. Washington. 343 pp.

MARTIN, J. H., TAYLOR, J. W., and LENKEL, R. W. 1935. Effect of soil temperature and depth of planting on the emergence and development of sorghum seedlings in the greenhouse. Journal of the American Society of Agronomy 27:660-665.

MCCREE, K. J. 1974. Equations for the rate of dark respiration of white clover and grain sorghum, as functions of dry weight, photosynthetic rate and temperature. Crop Science 14:509-514.

MCCREE, K. J., and DAVIS, S. D. 1974. Effect of water stress and temperature on leaf size and on size and number of epidermal cells in grain sorghum. Crop Science 14:751-755.

MCWILLIAM, J. R. 1981. Physiological basis for chilling stress and the consequences for crop production. *In* Crop reactions to water and temperature stresses in humid, temperate climates, eds. D. Raper and P.J. Kramer. Westfield Press.

MCWILLIAM, J. R.. MANOKARAN, W., and KIPNIS, T. 1979. Adaptation to chilling stress in sorghum. Pages 491 -505 *in* Low temperature stress in crop plants, eds. J M. Lyons, D. Graham, and J. R. Raison. New York and London: Academic Press.

MELCAREK, P. K., and BROWN, G. A. 1977. Effects of chilling stress on prompt and delayed chlorophyll fluorescence from leaves. Plant Physiology 60:822 -825.

MILLER. F. R 1982. Genetic and environmental response characteristics of sorghum These Proceedings: ICRISAT

MOCK, J.J, and BAKRI, A. A. 1976. Recurrent selection for cold tolerance in maize. Crop Science 16: 230-233

MURATA, N., and FORK, D C. 1975 Temperature dependence of chlorophyll a fluorescence in relation to the physical phase of membrane lipids in algae and higher plants Plant Physiology 56: 791 796.

MURTY, K. S. and MAJUMDER, S. K. 1962 Modifications of the technique for determination of chlorophyll stability index in relation to studies of drought resistance in rice. Current Science 31 :470-471

MYERS, R. J. K., and ASHER, C. J. 1982. Mineral nutrition in grain sorghum: Macronutrients. These Proceedings: ICRISAT

NORCIO. N. V. 1976. Effect of high temperature and water stress on photosynthesis and respiration rates of grain sorghum Ph.D. Dissertation, University of Nebraska, Lincoln, Nebraska, USA

OGUNLELA, V. B. 1979. Physiological and agronomic response of a grain sorghum *[Sorghum bicolor* (L.) Moench) hybrid to elevated night temperatures. Ph.D. Thesis, University of Nebraska, Lincoln, Nebraska, USA.

PASTERNAK, D., and WILSON, G. L. 1969 Effects of heat waves on grain sorghum at the stage of head emergence. Australian Journal of Experimental Agriculture and Animal Husbandry 9 : 636-638.

PASTERNAK, D , and WILSON, G. L. 1972 After effects of night temperatures on stomatal behaviour and photosynthesis of sorghum New Phytologist 71 : 638-689

PATTERSON, B. D., MURATA, T., and GRAHAM, D. 1976. Electrolyte leakage induced by chilling in *Passiflora* species tolerant to different climates. Australian Journal of Plant Physiology 3:435-442.

PAULL, R. E., PATTERSON, B. D.. and GRAHAM. D. 1979 Chilling injury assays for plant breeding. Pages 507 -519 *in* Low temperature stress in crops plants, eds J M. Lyons, D. Graham and J. L. Raison. New York and London: Academic Press

PEACOCK, J. M. 1975a. Temperature and leaf growth in *Lolium perenne.* I. The thermal microclimate: its measurement and relation to crop growth. Journal of Applied Ecology 12:99-114

PEACOCK, J. M. 1975b. Temperature and leaf growth in *Lolium perenne.* II. The site of temperature perception Journal of Applied Ecology 12: 115-123.

PEACOCK, J. M. 1976a. Temperature and leaf growth in four grass species. Journal of Applied Ecology 13 : 225 -232

PEACOCK, J M. 1976b. The effect of seed source and size on sorghum seed germination. Dryland Farming Research Scheme (DLFRS). Botswana. Pages 46-49 *in* Initial Scientific Report Phase II.

PEACOCK, J. M. 1977. The weather at Content Farm, Sebele Botswana. Dryland Farming Research Scheme (DLFRS) Botswana. Pages 85-89 *in* Interim Scientific Report Phase II.

PEACOCK, J. M. 1979 The effect of water on the growth, development and yield of sorghum *[Sorghum bicolor)* cv RS. 610 Dryland Farming Research Scheme (DLFRS) Botswana. Pages 29-52 *in* Final Scientific Report Phase II Sorghum Physiology and Crop Climate Studies.

PEACOCK, J. M 1980. Sorghum improvement at ICRISAT: What is the role of the crop physiologist? Internal report, ICRISAT.

PEACOCK, J.M., and NTSHOLE, M. R. 1976 The effect of row spacing and plant population of the growth, development, grain yield, microclimate and water use of *Sorghum bicolor cv* 65D. Dryland Farming Research Scheme (DLFRS) Botswana. Pages 31-44 *in* Initial scientific report

PEACOCK, J. M.. TSELE. K., and MOLEFE, M. 1979. The effect of row spacing, plant population and fertilizer on the growth, development, grain yield and water use of sorghum (*Sorghum bicolor)* cv RS 610. Dryland Farming Research Scheme (DLFRS) Botswana. Pages 1 -27 *in* Final Scientific Report Phase 11. Sorghum Physiology and Crop Climate Studies.

PINTHUS, M. J., and ROSENBLUM, J. 1961. Germination and seedling emergence of sorghum at low temperatures. Crop Science 61 : 293-296.

QUINBY. J. R., HESKETH, J. D.. and VOIGT, R. L. 1973. Influence of temperature and photoperiod on floral initiation and leaf number in sorghum. Crop Science 13:243-246

QUINBY, J. R., KRAMER, N. W., STEPHENS. J C, LAHR, K. A., and KARPER, R. E. 1958. Grain sorghum production in Texas. Texas Agriculture Experimental Station Bulletin 912. 36pp.

RAPER, D., and KRAMER, P. J. (eds.) 1981 Crop reactions to water and temperature stresses in humid, temperate climates. Westfield Press.

ROSBACO, U. 1958. The production of hybrid sorghum seed in the USA. Idia 127:17-19

ROSENOW, D. T., CASADY, A. J., and HEYNE. E. G 1962. Effects of freezing on germination of sorghum seed. Crop Science 2:99-102.

ROSENTHAL, K. M., and HAMMER, G. L. 1979. Heatwave and maximum temperature probabilities. Queensland Agricultural Journal. 105:72-93.

SINGH, N. T., and DHALIWAL, G. S. 1972. Effect of soil temperature on seedling emergence in different crops. Plant and Soil 37:441-444.

SINGH, S. P. 1977. Breeding grain sorghum for cold tolerance. Presented at the International Sorghum Workshop. ICRISAT, 6-12 Mar, Hyderabad. India.

SIVAKUMAR, M. V. K., and VIRMANI. S. M., 1982. The physical environment. These Proceedings: ICRISAT.

SLACK, C. R., ROUGHAN, P. G., and BASSETT. H.C.M. 1974. Selective inhibition of mesophyll chloroplast development in some C_4pathway species by low night temperature. Bulletin, The Royal Society of New Zealand. 12:499-504

SMILLIE, R. M. 1979a. Coloured components of chloroplast membranes as intrinsic membrane probes for monitoring the development of heat injury in intact tissues. Australian Journal of Plant Physiology 6:121 -133.

SMILLIE, R. M. 1979b. The useful chloroplast: a new approach for investigating chilling stress in plants. Pages 187-202 *in* Low temperature stress in crop plants, eds. J. M. Lyon. D. Graham and J. K. Raison. New York and London: Academic Press.

SMILLIE, R. M., and NOTT, R. 1979. Heat injury in leaves of Alpine temperate and tropical plants. Australian Journal of Plant Physiology 6:135-141.

SOMAN, P. 1981. Factors affecting seed germination and seedling emergence in millet and sorghum: A report on some experimental techniques and results. Internal Report, ICRISAT.

STICKLER, F. C, PAULI, A. W., and CASADY, A. J. 1962. Comparative responses of Kaoliang (sorghum originating in China) and other grain sorghum types to temperature. Crop Science 2:136-139

STOPFER, R. V., and VAN RIPER, G. E. 1963. Effect of soil temperature and soil moisture on the physiology of sorghum. Agronomy Journal 55:447-450

SULLIVAN, C. Y., 1972. Mechanisms of heat and drought resistance in grain sorghum and methods of measurement. Pages 247-263 in Sorghum in seventies, eds N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co.

SULLIVAN, C. Y., and BLUM, A. 1970. Drought and heat resistance of sorghum and corn. Pages 55-56 *in* Proceedings of the 25th Annual Corn and Sorghum Research Conference of the American Seed Trade Association, Wichita, Kansas, USA.

SULLIVAN, C. Y., and KINBACHER, E. J. 1967. Thermal stability of fraction I protein from heat hardened *Phaseolus acutifolius* Gray 'Tepary Buff. Crop Science 7:241-244.

SULLIVAN, C. Y., NORCIO, N. V., and EASTIN, J. D. 1977. Plant responses to high temperatures. Pages 301 -307 *in* Genetic diversity in plants, eds. A. Muhammed, R. Askel and R. C. von Borstel. New York, USA: Plenum Publishing Corp.

SULLIVAN, C. Y., and Ross. W. M. 1979. Selecting for drought and heat resistance in grain sorghum. Pages 263-281 *in* Stress physiology in crop plants, eds. H. Mussell and R. C. Staples. New York, USA: Wiley-Interscience.

SUMAYAO, C. R.. KANEMASU. E. T.. and HODGES, T. 1977. Soil moisture effects on transpiration and net carbon dioxide exchange of sorghum. Agricultural Meteorology 18:401-408.

TATENO, K., and OJIMA, M. 1976. Effects of temperature and soil water content during grain filling period on the yields of grain sorghum. Proceedings of Crop Science Society of Japan 45 : 63-68.

TAYLOR, A. O. 1973 An environmental problem with grain sorghums. Proceedings of the Agronomy Society of New Zealand 3:57-62.

TAYLOR, A. O., SLACK, C. R., and MCPHERSON, H. G. 1974b. Plants under climatic stress. 6. Chilling and light effects on the photosynthetic enzymes of sorghum and maize. Plant Physiology 54:696-701.

THOMAS, G. L. and MILLER, F. R. 1979. Base temperatures for germination for temperate and tropically adapted sorghums. Eleventh Biennial Grain Sorghum Research and Utilization Conference. 28 Feb-1 March, 1979, Lubbock. Texas.

TROUGHTON, J. H., BJORKMAN, O., and BERRY. J. A. 1974. Growth of sorghum at high temperature. Carnegie Institution Year Book. 73:835-838.

TURNER, N. C, and KRAMER, P. J. (eds.) 1980. Adaptation of plants to water and high temperature stress. New York, USA: Wiley-Interscience. 482pp.

VAN ARKEL, H. 1977. New forage crop introductions for the semi-arid highland areas of Kenya as a means to increase beef production: Netherlands Journal of Agricultural Science 25:135-150

VONG, N. Q., and MURATA. Y. 1977. Studies in the physiological characteristics of C_3 and C_4 crop species 1. The effects of air temperature on the apparent photosynthesis, dark respiration, and nutrient absorption of some crops, Japanese Journal of Crop Science 46:45-52.

WADE, L. J., SEETHARAMA, N, and PEACOCK. J. *M.* (In preparation). Leaf growth studies in sorghum *Sorghum bicolor.* I. Glasshouse study Techniques and problems.

WATTS, W. R. 1974 Leaf extension in *Zea mays* III Field measurements of leaf extension in response to temperature and leaf water potential. Journal of Experimental Botany 25: 1085-1096.

WILSON, G. L, and EASTIN, J. D. 1982 The plant and its environment. These Proceedings: ICRISAT.

WILSON, G. L„ RAJU. P. S., and PEACOCK, J, M. 1982. Effect of soil temperature on sorghum emergence Indian Journal of Agricultural Science 52:

Mineral Nutrition of Grain Sorghum: Macronutrients

R. J. K. Myers and C. J. Asher*

Recent FAO statistics (FAO 1979) indicate a total world production of grain sorghum of the order of 6.9 x 10' tonnes per year from a harvested area of about 5.2 x 10' ha. These values are almost certainly an underestimate since, for some countries, sorghum data is included within the totals given for millet. Although 70 countries produce more than 10^3 tonnes of sorghum per year, 90.6% of the total production and 89.5% of the harvested area is accounted for by 12 countries in Asia, the Americas, Africa, and Oceania (Table 1).

Sorghum is essentially a crop of the semi-arid tropics, but much of the crop improvement research on it has been conducted at latitudes well outside the tropics. It is perhaps for this reason that the highest average sorghum yields come from countries with their main sorghum producing areas in temperate or subtropical zones (e.g.. USA., Mexico, Argentina) rather than the tropics.

It is clear from Table 1 that even if we consider only the major sorghum soils of the major sorghum producing countries, much diversity exists. It is likely that a much wider range of soils is actually involved within the countries listed in Table 1, and a wider range still in the many other countries of the world with smaller but still substantial sorghum industries. Such a diversity of soils carries with it the expectation of a variety of soil fertility and plant nutrition problems. However, comparatively little attention was devoted to these problems in the last major symposium on the topic "Sorghum in Seventies" (Rao and House 1971). We have found more than 200 references published in the last 10 years on effects of macronutrients on sorghum. Many of these are of local rather than general significance. In preparing this review we have included only those papers which help to illustrate the important principles.

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Factors Affecting Sorghum Nutrition

Three main factors markedly affecting the mineral nutrition of any crop are the demand for nutrients to sustain growth, the nutrient status of the soil, and the efficiency with which mineral nutrients are absorbed, distributed and utilized during the growing season. Positive responses to fertilizers are likely only when the crop demand for one or more nutrient elements exceeds the ability of the soil to supply the element or elements in question. Each of these main factors is influenced by many other factors, some of which are discussed below.

Crop Demand for Nutrients

Crop demand can be regarded as the product of two components, i.e., total dry matter production for the whole growing season or any portion of it, and average nutrient concentrations needed in the plant tissues to achieve this dry matter production. Observations on seasonal patterns of nutrient uptake do not always give a reliable indication of nutrient demand, because uptake is often limited by nutrient availability, particularly in the latter part of the growing season.

Tissue Concentration

Relatively little attention has been given to the study of macronutrient concentrations in field

International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81. Patancheru, A.P., India. Patancheru, A.P. India: ICRISAT.

Table 1. Major grain sorghum producing countries of the world and predominant toil types used.

Geographical region and country	% of world's sorghum*		Predominant soils used	
	Production	Area	FAO—UNESCO"	U.S. Soil Taxonomy
Asia				
India	17.4	30,8	Vertisols, Luvisols	Vertisols, Alfisols
China	15.9	16,4	—[c]	—[c]
Yemen A. R.	0.8	1.8	Yermosols	Alfisols
North & Central America				
USA	27.5	10.6	Kastanozems. Phaeozems	Mollisols
Mexico	6.1	2,7	Vertisols, Luvisols, Kastanozems	Vertisols, Alfisols, Mollisols
South America				
Argentina	10.6	4,5	Phaeozems	Mollisols
Africa				
Nigeria	5.5	11.6	Luvisols	Alfisols
Sudan	3.5	5.3	Vertisols Luvisols	Vertisols Alfisols
Upper Volta	0.9	2.1	Arenosols	Entisols
Niger	0.5	1.5	Luvisols	Alfisols
Ethiopia[d]	0.9	1.4	Arenosols Regosols, Cambisols, Nitosols, Vertisols	Entisols, Entisols, Inceptisols, Alfisols, Vertisols
Oceania				
Australia	1.0	0.8	Vertisols	Vertisols
Total	90.6	895		

a. From FAO Production Yearbook 1978 (FAO 1979).
b. FAO-UNESCO Soil Map of the World.
c. Information not available to authors.
d. Additional information from Westphal (1975).

grown grain sorghum, or of the minimum whole-plant concentrations for maximum growth. Lockman (1972a) published whole-plant concentrations tor young grain sorghum plants (20 to 36 days from planting) for N, P, K, Ca, and Mg, and proposed a set of nutrient sufficiency values (Lockman 1972b), which could be used to estimate nutrient demand for young plants. Several workers have observed marked seasonal decreases in the average concentrations of macronutrient elements in sorghum tops including N (Raheja and Krantz 1958), P (Srivastava 1971), and Ca and Mg (Jacques et al. 1975).

Since sorghum roots remain active and capable of nutrient absorption until very late in the growing season (see below), the seasonal changes in nutrient concentration are probably due in part to increasing dilution of the nutrient with woody material as plant age increases, and in part to decreases in the amounts of plant-available nutrients remaining in the soil as the season progresses. Uncertainty about concentrations needed in the plant tissues for healthy growth hampers the assessment of nutrient demand in grain sorghum, especially in the latter two-thirds of the growing season.

Dry Matter Production

Grain sorghum exhibits a typical sigmoid growth curve with substantial growth after anthesis. When water and mineral nutrients are adequate a substantial part of the nutrient uptake may occur following anthesis, indicating continuing root activity. Thus, with dryland sorghum, Smith and Myers (1978) found that 46% of the total N accumulated into the tops and 37% of the P occurred during grain filling despite a major moisture deficit during this period. In other studies Roy and Wright (1974) found that approximately 60% of the N and P were taken up after anthesis while Srivastava (1971) found that 83.9% of the total P was taken up after day 47.

Any factor which reduces dry matter production is likely to reduce the crop demand for nutrients and therefore the likelihood of a response to fertilizer application. Growth reduction due to pests and diseases can reduce growth and hence nutrient demand. Similarly, growth reductions due to a deficiency or toxic excess of one mineral element can lead to a reduction in the demand for other mineral elements. Also the correction of a deficiency or excess of one element increases the demand for other essential elements and hence increases the probability that one of these could become deficient.

Some factors with marked effects on dry matter production are discussed briefly below.

PLANTING DENSITY AND DURATION OF GROWTH PERIOD. Planting density can markedly affect dry matter production and hence the demand for nutrients. With cv RS610 grown under high fertility conditions and with adequate water, Fischer and Wilson (1975) found that the total dry weight of tops at maturity varied from 8 t/ha at a low plant density of about 14 000 plants/ha to almost 28 t/ha at a very high density of about 646 000 plants/ha. Though there appears to be little genetic variation in relative growth rate, total dry matter production varies greatly between cultivars with different growth duration. Thus Goldsworthy and Taylor (1970) showed that the weight of stems plus grain produced by a long season Nigerian variety (171 days to maturity) was double that of a short season (100 days) American hybrid at equal plant densities.

SALINITY. Patel et al. (1975) concluded that while it was important to maintain soil fertility when growing sorghum under saline conditions, fertilizer requirements were reduced because of reduced growth. Salinity may affect growth in a number of quite distinct ways (cf reviews by Greenway 1973; Maas and Nieman 1978): (i) water stress due to low osmotic potentials in the soil solution; (ii) toxicity of particular elements accumulating to high concentrations in the plant tissues; and (iii) deficiencies of particular elements resulting from competition among ions for uptake in a saline environment. The last mentioned of these may be particularly important for sorghum. Thus Monadjemi (19761 found in glasshouse trials that raising the exchangeable sodium percentage of a soil with NaCl or $NaHC0_3$ lowered the Ca content of the plants and at the higher levels caused severe Ca deficiency. Again, Pathmanabhan and Rao (1976) found that increasing salinity reduced K uptake, there being an inverse relationship between the K concentration in 30-day-old seedlings and the susceptibility of sorghum cultivars to salinity.

The bulk of evidence seems to indicate that grain sorghum is only moderately tolerant of salinity, being less tolerant than wheat, cotton or barley (Eaton 1942; Hart 1974). An electrical conductivity (EC) value (saturation extract) of 12 mS/cm was required for 50% yield reduction (Hart 1974). Maliwal (1967) suggested the existence of differences among sorghum cultivars in tolerance to salinity. In solution culture experiments, Taylor et al. (1975) compared the salt tolerance of 48 sorghum cvs and found that at 5000 mg/l of salt (approx. 10 mS/cm) yield reductions ranged from about 71 % for cv Midland to only 22% for cv Desert Maize. They pointed out that if such differences are heritable, it should be possible to develop salt resistant cultivars by plant breeding. Indeed Epstein et al. (1978) made a strong plea for greater emphasis on plant breeding as a means of overcoming salinity problems. They list two recent projects concerned with breeding of salt tolerance of sorghum in the USA., and one project each in India, Egypt, and USSR.

ALKALINITY. Nutritional problems encountered by plants in alkaline soils have been reviewed by Mortvedt (1976) and Brown (1978). Frequently these soils are high in Na and high in total soluble salts, so much of what has been said about salinity applies to them also. In addition, high pH lowers the solubility of the micronutrients Fe, Mn, Zn, and Cu and may cause deficiencies (cf Clark 1982). In calcareous alkaline soils phosphate may be precipitated and the problem may be worsened by the depressive effects of high pH on phosphate absorption by roots (Hagen and Hopkins 1955). Some alkaline soils are high in bicarbonate ions which are much more toxic when present in excess than chloride ions.

Very little information is available on effects of alkalinity on grain sorghum. Maliwal (1967) used the sodium adsorption ratio (S.A.R.) as an index of alkalinity in germination tests with grain sorghum. All sorghum cultivars were sensitive to alkalinity but there are problems of interpretation with this study. Chapco (1977), on the other hand, is reported to have found that sorghum, along with sudan grass and sugar beet has a high tolerance to sodium carbonate concentrations in the soil.

A need exists for well controlled experiments on effects of salinity and alkalinity on grain sorghum to resolve the apparent conflicts among a number of the studies referred to above.

CLIMATIC FACTORS. The paper of Wilson and Eastin (1982) deals with climatic and other environmental factors. As a crop of the semi-arid tropics, sorghum is often subject to growth limitations due to water stress. This is discussed by Jordan and Sullivan (1982) and only those aspects specifically associated with crop nutrition will be considered here.

In low rainfall country, it is common to grow rainfed sorghum at low plant densities and wide row spacing to increase the probability of there being sufficient moisture available for grain filling. These practices reduce total dry matter production and hence the demand for nutrients even if the anticipated dry seasonal conditions do not eventuate. Thus such dryland crops are less likely to respond to fertilizer than a densely-planted narrow-row irrigated crop.

For crops grown predominantly on stored water, progressive drying of the soil from the surface downwards as the season progresses may render unavailable the mineral nutrients in the upper part of the profile. A dry topsoil also means that side dressings of fertilizer will remain ineffective unless rain falls or the crop can be irrigated.

Seasonal differences in water available to the crop can have large effects on responsiveness to fertilizer nutrients. On a relatively infertile soil at Katherine. Australia, Myers (1978a) found that maximum grain yield (5.4 t/ha) and total above ground dry matter production (15.5 t/ha) occurred in a season of above average rainfall (989 mm from October to April) with 150kgN/ha(Fig. 1). In a season of average rainfall (855 mm) there was again a strong response to N, maximum yields of grain and dry matter (3.3 and 7.7 t/ha) occurring at both 150 and 200 kg N/ha. However in a season of below average rainfall (677 + 60 mm irrigation) vegetative growth was stimulated by N up to 90 kg N/ha during the first 56 days of growth but maximum grain yields occurred (2.0 t/ha) at approx. 22 kg N/ha, with higher rates of N significantly depressing the yield. Shortage of water during the grain filling stage following excessive earlier vegetative growth at the higher N level appeared to be the major factor causing the yield depression.

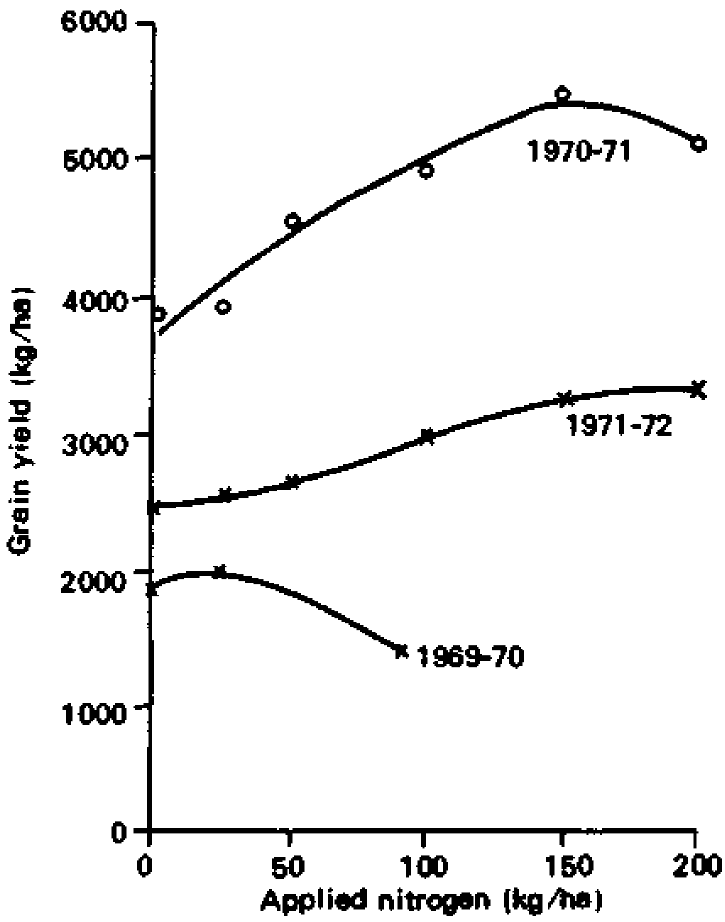

Figure 1. Grain sorghum response to nitrogen in 3 years at Katherine in the Northern Territory, Australia. (Data from Myers 1978.)

Nutrient Status of the Soil

Soil Solution Composition

The mineral nutrients essential for crop growth exist in the soil in a variety of physical and chemical forms. Usually, only a small portion of the total supply of an element will be present in the soil solution, but the soil solution has important effects on crop nutrition because nutrients present in other components of the soil system must first pass into the soil solution before they can be absorbed by the roots (Fig. 2). At any time, the availability of a mineral element to the crop will depend on the concentration (or strictly speaking the activity) of that element in the soil solution. If the concentration is too low, uptake rates by the roots may be insufficient to meet crop demand, or if too high, uptake may be excessive and growth of the crop restricted by toxicity.

Unfortunately, few reliable data are available concerning optimum soil solution concentrations of mineral elements for grain sorghum growth. Limited information is available, however, from recent experiments conducted in continuously flowing nutrient solutions in which solution composition, pH, and temperature were closely controlled. Forno (1977) showed that young sorghum plants made unrestricted growth when nitrate concentrations in the root environment were in the range of 500-5000 uM (7-70 pg N/ml) but that significant growth depression occurred at concentrations <50 pM. With ammonium, maximum growth occurred in the region of 500 pM (7 pg N/ml), the highest concentration studied. Sorghum growth declined sharply at ammonium concentrations below 30 pM.

These results may be contrasted with those of Cox and Reisenauer (1973) who found that in wheat maximum growth occurred with only 40 to 50 pM ammonium, higher concentrations leading to growth depression. Islam (1981) studied the response to sorghum and a number of other crops to Ca in flowing solution culture using calcium sulphate as the Ca source. Sorghum required a high Ca concentration (>3000 pM) for maximum growth. Further research on relationships between external concentrations of nutrients and the growth of sorghum is needed to provide a basic understanding of the nutritional physiology of the crop. Such studies are relevant also to the use of thermodynamic approaches to the assessment of soil nutrient availability which are discussed later.

Role of Solid-phase Nutrients

The main reservoir of nutrients in practically all soils is the solid phase which replenishes the soil solution in a variety of ways as nutrients are removed by the growing crop. Conceptually, the solid phase can be regarded as consisting of primary and secondary minerals, the exchange complex, and organic matter (Fig. 2). However, in practice these subdivisions overlap, e.g., the

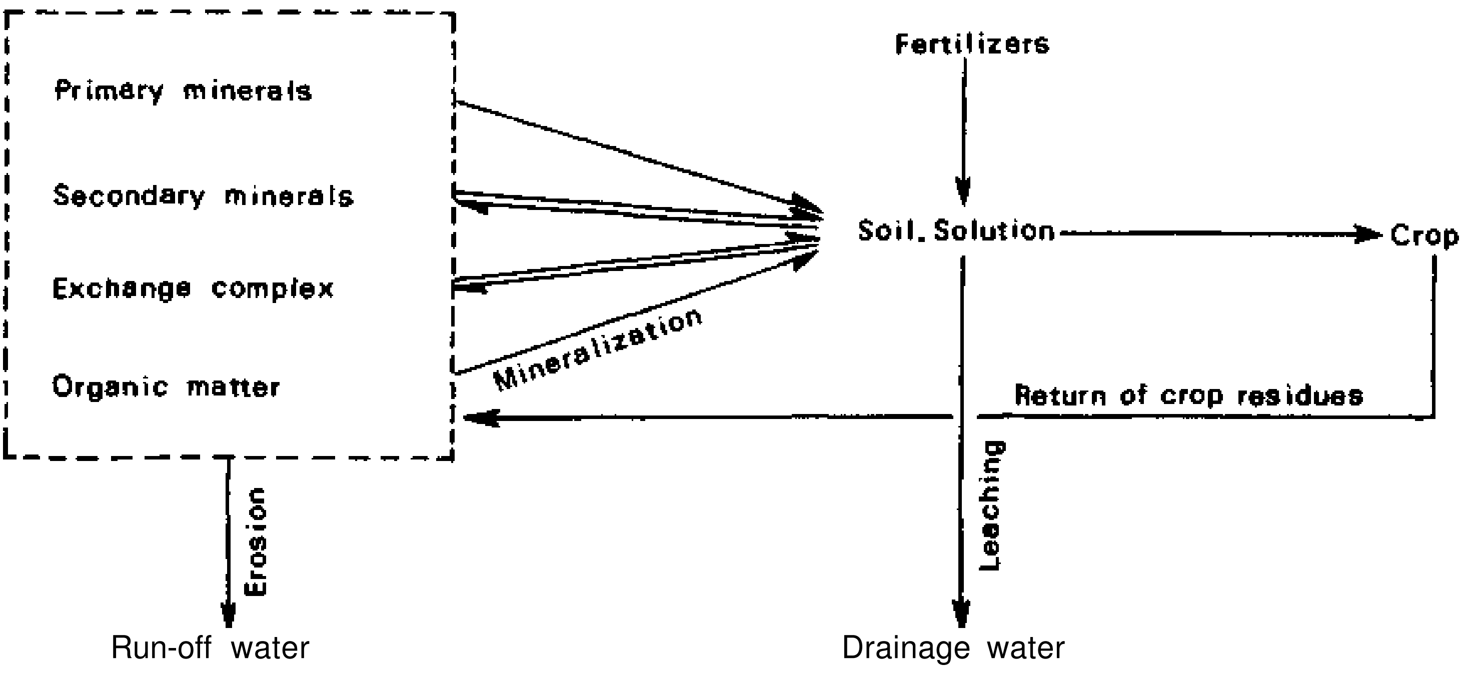

Figure 2. Nutrient sources and nutrient flows in the soil plant system.

exchange complex exists because of surface characteristics of some secondary minerals and the organic matter. In most soils the solubility of the primary minerals is very low and their contribution to maintenance of soil solution concentrations is small in the short term. In some soils of the semi-arid tropics, calcium carbonate or gypsum may be important secondary minerals influencing soil solution composition.

The exchange complex is of particular importance as a source of plant available nutrients because of rapid equilibration with the soil solution. Sometimes the amount of an element held on the exchange complex is used as an estimate of nutrient availability. The organic matter fraction is important as a source of mineral nutrients released on mineralization (especially N and S), and because of its role in the maintenance of soil structure. Maintenance of adequate levels of soil organic matter is difficult when soils (particularly those in the tropics) are repeatedly cropped, especially if crop residues are not returned. Erosion can cause serious reductions in soil fertility because the surface soil, which is most at risk, usually contains the highest concentrations of plant-available nutrients and most of the soil organic matter, and because within the surface the material moved by erosion is highest in nutrients and organic matter.

Assessment of Nutrient Status

The nutrient status of soils is commonly assessed by chemical or microbiological tests, glasshouse pot tests, or a combination of these. A good example of the use of both chemical tests and pot experiments to provide a detailed assessment of nutrient status is provided by the work of Crack and Isbell (1970) and Jones and Crack (1970). For both chemical tests and pot tests, decisions are required concerning the portion or portions of the soil profile to be sampled.

CHOICE OF SAMPLING DEPTH. The sampling procedures adopted need to take into account the characteristics of the sorghum root system. Sorghum roots are capable of penetrating the soil at approximately 2 to 5 cm/day (Nakayama and Van Bavel 1963) and reaching considerable depths quite early in the growing season. For example, Kaigama et al. (1977) found that the roots of cv Pioneer 846 had reached their maximum depth (140 to 150 cm) by 42 days after emergence, and Myers (1980) reported that roots of both cv Pioneer 846 and cv RS610 had reached 135 cm by floral initiation, approximately 22 days after emergence. In both studies a high proportion of the total root mass was within 15 to 20 cm of the soil surface. In the study of Kaigama et al. (1977) more than 90% of the total root weight was in the top 15 cm of the profile throughout the crop growth cycle. Under these conditions, the usual practice of restricting soil sampling to the top 10, 15 or 20 cm of soil profiles seems justified. Under drier conditions, the proportion is less. Thus Myers (1980) found only 76-79% of the root mass in the 0-20 cm layer. In a recent study Myers et al. (unpubl.) found that as water supply changed from near-optimal to severely water stressed, the proportion of the root system in the surface 20 cm declined, and under very dry conditions, the zone of maximum root accumulation was not in the surface soil (Table 2).

Accumulations of nutrients sometimes occur at depth, and the nutrient-rich surface soil is sometimes too dry for significant nutrient uptake to occur. Lavy and Eastin (1969) found that substantial absorption of ^{32}P occurred at depths of 30 and 60 cm. Similarly Smith and Myers (1978) attributed much of the P and N uptake of water stressed dryland sorghum during grain filling to uptake from the subsoil. Hence there may be circumstances where assessment of the nutrient status of the subsoil is important for a correct interpretation of the results of a field experiment.

Table 2. Depth distribution of grain sorghum roots (mean of four cultivars) as affected by water regime (R. J. K. Myers, M. A. Foale and A. A. Done, unpublished data).

Soil depth (cm)	Irrigation interval 7-day	28-day	Once only at planting
	Root lengths (cm/g)		
0-10	8.8	2.4	1.2
10-20	3.4	2.7	1.7
20-40	1.3	0.9	0.6
40-60	0.6	0.7	0.6
60-80	0.6	0.7	0.7
80-100	0.2	0.8	0.7
100-140	0.1	0.7	0.7
140-180	0.1	0.2	02
Percentage in 0-20 cm	67%	52%	24%

CHEMICAL TESTS Soil chemical tests can be broadly grouped into three kinds: soil extraction procedures; soil incubation-extraction procedures; and procedures based on thermodynamic approaches to nutrient availability.

i. Soil extraction procedures. The most common method of estimating potentially available mineral nutrients is to measure the amounts of nutrient elements extractable with various reagents under defined laboratory conditions. This empirical approach usually takes little account of the mineralogy of the soil being tested, or the dynamic interactions which occur between the soil solution and the solid phase of the soil (cf Fig. 2). For soil testing purposes, it is possible to calibrate such soil tests for a particular combination of crop, nutrient, soil, climate, and production system so that soil analysis can give an estimate of the fertilizer required for a specified yield level.

   However in sorghum agronomy we are usually dealing with soil test procedures calibrated on other crop species, on other soils, and in different climatic and management environments. Hence substantial extrapolation is involved and a reliable indication of quantitative fertilizer requirement is unlikely. The best that can be hoped for is a tentative indication of the adequacy or otherwise of a particular nutrient.

ii. Soil incubation-extraction procedures. In the case of N it is possible to measure the amount of N that is currently present in the soil profile, and following incubation under standard conditions, the amount potentially available. A simple procedure for using these estimates to predict N fertilizer required by sugar beet has been reported (Stanford et al. 1977) and similar procedures could be used for sorghum. Such procedures are well within the capabilities of research laboratories, and soil testing laboratories should be able to use short-cut methods for mineralizable N (e.g., Stanford and Smith 1976).

iii. Thermodynamic approaches to nutrient availability. For P and the nutrient cations, in which relatively rapid adsorption/desorption reactions with solid phase constituents buffer the composition of the soil solution, it is possible to assess the nutrient status of a soil from sorption isotherms. A valuable feature of this approach is that changes in soil solution concentration resulting from a given addition of an element as fertilizer or a given withdrawal of an element through crop uptake can be predicted. For example, Myers (1978b) reported that in a soil used for field experiments with sorghum, a change of approximately 11 ug/g in P sorbed on to the solid phase of the soil corresponded with a change of 0.1 ug/ml (approx. 3 u.m) in the equilibrium concentration of P in solution. If the lowest soil solution concentration for healthy growth is known, and an estimate of crop demand is available, it is possible to predict the amount of fertilizer required to ensure adequate nutrition of the crop. The amount of work involved in establishing sorption isotherms has so far prevented this approach from being used by routine soil testing services, but is commonly used at our laboratories, particularly in relation to P (e.g., Carvalho et al. 1980).

POT EXPERIMENTS. Pot experiments provide a valuable means of confirming tentative conclusions based on soil analysis and can, in addition, provide information about the availability of elements for which reliable and generally accepted chemical tests are not yet available (e.g., sulphur and some micronutrients). The costs are usually much smaller than those of major field trials and the information gained can often prevent costly mistakes in the design of such trials in terms of presence of hitherto unsuspected nutritional problems, or in the case of fertilizer experiments, the selection of inappropriate treatment rates and combinations.

Pot experiments are usually of one of two kinds: (i) those aimed at identifying nutritional factors that, are likely to limit plant growth on a particular soil; and (ii) those aimed at establishing approximate optimum rates of application of nutrient elements to overcome such limitations (nutrient rate experiments). In the first, subtractive ("missing element") designs have often been used to good effect in tropical and subtropical regions (cf Andrew and Henzell 1964, Sanchez 1976). In these experiments,, relatively pure laboratory chemicals should be used and they should supply only one essential element per chemical to remove any risk of incorrect interpretation. The need for nutrient-rate pot experiments may be reduced or eliminated where thermodynamic methods have been used to assess nutrient availability. Once the deficient elements have been identified and the approximate degree of deficiency established, field trials can be conducted using commercial fertilizer materials which supply the deficient elements in the most cost-effective form.

Plant Acquisition, Distribution, and Utilization of Mineral Nutrients

Information on these topics is limited and fragmentary, and there is a clear need for more research on the basic mineral nutrition of the crop.

Uptake Mechanisms

Root function in sorghum has been little studied. Although uptake mechanisms probably will be qualitatively similar to those in other species, there may be important quantitative differences likely to affect field performance.

Warncke and Barber (1974) found that sorghum and maize plants were capable of absorbing nitrate down to similar very low concentrations. Thus sorghum roots reduced the N concentration to 2.7 u.M before uptake ceased whereas the range for three maize cultivars was 2 to 4 uM. However Forno (1977) found that sorghum required higher nitrate concentrations in the root environment for maximum growth. When N was supplied as ammonium, the external concentration required by sorghum was again higher than for maize.

Kawasaki and Moritsugu (1979) found that Ca uptake rates by excised sorghum roots were similar to or slightly greater than those of excised maize roots. However, in longer term experiments with intact plants, Islam (1981) found large differences between these two species in ability to absorb adequate calcium for healthy growth. Whereas maize plants required only low external Ca concentrations (approx. 10 uM) for healthy growth, sorghum yields increased up to 3000 u*M* Ca, the highest concentration studied. More research is needed to resolve the apparent conflict between the studies with excised roots and those with intact plants.

Recent research suggests that substantial differences exist among sorghum cultivars in ability to absorb particular macronutrients and micronutrients. Thus Brown and Jones (1975) found that the ability of sorghum cultivars to absorb P from an acid soil of high Al status decreased in the order B-line > Wheatland > Pioneer 846 >KS5. Such differences open up exciting possibilities for breeding genotypes adapted to specific sets of soil conditions. However much careful work is needed before this becomes a practical reality. For example Brown et al. (1977) found that efficiency of P uptake tended to be associated with susceptibility to deficiencies of Fe and Cu.

Role of Root-microorganism Interactions

NITROGEN In recent years there has been much interest in associative N fixation in cereal and grass root systems. The successful manipulation of such N fixation systems has the potential of providing a low-cost yield improvement to N fertilizer, but practical applications seem a long way off.

Barber et al. (1976) inoculated maize and sorghum with N-fixing *Azospirillum* strains but estimated the resultant N fixation in the field to be <4 g/ha per day. In a similar experiment Tjepkema and van Berkum (1977) estimated the average N fixation for naturally infected maize and sorghum root systems at 2.8 g/ha per day compared with 1700 g/ha per day for nodulated soybeans. Pedersen et al. (1978) found sorghum roots to be infected with N-fixing *Enterobacteria* but the maximum rate of nitrogen fixation was estimated at only 2.5 g N/ha per day. While these rates of fixation are low, recent work by Dart and Wani (1982) suggests that associative N fixation in sorghum merits further evaluation.

Sanoria and Rao (1975) found that inoculation of sorghum seed with *Azotobacter* produced variable results with some significant increases in forage yields in pots but not in the field. Subsequently Reddy et al. (1977) obtained significant grain yield responses of 15% and 19% to inoculation with *Azotobacter* at a N deficient field site in two consecutive seasons. Although such responses have not been clearly shown to be associated with N fixation, and are often quite variable, further research seems justified.

PHOSPHORUS Moawad (1979) found that inoculation of sorghum plants with the vesicular-arbuscular endophyte *Glomus macrocarpus* substantially increased dry matter production and uptake of P from a soil fertilized with the insoluble phosphate $Ca_5(PO_4)_3OH$.

Nutrient Distribution

In recent years there have been several studies of macronutrient distribution in grain sorghum. Cowie (1973) conducted a detailed study of effects of N supply and the timing of N stress on N distribution in cv RS610 in solution culture. Roy and Wright (1974) followed seasonal patterns of N, P, and K accumulation in the leaf, stem, and panicle in cv CSH 1 grown in the field with supplemental irrigation, and with various levels of N and P fertilizer. Smith and Myers (1978) made a similar study of N and P distribution in cv Goldfinger grown under dryland conditions with water stress for much of the growing season. Jacques et al. (1975) followed in detail the distribution of Ca and Mg in two sorghum cv over two consecutive seasons.

The transfer of N and other mineral elements to the grain is important both in terms of the physiology of grain filling and of the nutritive value of the grain. The developing grains have two sources of mineral nutrients: (i) those entering the roots during grain filling and carried upwards to the panicle by the transpirational flow through the xylem; and (ii) those previously accumulated in leaves and stem, and transferred to the grain, along with products of photosynthesis, through the phloem transport system. The possibility exists that mineral nutrients temporarily stored in stem tissues bordering the xylem pathway may supplement the supply of mineral nutrients coming in through the roots during grain filling but experimental evidence on this point is lacking for sorghum.

The relative importance of xylem and phloem transport to the grain appears to be strongly influenced by the availability of water and mineral nutrients in the root environment during grain filling. Thus Roy and Wright (1974) showed that with unfertilized grain sorghum (N_6, P_o treatment) grain filling was associated with large reductions in the total N and P contents of leaves and stems (Fig. 3a), whereas with well fertilized plants (N_{120}, P_{26} treatment) the proportion of gram N and P coming from leaves and stems was much smaller (Fig. 3b). The data of Smith and Myers (1978) for dryland sorghum, in which the top 10 cm of soil was dry during grain filling, show that redistribution of N and P from leaves and stems played an important part in supplying these two elements to the grain under water stress conditions (Fig. 3c). Since Ca has very low mobility in the phloem of higher plants, the main supply of Ca to the developing grains is presumably via the xylem. The widely differing patterns of distribution of Ca and Mg reported by Jacques et al. (1975) confirm that Ca, unlike Mg. does not move out of leaves and stems during grain filling.

Grain N concentration is an important quality factor in sorghum. In precisely controlled solution culture experiments with cv RS 610, N supply had major effects on grain number (and hence yield) and on grain N concentration (Cowie 1973; Asher and Cowie 1974). Plants subjected to N deficiency between planting and floral initiation produced only a small panicle with fewer primary branches, secondary branches, and visible florets at head emergence than control plants supplied with adequate N. Nitrogen stress between floral initiation and anthesis caused between 16 and 30% of the initiated florets to abort. Nitrogen stress following anthesis had little effect on grain yield but greatly reduced grain N concentration compared with plants receiving adequate N (Table 3). With continuous N stress, the reductions in grain number due to reduced floral initiation and subsequent abortions brought the grain number into sufficient balance with the N supply to produce grain of acceptable N content (Table 3).

In the field, under favorable growing conditions very little mineral N remained within the rooting zone by anthesis with fertilizer rates up to 112 kg N/ha (Cowie 1973). Only in the highest N treatment (336 kg N/ha) was there sufficient mineral N left in the profile during grain filling for grain N levels to exceed 1.47% (Table 4). Side dressing of urea was highly effective in raising grain N concentrations. The greatest effect on grain composition occurred if the sidedressing was made at anthesis. However, an earlier side dressing at the boot stage increased both the yield of the lower N treatments (presumably by reducing floral abortion) and the grain N concentration (Table 4).

Herron et al. (1963) and Cowie (1973) observed significant net losses of N from N stressed sorghum after flowering. Gaseous N losses from a range of crops including sorghum have now been documented (Stutte and Wieland 1978; Wetselaar and Farquhar 1980), with the greatest losses apparently from senescing leaves of N stressed plants. So far the practical significance of such losses has not been assessed.

Efficiency of Utilization

In recent years there has been growing interest in the efficiency of utilization of mineral nutrients and various concepts of efficiency have been

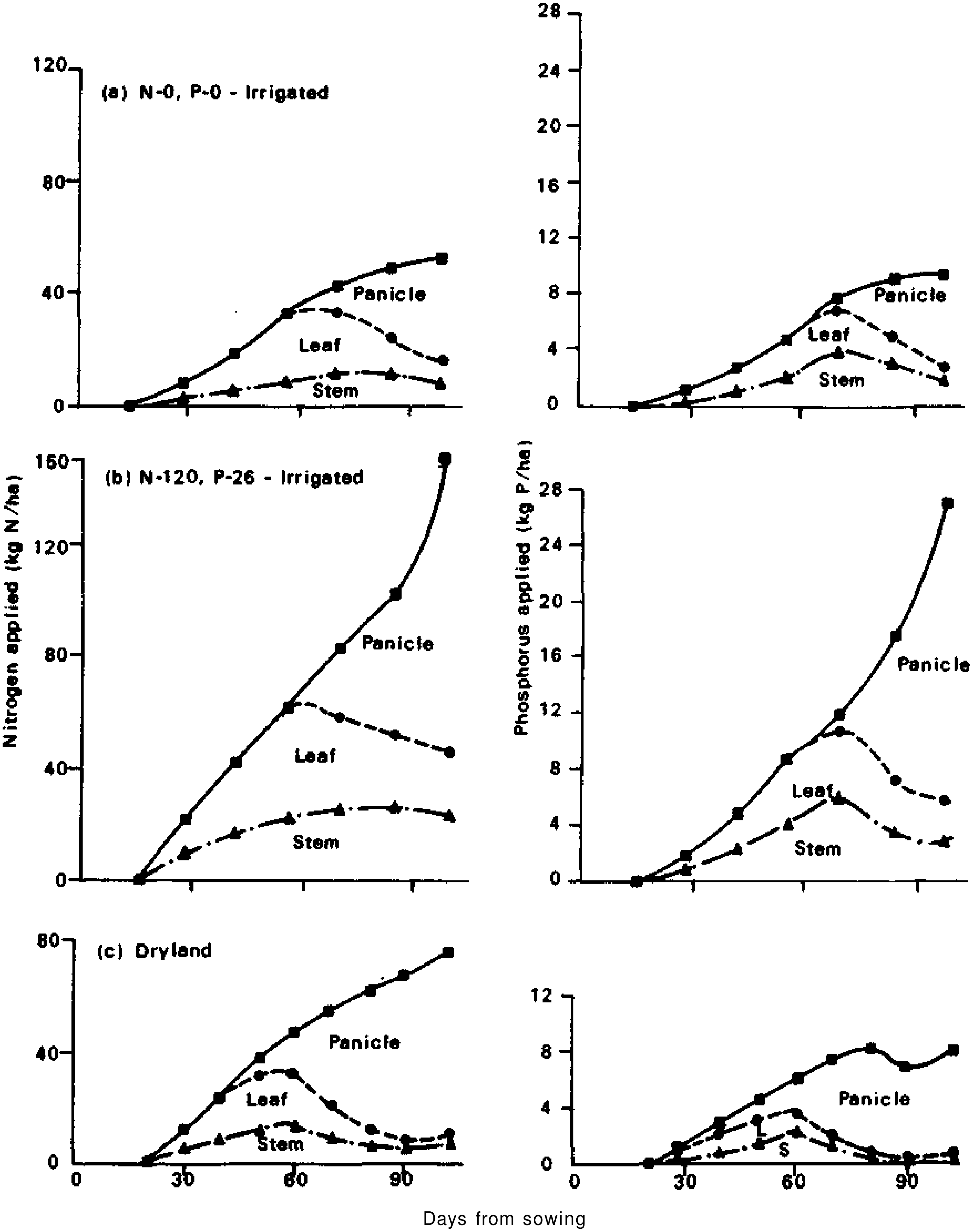

Figure 3. Nitrogen and phosphorus yields of sorghum stems, leaves, and panicles under different growth conditions: (a) Irrigated, no N or P applied (redrawn from Roy and Wright 1974); (b) Irrigated, 120 kg N/ha and 26 kg P/ha applied (redrawn from Roy and Wright 1974); (c) Dryland, N and P adequate (redrawn from Smith and Myers 1978).

Table 3. Effects of nitrogan supply ragime on grain production and grain nitrogen concentration in cvRS610 plants In a glasshouse solution culture experiment (modified after Asher and Cowie 1974).

Nitrogen supply regime			Grain production		Grain nitrogen concentration	
Planting-initiation	Initiation-anthesis	Anthesis-maturity	Number/plant	Weight (g/plant)	N (%)	Crude protein (%)
High	High	High	2485	62.3	2.78	17.4
High	Low	High	2061	50.3	2.82	17.6
Low	High	High	1550	37.1	292	18.4
Low	Low	High	1021	26.2	294	18.6
High	High	Low	2220	562	1.30	8.1
High	Low	Low	1738	44.4	1.21	7.6
Low	High	Low	1260	31.1	1.36	8.5
Low	Low	Low	896	22.5	1.48	9.3

Table 4. Effects of a sidedressing of 34 kg N/ha applied at the boot stage on the yield and grain nitrogen concentration of cv RS610 grown at Gatton, Australia (from Asher and Cowie 1974).

N applied at planting (kg/ha)	Without sidedressing		With sidedressing	
	Yield (t/ha)	N (%)	Yield (t/ha)	N (%)
0	0.8	1.24	2.2	2.35
34	1.1	1.06	2.0	2.02
112	42	1.41	6.1	2.03
336	9.2	1.80	9.1	2.68

defined (Wright 1976; Jung 1979). However, there appears to be no general agreement concerning either terminology or experimental methods for assessing the efficiency of particular genotypes.

Clearly if genotypes A and B have a similar yield potential under favorable growing conditions but A requires a lower average concentration of a particular mineral nutrient in its tissues for maximum growth than B, then A is the more efficient because it requires less of the mineral nutrient to achieve its yield potential. If the root systems of both have equal capacity to extract the mineral nutrient in question from a particular soil, then genotype A should outyield genotype B when the nutrient supply is limiting and should require a smaller input of fertilizer for maximum yield.

One approach is the utilization quotient (Steenbjerg and Jakobsen 1963; Loneragan and Asher 1967) or the efficiency ratio (Gerloff 1976) defined as the reciprocal of the average tissue concentration (expressed as quantity of dry matter/unit quantity of mineral element). Unfortunately utilization quotients are not a constant property of a genotype, but undergo large changes, as much as tenfold, with changes in nutrient supply (Loneragan and Asher 1967). They also tend to increase with time as the proportion of structural material in the tissue increases. This will be greatly accelerated when plants are given a fixed initial supply of P and allowed to deplete this supply over time (Clark et al. 1978). In such experiments faster growing genotypes will deplete the supply more rapidly and at final harvest will have lower tissue concentrations and appear more efficient. These genotypes are also the most likely to develop nutrient deficiency symptoms (Clark et al. 1978) because of their rapid exhaustion of the culture medium. Efficiency of vegetative dry matter production may not always be a good predictor of efficiency of grain production, and the recent attempt to use grain production per unit of N uptake as an index of N efficiency (Maranville et al. 1980) appears to be a step in the right direction.

Research on efficiency of nutrient acquisition from the root environment and subsequent utilization seem likely to be of growing importance if the trend of steeply rising fertilizer prices continues. Practical benefits from such research appear some distance off, and may have to await improved understanding of the processes involved in efficiency differences among genotypes. Better methodology may prove to be the key to this improved understanding.

Diagnosis and Correction of Nutritional Problems in Sorghum

Visible Symptoms

Most nutritional disorders of crop plants produce visible symptoms which are useful for diagnostic purposes. Krantz and Melsted (1964) described symptoms of macronutrient and micronutrient deficiencies in maize, sorghum, and small grains. However, for the macronutrient elements most of the emphasis in the paper and all the photographs dealt with maize. They remarked that Mg deficiency of sorghum had not yet been reported. Subsequently Gallaher et al. (1975) observed Mg deficiency in grain sorghum and briefly described the symptoms. Kawasaki and Moritsugu (1979) reported Ca deficiency in maize and sorghum, and included photographs of the sorghum symptoms.

We believe that all researchers involved in field or glasshouse experiments with a major crop such as grain sorghum should have access to adequate descriptions of the symptoms of nutritional disorders likely to be encountered. There is a need for a color-illustrated bulletin dealing specifically with the nutritional disorders of sorghum including symptoms of toxicity and salt injury as well as deficiencies of the macronutrient and micronutrient elements.

Soil and Plant Analysis

Considerable yield reduction occurs before visible symptoms occur. Soil analysis data can be of considerable predictive value, indicating likely nutritional problems on a particular soil. As nutrient accumulations sometimes occur in the subsoil, the value of soil analysis can be enhanced if some measurements are made also on subsoil samples.

As with soil analysis, plant analysis tests require calibration before- they can be interpreted with confidence. Bennett (1971) concluded that differences in chemical composition between sorghum and maize growing in adjacent fields on the same soil type were sufficiently large and consistent to render inadvisable the use of maize critical concentration values for the interpretation of sorghum analyses.

Lockman (1972b) has published nutrient sufficiency ranges for N, P, K, Ca, and Mg plus some micronutrients, in field-grown grain sorghum at various stages of growth. This comprehensive statement falls short of providing precise critical concentration values. For S, no data were included for field grown plants although suggested ranges were given for young plants grown in sand culture. For Mg, the normal range of 0.2 to 0.5% in the third leaf from the top of the plant at bloom agrees with Gallaher et al. (1975) that grain sorghum responds to Mg fertilizer when Mg in the fourth leaf from the top falls below 0.2% at late pollination. With N, Lockman (1972b) considered 3.3 to 4.0% in the third leaf at bloom to be normal. At the same stage of growth Hipp and Gerard (1971) found that an average of about 2.3% N across all leaves was associated with maximum grain yield. At lower yield levels associated with poorer moisture supply, Brawand and Hossner (1976) reported linear releationships between grain yield and N and P in the second leaf from the top. Over the range 1.7 to approx. 3.5% N, grain yield increased 1.6 t/ha for each 1% increase in leaf N. and over the range 0.2 to 0.5% P. 1.14 t/ha for each 0.1% increase in leaf P. Further research on relationships between grain yield and leaf composition particularly in the presence of varying seasonal conditions is needed to place diagnosis based on leaf analysis on a firm basis. The suggested handbook of visible symptoms would be even more valuable if it included critical nutrient concentrations.

Fertilizer Experiments

Soil analysis and glasshouse pot experiments while providing much valuable information cannot adequately take into account many of the factors which strongly influence fertilizer responses in the field, e.g.. seasonal conditions, crop spacing and density, weed and pest control, fertilizer placement, single or split applications of fertilizer, and site drainage and water management. Hence field experiments are essential before soundly based recommendations can be made.

We believe that monitoring of weather conditions, soil characterization, and the frequency and detail of observation during the course of a field experiment, should be such as to allow an understanding of the fertilizer responses obtained. Only in this way can the results be extrapolated to other field situations with a

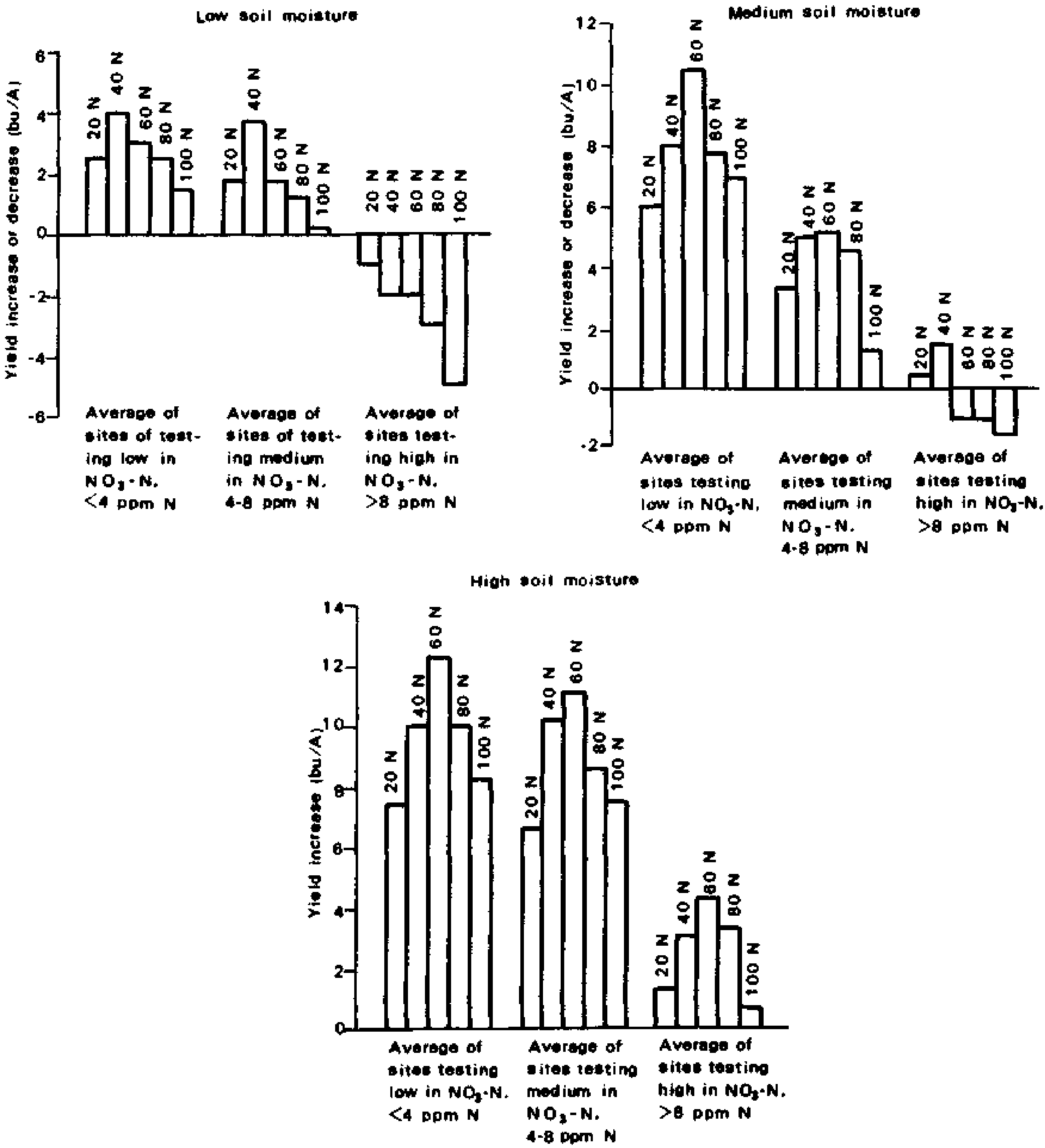

Figure 4. Grain sorghum yield response to applied nitrogen in Kansas as affected by soil moisture and nitrate at sowing time. (From C.A. Thompson 1974.)

differing mix of site factors. The initial soil characterization is particularly important. An example is seen in the report by Thompson (1974) where interpretation of the results of 58 field experiments has been made possible through relating the response to added N to the amounts of soil water in the profile at planting and the soil nitrate in the surface 30 cm of soil at planting (Fig. 4). At low soil moisture, the response was positive with medium or low soil nitrate, but negative at high soil nitrate. As soil moisture increased, the magnitude of positive response increased, the negative response at high nitrate changed to a positive response and the fertilizer requirement increased. The data of Hipp and Gerard (1971) may be taken as another example. Marked differences in crop response between fallowed and cropped land were due to differences in plant available N and the quantitative response of grain sorghum to N fertilizer could be predicted with reasonable certainty if the nitrate nitrogen in the top 120 cm of the profile was known prior to planting. Unfortunately the vast majority of reported field experiments cannot be so easily explained. Frequently, the relevant climatic or soil data or both are insufficient to allow interpretation of the response, let alone extrapolate to other situations. In general, we believe that available resources for research on fertilizer requirements of sorghum would be used more effectively if fewer experiments were carried out than at present, but each experiment was more fully and appropriately documented. While it is tempting to prescribe a minimum data set for all experiments, the data required will vary with the objectives of the experiment. Careful consideration of the principles of the nutritional physiology of the crop, as outlined in the first section of this paper, should allow the researcher to deduce what measurements are necessary for the interpretation of his experiment and allow a better understanding of the macronutrient nutrition of sorghum in the eighties.

References

ANDREW, C. S., and HENZELL, E. F. 1964. Mineral nutrition of plants. Pages 93-101 *in* Some concepts and methods in subtropical pasture research. Commonwealth Bureau of Pastures and Field Crops Bulletin no. 47. Famham Royal, UK: Commonwealth Agricultural Bureaux.

ASHER, C. J., and COWIE, A.M. 1974. Grain sorghum —high yield, satisfactory protein content or both? Proceedings of the Agronomy Society of New Zealand 4:79-82.

BARBER. L. E., TJEPKEMA, J. D., RUSSELL, S. A., and EVANS, H. J. 1976. Acetylene reduction (nitrogen fixation) associated with corn inoculated with *Spirillum.* Applied and Environmental Microbiology 32:108-113.

BENNETT, W. F. 1971. A comparison of the chemical composition of the corn leaf and the grain sorghum leaf. Communications in Soil Science and Plant Analysis 2:399-405.

BRAWAND, H., and HOSSNER, L. R. 1976. Nutrient content of sorghum leaves and grain as influenced by long-term crop rotation and fertilizer treatment. Agronomy Journal 68:277-280.

BROWN, J. C. 1978. Physiology of plant tolerance to alkaline soils. Pages 257-276 *in* Crop tolerance to suboptimal land conditions, ed. G. A. Jung. Madison, Wisconsin, USA: Amercian Society of Agronomy.

BROWN. J. C, CLARK, R. B., and JONES, W. E. 1977. Efficient and inefficient use of phosphorus by sorghum. Soil Science Society of America Journal 41 : 747-750.

BROWN, J. C. and JONES, W. E. 1975. Phosphorus efficiency as related to iron inefficiency in sorghum. Agronomy Journal 67:468-472.

CARVALHO, M. M. DE, ANDREW, C. S., EDWARDS, D. G., and ASHER, C. J. 1980. Comparative performance of six *Stylosanthes* species in three acid soils. Australian Journal of Agricultural Research 31:61-76.

CHAPCO. P. M. 1977. (Selection of fodder crops for. cultivation on alkali soils). Visnik Sil's'kogospodars'koi Nauki. No. 7, 50-55. 117-118, cited in Herbage Abstracts 48:428.

CLARK, R. B. 1982. Mineral nutritional factors reducing sorghum yields: Micronutrients and acidity. These Proceedings: ICRISAT.

CLARK. R. B., MARANVILLE, J. W., and GORZ. H. J. 1978. Phosphorus efficiency of grain sorghum grown with limited phosphorus. Pages 93-99 *in* Plant nutrition. 1978, Proceedings of the 8th International Colloquium on Plant Analysis and Fertilizer Problems, eds. A. R. Ferguson. R. L. Bieleski, and I. B. Ferguson. Wellington. New Zealand: Government Printer.

COWIE, A. M. 1973. Effects of nitrogen supply on grain yield and protein content in hybrid grain sorghum. Ph.D. Thesis, Department of Agriculture, University of Queensland, St. Lucia, Queensland, Australia.

Cox. W, J., and REISENAUER. H. M. 1973. Growth and ion uptake by wheat supplied nitrogen as nitrate, or ammonium, or both. Plant and Soil 38:363-380.

CRACK, B. J., and ISBELL, R. F. 1970. Studies on some solodic soils in north-eastern Queensland. 1. Morphological and chemical characteristics. Australian Journal of Experimental Agriculture and Animal Husbandry 10:334-341.

DART, P. J., and WANI, S P. 1982 Non symbiotic N_2-fixation and soil nitrogen status in the semi-arid tropics. Transactions of the 12th International Congress of Soil Science. 2:3-27, 8-16 Feb 1982, New Delhi, India.

EATON, F. M. 1942. Toxicity and accumulation of chloride and sulphate salts in plants. Journal of Agricultural Research 63:357-399.

EPSTEIN, E., CUNNINGHAM, G. A.. KELLEY, D. B., KINGSBURY, R. W., NORLYN. J. D.. RUSH, D. W.. and WRONA. A. F. 1978. Crop production in arid and semi-arid regions using saline water. Report to U.S. National Science Foundation, University of California, Davis, USA.

FAO (Food and Agriculture Organization). 1979. FAO production yearbook 1978. Rome, Italy: FAO.

FISCHER. K. S., and WILSON, G. L. 1975. Studies of grain production in *Sorghum* bicolor(L.) Moench. *V.* Effect of planting density on growth and yield. Australian Journal of Agricultural Research 26:31-41.

FORNO, D. A. 1977. The mineral nutrition of cassava *(Manihot esculenta* Crantz) with particular reference to nitrogen. Ph.D. Thesis, Department of Agriculture. University of Queensland, St. Lucia. Queensland, Australia.

GALLAHER, R. N., HARRIS, H. B., ANDERSON, O. E., and DOBSON, J. W., JR. 1975. Hybrid grain sorghum response to magnesium fertilization. Agronomy Journal 67:297-300.

GERLOFF, G. C. 1976. Plant efficiencies in the use of nitrogen, phosphorus and potassium. Pages 161-173 *in* Plant adaptation to mineral stress in problem soils, ed. M. J. Wright. Ithaca. New York. USA: Cornell University Experiment Station.

GOLOSWORTHY, P. R„ and TAYLER. R. S. 1970. The effect of plant spacing on grain yield of tall and short sorghum in Nigeria. Journal of Agricultural Science. Cambridge 74:1-10.

GREENWAY, H. 1973. Salinity, plant growth and metabolism. Journal of Australian Institute of Agricultural Science 39:24-34.

HAGEN, C E., and HOPKINS, H. T 1955. Ionic species in orthophosphate absorption by barley roots. Plant Physiology 30: 193-199

HART, B. T. 1974 A compilation of Australian water quality criteria. Australian Water Resources Council Technical Paper No 7. Canberra, Australia: Australian Government Publishing Service.

HERRON, G. M , GRIMES, D. W., and MUSICK, J. T. 1963 Effects of soil moisture and nitrogen fertilization of irrigated grain sorghum on dry matter production and nitrogen uptake at selected stages of plant development Agronomy Journal 55 : 393-396.

HIPP, B W., and GERRARD, C. J. 1971. Influence of previous crop and nitrogen mineralization on crop response to applied nitrogen. Agronomy Journal 63:583-586.

ISLAM, A. K. M. S. 1981. Effects of soil pH on yield and mineral nutrition of ginger *(Zingiber officinale* Roscoe). Ph.D. Thesis, Department of Agriculture, University of Queensland, St. Lucia. Queensland, Australia

JACQUES, G. L. VANDERLIP, R. L . and WHITNEY, D. A 1975. Growth and nutrient accumulation and distribution in grain sorghum. I. Dry matter production and Ca and Mg uptake and distribution. Agronomy Journal 67:607 -611.

JONES, R. K., and CRACK, B. J. 1970. Studies on some solodic soils in north-eastern Queensland. 2. Glasshouse assessment of plant nutrient status. Australian Journal of Experimental Agriculture and Animal Husbandry 10:342-349.

JORDAN, R. W., and SULLIVAN. C. Y. 1982. Reaction and resistance of grain sorghum to heat and drought. These Proceedings: ICRISAT.

JUNG, G. A. (ed.) 1979. Crop tolerance to suboptimal land conditions. Madison, Wisconsin. USA: American Society of Agronomy.

KAIGAMA, B. K„ TEARE, I. D., STONE, L. R., and POWERS, W. L. 1977. Root and top growth of irrigated and non-irrigated grain sorghum. Crop Science 17:555-559.

KAWASAKI, T., and MORITSUGU, M. 1979. A characteristic symptom of calcium deficiency in maize and sorghum. Communications in Soil Science and Plant Analysis 10:41-56

KRANTZ. B. A., and MELSTED, S. W. 1964. Nutrient deficiencies in com, sorghums and small grains. Pages 25-57 *in* Hunger signs in crops. 3rd Edition, ed. H. B. Sprague. New York,USA: David McKay Company Inc.

LAW, T. L, and EASTIN, J. D. 1969. Effect of soil depth and plant age on ^{32}phosphorus uptake by corn and sorghum. Agronomy Journal 61 :677-680.

LOCKMAN, R. B. 1972a. Mineral composition of grain sorghum plant samples. Part I: Comparative analysis with corn at various stages of growth and under different environments. Communications in Soil Science and Plant Analysis 3:271-281

LOCKMAN, R. B. 1972b. Mineral composition of grain sorghum plant samples. Part III: Suggested nutrient sufficiency limits at various stages of growth Communications in Soil Science and Plant Analysis 3 : 295 -303.

LONERAGAN, J. F., and ASHER, C. J. 1967. Response of plants to phosphate concentration in solution culture II. Rate of phosphate absorption and its relation to growth. Soil Science 103:311-318

MAAS, E. V.. and NIEMAN. R H 1978. Physiology of plant tolerance to salinity Pages 277-299 *in* Crop tolerance in suboptimal land conditions, ed. G A Jung Madison, Wisconsin, USA: American Society of Agronomy.

MALIWAL, G. L. 1967. Salt tolerance studies at germination. III. Jowar (*Sorghum vulgare),* mung *{Phaseolus aureus),* and tobacco *(Nicotiana tabacum)* varieties Indian Journal of Plant Physiology 10:95-104.

MARANVILLE, J. W., CLARK, R. B., and Ross, W. M 1980 Nitrogen .efficiency in grain sorghum. Journal of Plant Nutrition 2:577-589.

MOAWAD, M. 1979. Ecophysiology of the vesicular-arbuscular mycorrhiza in the tropics. Pages 197-209 *in* The soil-root interface, eds. J. L. Harley and R. Scott Russell. London, UK: Academic Press

MONADJEMI, M. 1976. Effect of ESP, soluble Na and P fertility on growth of wheat and sorghum. Ph.D. Thesis, Colorado State University, USA.

MORTVEDT, J. J. 1976. Soil chemical constraints in tailoring plants to fit problem soils. 2. Alkaline soils. Pages 141-149 *in* Plant adaptation to mineral stress in problem soils, ed. M. J. Wright. Ithaca, New York USA: Cornell University Experiment Station.

MYERS. R. J. K. 1978a. Nitrogen and phosphorus nutrition of dryland grain sorghum at Katherine, Northem Territory. 1. Effect of rate of nitrogen fertilizer. Australian Journal of Experimental Agriculture and Animal Husbandry 18:554-563.

MYERS, R. J. K. 1978b. Nitrogen and phosphorus nutrition of dryland grain sorghum at Katherine, Northern Territory. 2. Effect of rate ana source of phosphorus fertilizer. Australian Journal of Experimental Agriculture and Animal Husbandry 18:564-572.

MYERS, R. J. K. 1980. The root system of a grain sorghum crop. Field Crops Research 3:53-64.

NAKAYAMA, F. S., and VAN BAVEL, C. H. M. 1963. Root activity distribution patterns of sorghum and soil moisture conditions. Agronomy Journal 55 : 271 -275.

PATEL, P. M., WALLACE, A., and WALLIHAN, E. G. 1975. Influence of salinity and N-P fertility levels on mineral content and growth of sorghum in sand culture. Agronomy Journal 67 : 622-625

PATHMANABHAN, G., and RAO, J. S. 1976. Note on potassium as a possible index for screening sorghum varieties for salt tolerance. Indian Journal of Agricultural Science 46:392-394.

PEDERSEN, W. L., CHAKRABARTY, K., KLUCAS, R. V., and VIDAVER, A. K. 1978 Nitrogen fixation (acetylene reduction) association with roots of winter wheat and sorghum in Nebraska Applied and Environmental Microbiology 35: 129-135.

RAHEJA, P. C, and KRANTZ, B. A 1958 Growth, nutrient uptake, and yield of grain sorghums as influenced by fertilization in Imperial Valley, California Indian Journal of Agronomy 11 :125-132.

RAO, N G P.. and HOUSE, L. R. (eds.) 1972. Sorghum in seventies. New Delhi India: Oxford and IBH Publishing Co. 638 pp.

REDDY, K. R., REDDY, G. B., REDDY, M. R., and CHARI, A. V 1977. Effects of *Azotobacter* inoculation and nitrogen levels on yield of sorghum. Indian Journal of Agronomy 22:203-205.

ROY, R. N., and WRIGHT, B. C. 1974. Sorghum growth and nutrient uptake in relation to soil fertility. II. N, P, and K uptake pattern by various plant parts. Agronomy Journal 66: 5-10.

SANCHEZ, P. A. 1976. Soil fertility evaluation. Pages 295-345 *in* Properties and management of soils of the tropics. New York, USA: John Wiley and Sons.

SANORIA, C. L, and RAO, W. V. B. S. 1975. Effect of seed bacterization with *Azotobacter chroococcum* on sorghum and wheat. Indian Journal of Agricultural Science 45:224-226

SMITH. F. W., and MYERS, R. J. K. 1978. Patterns of uptake and distribution of phosphorus and nitrogen in grain sorghum during its development. Pages 491 -498 *in* Plant nutrition 1978—Proceedings of the 8th International Colloquium on Plant Analysis and Fertilizer Problems, eds A. R. Ferguson R. L. Bieleski, and I. B. Ferguson Wellington, New Zealand: Government Printer.

SRIVASTAVA, S P. 1971. Content and uptake of phosphorus by dwarf sorghum *{Sorghum vulgare* Pers). Indian Journal of Agronomy 16: 126-128.

STANFORD. G., CARTER, J. N„ WESTERMANN, D. T., and MEISINGER, J. J. 1977. Residual nitrate and mineralizable soil nitrogen in relation to nitrogen uptake by irrigated sugarbeets. Agronomy Journal 69 : 303-308.

STANFORD, G., and SMITH, S. J. 1976. Estimating potentially minerahzable soil nitrogen from a chemical index of soil nitrogen availability. Soil Science 122:71-76

STEENBJERG, F , and JAKOBSEN, S. T. 1963. Plant nutrition and yield curves. Soil Science 95:69-88.

STUTTE, C. A , and WIELAND, R .T. 1978. Gaseous nitrogen loss and transpiration of several crop and weed species Crop Science 18:887-889

TAYLOR, R. M . YOUNG, E J.. JR., and RIVERA, R. L. 1975. Salt tolerance in cultivars of grain sorghum Crop Science 15:734-735

THOMPSON. C. A 1974 Fertilizing dryland grain sorghum. Kansas State University Agricultural Experiment Station Bulletin No 579.

TJEPKEMA. J , and VAN BERKUM, P. 1977 Acetylene reduction by soil cores of maize and sorghum in Brazil Applied and Environmental Microbiology 33 : 626 629

WARNCKE, D. D., and BARBER. S. A. 1974 Nitrate uptake effectiveness of four plant species Journal of Environmental Quality 3:28-30.

WESTPHAL, E. 1975 Agricultural systems in Ethiopia Agricultural Research Report 826, Centre for Agricultural Publishing and Documentation. Wageningen. The Netherlands.

WETSELAAR, R., and FAROUHAR, G. D 1980 Nitrogen losses from tops of plants. Advances in Agronomy 33:253-299

WILSON, G. L. and EASTIN. J. D 1982. The plant and environment. These Proceedings: ICRISAT

WRIGHT, M. J. 1976. Plant adaptation to mineral stress in problem soils. Ithaca, New York, USA: Cornell University Experiment Station

Mineral Nutritional Factors Reducing Sorghum Yields: Micronutrients and Acidity

R. B. Clark*

Sorghum, like all plants, requires mineral elements to grow and complete its life cycle. Without proper supply, availability, and balance of mineral elements, plant productivity will be less than optimum. Therefore, it is important that these elements be maintained at adequate levels for plant use, that plants have a greater ability to use the elements present in the soil, or that plants have greater tolerance to deficient and toxic levels of mineral elements.

Deficiencies and toxicities of mineral elements in sorghum will vary among soils and geographic areas of the world where the crop is grown. Nitrogen is universally lacking in most soils and additions are needed for sorghum to grow properly. Supplemental amounts of the other elements may be needed, dependent on soil and previous cropping practices. Other than N, nearly one-fourth of the soils of the world (estimated at 2960 million hectares) have some kind of inherent mineral deficiency or toxicity problem (Dudal 1976).

Mineral element deficiency and toxicity problems in soils can often be related to the kind of parent material making up a particular soil. Because of this, many element deficiencies and toxicities may be predicted from the substratum of the soil and from the type of soil-forming processes characteristic of the soil (Dudal 1976). In other soils, mineral problems may not be consistent with soil classes because of variability within soils. The distribution of mineral element deficiencies and toxicities depends on the distribution of soil groups and has often been associated with the pH of soils.

Even though distinct separations between acid and alkaline soils are difficult to make, the amount of precipitation compared to the evapotranspiration, has often been used to separate them. If precipitation exceeds evapotranspiration, the soils are usually acid. If precipitation does not exceed evapotranspiration, the soils are usually neutral or alkaline. A general boundary between acid and alkaline soils is the natural boundary between areas where forests and prairies predominate (Flach 1976).

Alkaline soils usually contain fairly high amounts of salts in the profile. If groundwater is high or irrigation mismanaged, these soluble salts may accumulate at the soil surface and soils may become saline. Except for special conditions, alkaline soils are usually adequately supplied with Ca, Mg, and K. Sulfur deficiencies and B toxicities may occur on alkaline soils, and Mo is often high. Most alkaline soils contain sufficient Fe to supply plants indefinitely, but the Fe may not be readily available for plant use. Many soils that are neutral or alkaline are often calcareous.

Acid soils are usually low in exchangeable bases, highly leached, and may be high in Al. Fe, and Si oxides. Nearly all elements have to be added to maintain fertility in acid soils, and P availability is of special concern. The availability of Al, Mn, and Fe increases with acidity and these elements at sufficiently high levels are toxic. Nearly half of the nonirrigated arable lands and about one-third of the total land mass of the world are acid (Fig. 1).

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81. Patancheru. A.P., India. Patancheru, A.P. India: ICRISAT.

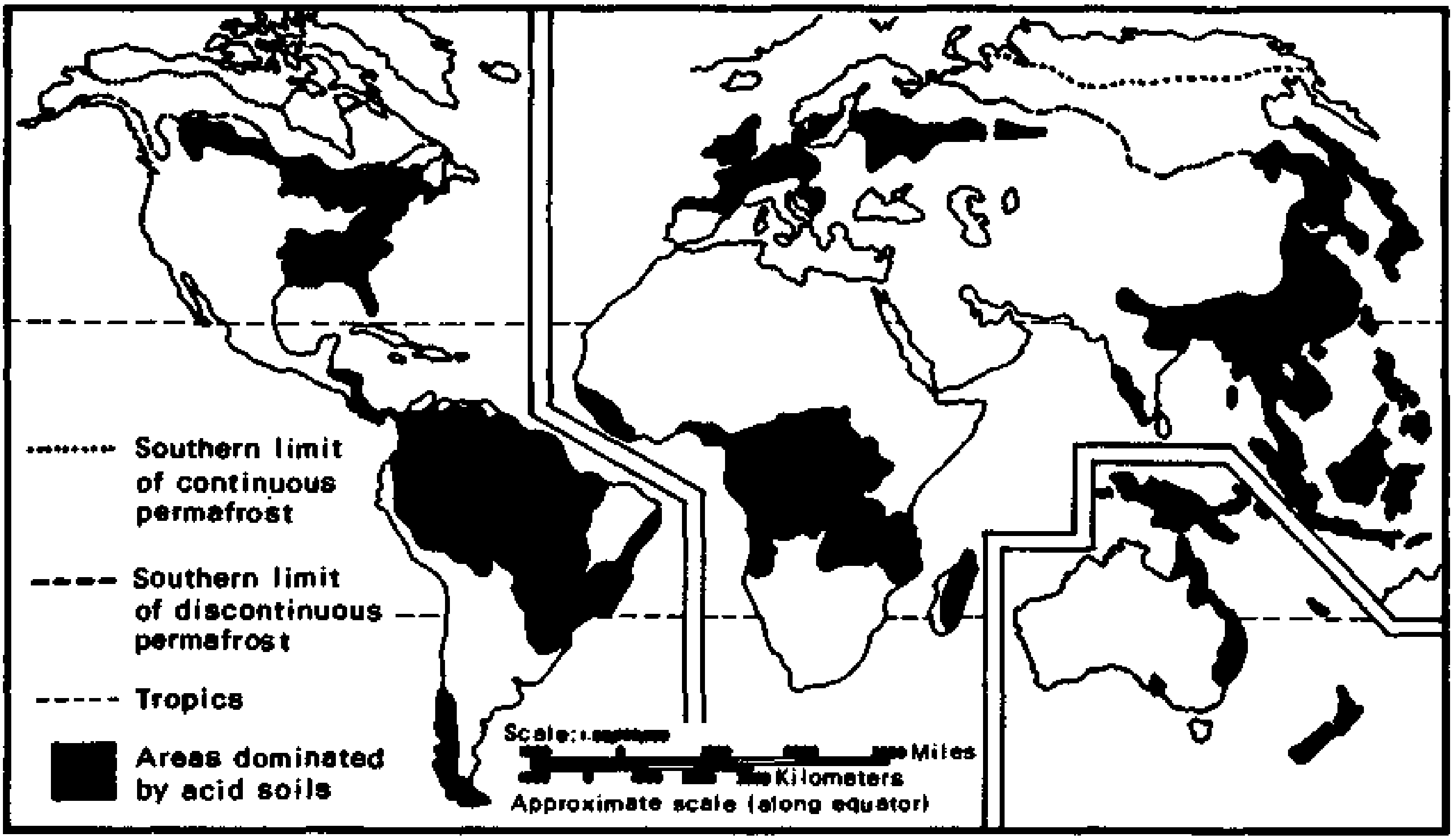

Figure 1. Distribution of acid soils in climates warmer than cryic throughout the world (from Van Wambeke).

Micronutrients

Micronutrient deficiencies occur on both alkaline and acid soils, but micronutrient toxicities occur mostly on acid soils, except for 6, unless unique conditions exist. By far, the most serious micronutrient problem in sorghum in the USA is Fe deficiency; sorghum is very susceptible to Fe deficiency. Iron deficiency occurs almost exclusively on neutral or alkaline, primarily calcareous soils. Iron toxicities may occur on acid soils, but these are relatively minor compared with other problems. To a much lesser extent, Zn deficiency is also a serious micronutrient deficiency problem for sorghum, and this occurs on both alkaline and acid soils. Few Zn toxicity problems arise unless plants are grown under high Zn conditions, such as on exposed mine and industrial waste sites. Manganese deficiency could be a problem for sorghum grown on alkaline soils, but few cases are reported; sorghum is fairly tolerant to low Mn. On acid soils, Mn toxicity may be a problem and is usually more of a problem than Mn deficiency is on alkaline soils. Cases of Cu, B, and Mo deficiency in sorghum are relatively few, and if they occur, Cu and Mo deficiency are most likely to appear on acid or high organic soils. Toxicities of Cu and Mo could occur if plants are grown on high Cu and Mo soils. Boron toxicity could occur when plants are grown on alkaline soils under high B conditions or with irrigation water high in B.

Soils and environmental conditions most likely to enhance micronutrient deficiencies are listed in Table 1. Micronutrient reactions in soils, relative susceptibilities or sensitivities of various crop plants and genotypes to low levels of micronutrients, visual deficiency symptoms of micronutrients, and means for alleviating micronutrient deficiencies are discussed extensively elsewhere (Brown et al. 1972; Lucas and Knezek 1972; Mengel and Kirkby 1979; Mortvedt and Cunningham 1971; Murphy and Walsh 1972), and will not be discussed in detail. A recent article describes micronutrient deficiency (and toxicity) symptoms and their effects on other mineral elements in sorghum (Clark et al., in press). In addition, two symposia on Cu ("Copper in soils and plants", in Australia) and Fe ("Iron nutrition and interactions in plants", in USA) have been held within recent months. The proceedings from these conferences should give interested readers information and research findings about these elements in plant-soil systems.

Table 1. Soils and environmental conditions that favor micronutrient deficiencies (Lucas and Knezek 1972, Mangel and Kirkby 1979, Mortvedt and Cunningham 1971, Murphy and Walsh 1972).

Element	Soils and Conditions
Iron	Low soil Fe (alkaline and acid); Neutral, alkaline, and especially calcareous soils; High $CaCO_3$ HCO^-_3, P, Cu. heavy metals, and pH; Cool weather; Wet or flooded conditions; Poor aeration; Low organic matter; Root damage; Susceptible genotypes
Zinc	Low soil Zn (Haplaquepts, Haplaquolls, Fluvents, Udipsamments, Histosols); Acid sandy, neutral, alkaline, and calcareous soils; Low organic matter in mineral soils; High rainfall areas; Cool weather; High P, N, Ca ($CaC0_3$), Mg, Fe, Cu, heavy metals, and pH; Restricted root zones (compacted soils or container-grown plants); Wet and flooded conditions; Subsoils exposed from land levelling or disturbances.
Manganese	Low soil Mn, poorly drained soils [Histosols, Aquods (ortstein), Udents, Udipsamments, Haplaquepts, Limmic Medisaprists (marly)|; Slightly acid, sandy neutral, alkaline, and especially calcareous, peat, and muck soils; High $CaCO_3$, Fe. Cu, Zn, and pH; Dry weather; Low light intensity. Low soil temperatures.
Copper	Sandy, muck, and peat soils; mineral soils with <5-6 *µglg* Cu, and organic soils with <30 µg/g Cu; High P. N, and Zn.
Boron	Low soil B (Fluvents, Spodosols, Histosols, Udipsamments, and Haplaquepts); Soils formed from acid igneous rocks or fresh-water sedimentary rocks; Leached acid, sandy, acid peat, or muck, some neutral, alkaline, and calcareous soils; Low organic matter in some soils; Moderate to heavy rainfall; Dry weather; Quantity (high) and quality of light.
Molybdenum	Low soil Mo [Udipsamments, Spodosols, Histosols, Aquods (orstein)]; Acid, sandy, highly podzolized, high in Fe and Al oxides, neutral and calcareous soils; High pH and Fe (soluble).

Iron Deficiency

Iron deficiency has been reported for many countries, and is a universal problem wherever alkaline or calcareous soils prevail. Sorghum is very susceptible to Fe deficiency. Because sorghum is relatively tolerant to drought and low water conditions, its production is found extensively in areas that receive limited amounts of precipitation, or where alkaline soils prevail.

In the USA, 75% of the area and total production of sorghum in 1979 was in Kansas, Texas, and Nebraska (USDA 1980, p.52). If the bordering states of Colorado, Iowa, Missouri, New Mexico, Oklahoma and South Dakota are included, the overall grain sorghum hectarage and production in these States then becomes 93% of the total in the USA. As such, a large amount of the sorghum produced in the USA is on neutral or alkaline soils.

Once the Fe from the seed has been exhausted by developing seedlings, plants must rely on the roots (or leaves in foliar applications) to supply sufficient Fe for continued growth. Since Fe availability in neutral and alkaline soils is low, young plant roots have not usually extended very far in the soil to make contact with sufficient Fe, or environmental conditions are conducive (usually cool and wet) to inactivate Fe and young sorghum plants many times turn yellow or chlorotic (Fe deficiency). Iron-deficient sorghum is a common sight in many fields of the Great Plains, USA, (Fig. 2). The chlorotic condition of the plants is not usually uniform, and plants in some areas of the field are green while adjacent plants are chlorotic. With time, most sorghum plants become green, and eventually produce a harvestable product with no readily apparent deficiency problems. Yields may have been reduced, but the extent of the losses are not generally known. The severity of Fe deficiencies varies from season to season, even on the same soils and on sites within fields.

Alleviation of Fe deficiencies in sorghum has usually been by soil or foliar applications of Fe and non-Fe compounds. If foliar applications of Fe are given, they normally have to be administered two or three times during the growing season or on the same crop. This is because Fe within the plant is relatively immobile, and as new growth appears it becomes chlorotic unless additional Fe is available. Soil applications of Fe may be more long-lasting than foliar applications during a grow-

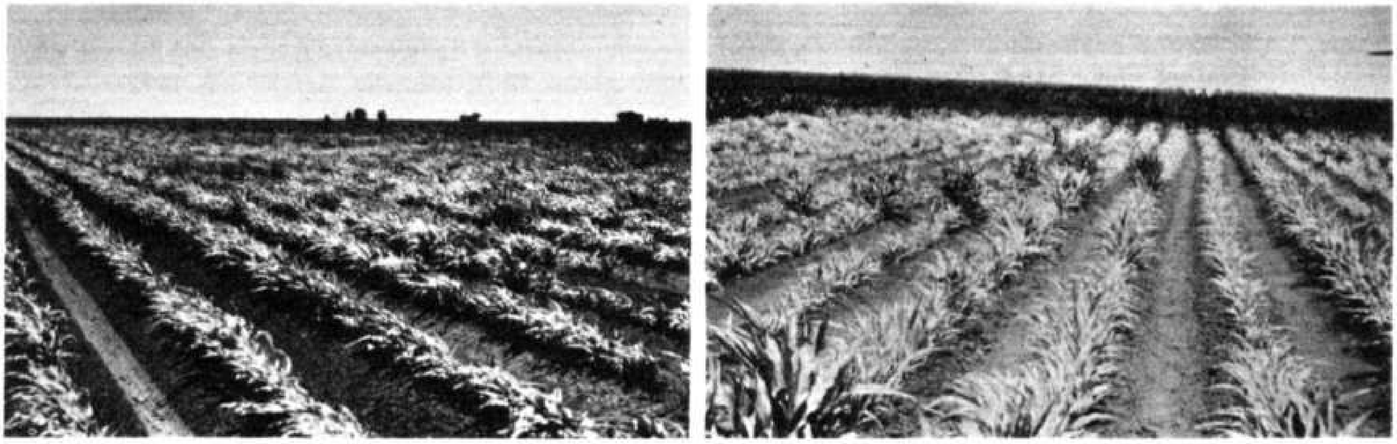

Figure 2. Iron-deficient sorghum fields in the Great Plains states (USA).

ing season or crop, but they must be repeated on the following crop or season because soil conditions favor the relatively rapid inactivation of Fe. The action of materials added to alleviate Fe deficiency is primarily to provide compounds that chelate Fe or to reduce the soil pH (at least a portion near the plant roots) to make Fe more available. Regardless of material added or used, Fe must be added frequently to maintain green plants. The residual effect of Fe amendments is low.

Plant species, including sorghum, differ in their ability to grow and develop under low Fe or under Fe deficiency conditions. Dicotyledonous plants generally grow better at low Fe and respond to Fe deficiency stresses better than monocotyledonous plants. Differences in these types of plants and how they respond to Fe deficiency have recently been reviewed (Clark et al. 1981).

Sorghum genotypes show differences in their ability to remain green and grow and develop under Fe deficiency conditions (Brown and Jones 1975, 1976, 1977; Brown et al. 1977; Esty et al. 1980; Kannan 1980a, b; Mikesell et al. 1973; Muhsi and Langston 1975; Williams et al., in press; Yusuf 1980; Yusuf and Clark 1979). Taking advantage of these genetic differences to develop plants with the ability to withstand low Fe has received considerable attention in recent years as a method to help alleviate Fe deficiency problems.

Genetic control of Fe deficiency in plants has been known for nearly 40 years, but has not been advantageously utilized. In sorghum, genotypes that have the ability to remain green and grow well at low Fe have been noted and identified as they were planted side by side on field sites where Fe deficiencies appeared. Screening sorghum genotypes for their ability to grow well at low Fe in both nutrient solutions and soils has been in progress for some years. Iron deficiency ratings of sorghum in nutrient solutions have agreed with field observations. However, relationships of nutrient solution ratings with grain or final product yields have not been assessed. The performance of sorghum F, progeny indicates that the ability of plants to grow well under Fe deficiency conditions is dominant. Duvick et al. (1981) suggested that pedigree breeding methods, using nutrient solution screening methods to determine differences among genotypes, might be used to develop better genotypes. If the ability of a plant to grow well under Fe deficiency conditions is dominant, only one parent needs to have that trait in an improved single-cross hybrid.

The most significant progress and achievement of purposeful breeding for plant ability to perform well at low Fe has been with soybeans. Soybean breeders have developed high yield, "tolerant" genotypes and have identified them for this trait when they are released for commercial use. Considerably more information is available on the inheritance, genetics, and control of plant abilities to grow with low Fe in soybeans than for any other plant species. There is no reason why improved sorghum genotypes canot be identified and developed for the ability to withstand Fe deficiencies which are widespread in the major sorghum production areas. Research efforts in this area are sorely needed, and improved hybrids for Fe deficient soils would be readily welcomed. Some areas that would otherwise grow sorghum cannot because of the seriousness of Fe deficiency problems.

Zinc Deficiency

Zinc deficiencies are relatively common throughout the world. Zinc deficiencies are found in relatively small soil areas as well as entire fields. Conditions that seemingly enhance Zn deficiencies are listed in Table 1. Like many of the cereals and grasses, sorghum is relatively tolerant to low levels of Zn. When Zn deficiencies have been noted in sorghum, many reports have been from India where extensive Zn deficiency problems occur (Randhawa et al. 1974).

Zinc deficiencies are readily corrected and alleviated by additions of Zn to soils. Zinc applications to soils last for several years, so Zn applications may not be needed often.

Differences among cultivars for ability to grow well at low Zn have been noted for a number of plant species, including sorghum (Rao et al. 1979; Shukla 1975; Shukla et al. 1973). As Mortvedt and Cunningham (1971) pointed out, "selection and development of hybrids which have a capacity for absorption and translocation of Zn may prove to be the best method for controlling Zn deficiencies in some crops". Advantage should be taken of these genotype differences to improve sorghum performance under Zn deficient conditions. The mode or source(s) of inheritance have not been identified for these plants. No doubt, improved sorghum genotypes could and should be developed for areas in Australia and India, where Zn deficiency is a major problem.

Manganese Deficiency

Manganese deficiency has been reported on many soils throughout the world. Many plant species, including the cereal crops, are quite susceptible to Mn deficiency. Although sorghum has been reported to be highly susceptible to Mn deficiency relative to some other crops, Mn deficiencies have seldom been observed in field-grown sorghum.

Manganese deficiencies are readily corrected with foliar or soil applications of Mn. The residual effects of added Mn vary, but the rates of Mn usually applied in the field are seldom sufficient to give any effective carryover for succeeding crops.

Genotype differences to Mn deficiency have been noted for several plant species, but only limited information on the heritability of tolerance to Mn deficiency exists. Screening sorghum genotypes for differences in tolerance to low (and high) Mn has recently begun in our laboratory. Preliminary results indicate that sorghum genotypes show considerable differences when grown at low levels of Mn in nutrient solutions. Improvement of sorghum for this trait appears feasible, but the amount of variability among sorghum genotypes and the mode of inheritance have not been investigated. Definitive answers on the progress that could be made for improving sorghum to withstand Mn deficiency conditions are unknown.

Copper Deficiency

Copper deficiencies are found primarily on humus rich and highly weathered sandy soils. However, Cu deficiencies may be found under various other soil conditions where Cu is low (Table 1). Problems of Cu deficiency have been reported extensively from Australia and New Zealand. Sorghum is not very susceptible to Cu deficiency, but Cu deficiency was noted on a sorghum genotype grown in an acid soil known to induce Cu deficiencies in many other plants {Brown et al. 1977), and Cu deficiency was induced in sorghum when plants were grown with high amounts of organic matter (half or more of the soil mixture volume) (Brown 1956). Except for artificially induced Cu deficiency conditions, reports of Cu deficiency in sorghum are not common. Copper deficiencies are often mistaken for Ca deficiencies, since Cu deficiencies closely resemble Ca deficiencies (Brawn et al. 1977).

Copper deficiencies are readily corrected by foliar or soil applications of Cu. Soil applications are used more frequently than foliar applications for field crops. Residual effects of Cu are long-lasting, and the magnitude of the effect depends on the rates of application and the soil type.

Cultivar differences for Cu deficiency have been reported for sorghum (Brown et al. 1977) and other plants. Even though genotypic differences have been noted within plant species, information on inheritance of these traits has not been reported. Recently, a unique, but important method for the incorporation of improved ability to withstand Cu deficiency was reported in wheat (Graham 1978).The trait for the ability of rye to grow well at low levels of Cu was located on one arm of a single chromosome and was transferred to triticale *(Triticalex).* and in turn, the relevant rye chromatin was transferred (by translocation) to wheat.

Boron Deficiency

Boron deficiencies may occur frequently on plants grown on soils in humid regions, especially on acid, sandy soils (Table 1). Monocotyledons usually require less B than dicotyledons. Dicotyledons with latex systems require even more B. Sorghum, a monocotyledon and member of the grass family, requires very little B. and as such, tolerates low B conditions. Reports of B deficiency in sorghum are nil, and attempts to induce B deficiency in sorghum grown in nutrientsolutions or in various soils have been unsuccessful.

Boron deficiencies are readily corrected for most other crops with soil or foliar applications of B; soil applications are more frequently used than foliar applications. Residual effects are relatively good (up to 3 years) from soil applications, dependent on soil type and moisture.

Molybdenum Deficiency

Molybdenum deficiencies have been reported in North America, Australia, and New Zealand. Few Mo deficiencies have been found in plants that have low requirements for Mo, especially for the nonleguminous plants. The Mo requirements for sorghum are low. Attempts to induce Mo deficiency in sorghum have been unsuccessful, although Mo deficiencies in maize have been noted by a number of investigators (Clark 1976).

Although genotypic differences to Mo deficiency have been noted for many plants, the economic advisability of breeding for this trait is questionable. Unless specialized conditions exist, the need to develop plants, especially sorghum, for the ability to withstand low Mo conditions does not appear warranted.

Acidity

For plants grown on acid soils, mineral element problems that occur most frequently are Al. Mn, and Fe toxicities and P, Zn, Ca, Mg, and Mo deficiencies. Any one of these mineral element problems can be severe and limit crop productivity. The most commonly reported mineral nutritional problems on acid soils are Al toxicity and P deficiency. Reactions and chemistry of these elements in acid soils, the physiology and chemistry of toxicities, means for alleviating these problems, and inheritance of these traits in plants are discussed in other articles (Adams 1981; Duvick et al. 1981; Foy 1973; Foy et al. 1978; Foy and Fleming 1978; Kamprath and Foy 1971; Lafever 1981; Sanchez and Uehara 1980).

Aluminum Toxicity

Aluminum toxicity is an important growth limiting factor for many crop plants grown on soils near pH 5.0 or below. It is especially serious for acid subsoils that are difficult to lime and is intensified by leaching and applications of some N fertilizers. Aluminum toxicity decreases the rooting depth and ability of plants to absorb water and nutrient elements.

Acid soils occur over much of the world, thus Al toxicity is a fairly common problem. South America has extensive Al toxicity problems since so much of the land is acidic (Fig. 1). Alleviation of Al toxicity problems is usually achieved through liming. Liming also improves the availability of many other mineral elements by increasing the pH. Adding lime may not be the only solution to alleviate Al toxicity problems in some soils because the applied lime may not reach the subsoil. In addition, liming may be more of a detriment than a benefit for some plants. Residual effects of lime amendments vary and depend on such factors as soil type, the rate of Ca and Mg replacement on soil exchange sites, the rate and kind of lime applied.rainfall, and the crop to be grown. Lime effects have been reported to last three to five years in some tropical soils, but generally longer in soils of the temperate regions. Some plants require less lime than others; legumes usually benefit more than grasses and cereals from higher additions. Phosphorus may also help alleviate Al toxicity problems, but the amount of P needed to inactivate Al is more costly than that for lime amendments.

Foliar symptoms of sorghum grown with high levels of Al usually resemble P deficiency, but reports of Al-toxic plants showing other element deficiencies have been recorded (Furlani, P.R. 1981; Furlani and Clark 1981). Root injury is the most prominent and clearly discernible symptom of Al toxicity; root elongation stops, tips and lateral roots become thick and turn dark, roots lack fine branching, and roots become stubby, corraloid, and brittle (Fig. 3).

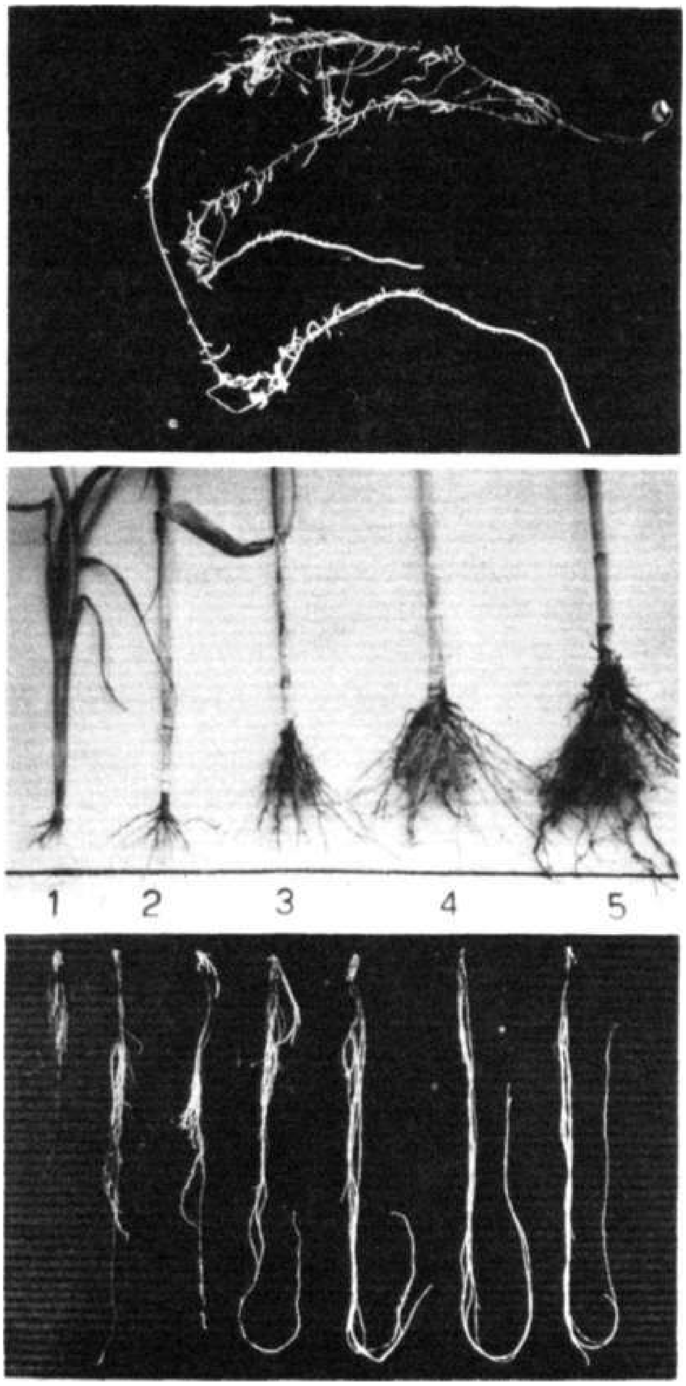

Figure 3. Aluminum toxicity symptoms and differences in sorghum genotypes for the ability to grow with Al. Upper. *closeup of sorghum root of plant grown with Al;* Middle, *five plants from a field plot showing root differences for plants grown in acid soil conditions (Sete Lagoas, Brazil);* Lower: *(left to right): differences in sorghum genotype roots (NB3494), TX415, Martin, KS57, Wheatland, NB9040, and SC369-3-IJB) grown with Al in nutrient solution.*

A promising method for overcoming Al toxicity has been to identify and develop plants with improved traits to withstand Al toxicity or acid soil conditions. Many plant species have genotypes that tolerate higher levels of Al than others. Sources of "tolerance" for the various plant species vary extensively and may not necessarily come from geographical areas where they might be expected to be located. Genetic control of "Al-tolerance" has been found for many plant species.

From studies on the inheritance of plants subjected to high levels of Al, the trait appears to be controlled by one or more major dominant genes, with modifier genes and different alleles being involved. Thus, inheritance of "Al-tolerance" in plants, including sorghum, is complex (Duvicketal. 1981; Furlani, P.R. 1981; Furlani et al. 1980; Lafever 1981). Preliminary studies with sorghum indicate that maternal (cytoplasmic) factors do not affect "Al-tolerance" (Furlani 1981). Even though nearly all studies with differential "Al-tolerance" in plants have found that inheritance is not simple, progress is being made in the improvement of genotypes since the trait has dominance. Duvick et al. (1981) suggested that where "Al-tolerance" is heritable, both pedigree and recurrent selection methods should improve plants for these traits. Results from screening genotypes in soils or nutrient solutions under controlled environments have agreed well with field responses in many cases, but few studies have confirmed screening results with field (grain yield) results.

The ability of sorghum to grow well in acid and high Al soils appears to be controlled by single genes. Grain yields for hybrids have been as high as for parents. Sorghum hybrids from selected male parents crossed to two Combine-Kafir-60 female parents containing different male-sterile cytoplasms showed no differences in "Al-tolerance". However, the male parents greatly influenced the "Al-tolerance" noted in the hybrids.

Sorghum generally has been considered to have a lower ablity to tolerate Al than many other crop plants. Even so, extensive differences in "Al-tolerance" have been reported for sorghum genotypes (Fig. 3, Duncan 1981a, b,c; Furlani 1979; Furlani, P.R. 1981; Furlani et al. 1980; Furlani and Clark 1981; Pitta et al. 1976, 1979a,b; Schaffert et al. 1975). Much of the early research on sorghum was conducted in Brazil. In the

Brazilian studies, genotypes found to grow well in acid soils and with relatively high Al were TX2536, ISI0926, BR006R, SC112-4, SC418, SC048, SC283, and SC175-14 (Schaffert et al. 1978). In field experiments, only five out of several hundred genotypes tested were considered to be "Al-tolerant". Even though this number may be low for the number of genotypes tested, these few genotypes may be the germplasm needed to help make good progress in improving sorghum for adaptation to the high levels of Al that exist in some acid soils.

Studies in the USA confirm that superior "Al-tolerance" traits can be identified in sorghum genotypes by either nutrient solution or field screening. "Aluminum-tolerance" has also been identified in individual plants from random mating populations. Nutrient solution screening results have agreed relatively well with field responses.

Manganese and Iron Toxicities

Manganese and Fe toxicities are problems generally associated with acid soil conditions, although incidents of these toxicities under other than acid soils have been reported. Manganese toxicity usually occurs in plants grown on soils formed from parent materials high in Mn or on soils exposed and associated with high Mn containing materials such as mine spoils, and on flooded or compacted soils. Manganese toxicities have been reported for a number of plants grown in Arkansas soils in the USA. Iron toxicity has been reported for plants grown under flooded or waterlogged conditions and on acid sulfate soils and Latosols.

Manganese and Fe toxicities have been reported for many plant species. Some plants tolerate excess Mn and Fe better than others. Among several tropical grasses, *Sorghum x alum* Parodi had intermediate ability to grow well with high Mn compared with the other grasses tested (Smith 1979).

Differences in genotypic abilities to withstand excess Mn have been noted. These differences have been investigated to some extent to determine feasibilities of improving plants for their ability to grow with excess Mn. Because Mn and Fe toxicities occur so sporadically in sorghum, the amount of effort that should be spent in this area is questionable.

Phosphorus Deficiency in Acid Soils

Phosphorus deficiencies in plants are common and serious in acid soils and have been closely associated with high Al. Some of the worst P deficiencies this author has witnessed were seen on acid, Al toxic soils of Brazil (Fig. 4). Alleviation of P deficiencies can be accomplished by adding P fertilizers. Readers interested in P nutrition of plants in general and in tropical and acid soils are referred to articles contained in Khasawneh et al

Figure 4. Sorghum plot (left) and field (right) showing the effects of added phosphorus on acid soils (Planaltina, Brazil). Note that plants show very little growth outside the area where phosphorus was added.

(1980). Olson et al. (1971). and Sanchez (1976).

The ability of plants to survive, grow, and produce under low P conditions depends on plant abilities to absorb and utilize P relative to their requirements for growth and development. Plants that can grow under low levels of P have different mechanisms whereby they can survive these conditions. The behavior of plants and of P under these conditions has been recently discussed (Loneragan 1978).

The variability of plant species and genotypes within species to absorb and utilize P has been reported for many years, but attempts to understand the genetics involved and to advantageously utilize these traits for breeding purposes have been relatively recent. Inheritance of plant ability to grow with low P shows various patterns: overdominance, multigenetic, and maternal patterns.

In sorghum, the ability to grow at low P appears to be heritable (Furlani, A.M.C. 1981). Higher general combining ability variances were noted for male parents that did not withstand low P. Greater "tolerance" to low P was associated with larger roots and tops and higher dry matter production per unit P. Differences in female parents for producing larger roots were also noted.

Calcium and Magnesium Deficiencies

Acid soils may have Ca and Mg deficiencies because of low cation exchange capacity and leaching. Calcium and Mg deficiencies associated with plants grown in acid soils may be more prevalent because of the effects of high Al than from low Ca and Mg per se. Where acid soils are limed to alleviate Al toxicity or acid problems, Ca (and often Mg) is added because Ca and Mg are components of lime. Thus, Ca and Mg deficiencies are usually alleviated by additions of lime.

Intraspecific genotypes differ in their ability to absorb and accumulate Ca and Mg and wide differences among genotypes exist. Sorghum genotypic differences for Ca and Mg have received little or no attention, but if an effort were made, differences would likely be found.

Conclusions

Mineral element deficiencies and toxicities can reduce sorghum yields extensively if the crop is grown under mineral stress conditions. With few exceptions, most of the mineral stress conditions can be alleviated by foliar or soil applications of the appropriate element or by the addition of lime. This may not be feasible nor practical in many cases because of such factors as high costs and unavailability of the appropriate materials and means of application, timeliness of application, and unexpected or sporadic development of specific problems. For many of the plant species that have been studied, considerable differences in the ability of plants to grow well under mineral stresses have been noted within genotypes. Differences among sorghum genotypes should be used advantageously to improve plants with the ability to withstand low or high levels of mineral elements. Some differences in sorghum to withstand mineral stresses have been reported, but the extent and variability of these differences in the sorghum germplasm pools have not been identified. Mineral stress performances have been improved in several plants through breeding efforts, and the traits appear to be heritable; in many cases the trait is dominant. The development and improvement of sorghum with a greater capability to adapt and perform on mineral stressed soils appears feasible and practical. Identification of the appropriate genotypes and their use in breeding programs could enhance the adaptability of sorghum for mineral stress conditions. Sorghum developed for these stress conditions could help assure greater stability of yields, lead to more dependable crop production, and help reduce costs and inputs needed for production. Plants should be developed to fit soil conditions as they exist rather than continually change the soil to fit the needs of pfants. This approach would be particularly important for helping overcome some of the severe Fe, Zn, and P deficiency and Al and Mn toxicity problems commonly encountered on soils used for the production of sorghum.

References

ADAMS, F. 1981. Nutritional imbalances and constraints to plant growth on acid soils. Journal of Plant Nutrition 4:81-87.

BROWN, J. C. 1956. Iron chlorosis. Annual Review of Plant Physiology 7:171-190.

BROWN, J. C, AMBLER. J. E., CHANEY, R. L, and FOY, C. D. 1972. Differential responses of plant genotypes to micronutrients. Pages 389-418 *in* Micronutrients in agriculture, eds. J. J. Mortvedt, P. M. Giordano, and W. L. Lindsay. Soil Science Society of America, Madison, Wisconsin.

BROWN, J. C, CLARK, R. B., and JONES, W. E. 1977 Efficient and inefficient use of phosphorus by sorghum. Soil Science Society of America Journal 41 : 747-750

BROWN, J. C, and JONES, W. E. 1975. Phosphorus efficiency as related to iron inefficiency in sorghum Agronomy Journal 67 :468-472.

BROWN, J. C, and JONES, W. E. 1976. A technique to determine iron efficiency in plants. Soil Science Society of America Journal 40: 398-405.

BROWN, J. C, and JONES, W. E. 1977. Fitting plants nutritionally to soils. III. Sorghum. Agronomy Journal 69:410-414.

CLARK, R. B. 1976. Plant efficiencies in the use of calcium, magnesium, and molybdenum. Pages 175 -191 *in* Plant adaptation to mineral stress in problem soils, ed. M. J. Wright. Ithaca, New York, USA: Cornell University Agricultural Experiment Station.

CLARK, R. B., BROWN, J. C, OLSEN R. A., and BENNETT, J H. (in press). Biological aspects of iron in plants. *In* Iron and its compounds, eds. S. Que Hee and V. N. Finelli

CLARK, R B., PIER. P. A., KNUDSEN, D., and MARANVILLE, J W. 1981 Effect of trace element deficiencies and excesses on mineral nutrients in sorghum. Journal of Plant Nutrition 3:357-374.

DUDAL, R. 1976. Inventory of the major soils of the world with special references to mineral stress hazards Pages 3-13 *in* Plant adaptation to mineral stress in problem soils, ed. M. J. Wright. Ithaca, New York, USA: Cornell University Agricultural Experiment Station.

DUNCAN, R. R. 1981a. Genetic variation in the uptake of critical elements for sorghum lines grown on an acid soil in Georgia. *In* Proceedings of 12th Grain Sorghum Research and Utilization Conference, Lubbock, Texas, USA.

DUNCAN, R. R. 1981b. Variability among sorghum genotypes for uptake of elements under acid field conditions Journal of Plant Nutrition 4:21-32.

DUNCAN, R. R. 1981C. Registration of GPIR acid soil tolerant sorghum germplasm population (Registration No. GP73). Crop Science 21 :637

DUVICK, D. N.. KLEESE, R. A„ and FREY. N. M. 1981. Breeding for tolerance of nutrient imbalances and constraints to growth in acid, alkaline, and saline soils. Journal of Plant Nutrition 4:111-129.

ESTY, J. C, ONKEN. A. B., HOSSNER, L. R., and MATHESON, R. 1980. Iron use efficiency in grain sorghum hybrids and parental lines. Agronomy Journal 72:589-592.

FLACH, K. W. 1976. Formation, distribution, and consequences of alkaline soils in agricultural development Pages 25-30 *in* Plant adaptation to mineral stress in problem soils, ed. M. J. Wright. Ithaca, New York, USA: Cornell University Agricultural Experiment Station.

FOY, C. D. 1973. Manganese and plants. Pages 51 -76 *in* Manganese. National Academy of Sciences. Washington, D.C., USA: National Research Council.

FOY. C. D., CHANEY, R. L, and WHITE, M. C .1978. The physiology of metal toxicity in plants. Annual Review of Plant Physiology 29: 511 -566.

FOY, C. D., and FLEMING, A. L. 1978. The physiology of plant tolerance to excess available aluminum and manganese in acid soils. Pages 301-328 *in* Crop tolerance to suboptimal land conditions, ed. G. A. Jung. Madison, Wisconsin, USA: American Society of Agronomy.

FURLANI, A. M. C. 1981. Differences in phosphorus uptake, distribution, and use by sorghum genotypes grown with low phosphorus. Ph.D. Dissertation, University of Nebraska, Lincoln, Nebraska, USA. 103 pp

FURLANI, P. R. 1979. Screening sorghum for aluminum tolerance. M. S. Dissertation, University of Nebraska, Lincoln, Nebraska, USA. 124 pp.

FURLANI, P. R. 1981. Effects of aluminum on growth and mineral nutrition of sorghum genotypes. Ph.D. Dissertation, University of Nebraska, Lincoln, Nebraska, USA. 136 pp.

FURLANI, P. R., and CLARK, R. B. 1981. Screening sorghum for aluminum tolerance in nutrient solutions Agronomy Journal 73: 587-594.

FURLANI, P. R.. CLARK, R. B., and Ross, W. M. 1980. Differential responses of sorghum genotypes to aluminum. Agronomy Abstracts 1980:81.

GRAHAM, R. D. 1978. Nutrient efficiency objectives in cereal breeding. Pages 165-170 *in* Plant nutrition —Proceedings of the 8th International Colloquium on Plant Analysis and Fertilizer Problems, eds A. R Ferguson, R. L. Bieleski, and I. B. Ferguson. Wellington, New Zeland: Government Printer.

KAMPRATH, E. J., and FOY, C. D. 1971. Lime-fertilizer-plant interactions in acid soils. Pages 105-151 *in* Fertilizer technology and use, eds. R.A. Olson, T. J. Army, J. J. Hanway, and V. J. Kilmer. Madison, Wisconsin, USA: Soil Science Society of America.

KANNAN, K. 1980a. Differences in iron stress response and iron uptake in some sorghum varieties. Journal of Plant Nutrition 2 : 347-358.

KANNAN, K. 1980b. Correlative influence of pH reduction on recovery from iron chlorosis in sorghum varieties. Journal of Plant Nutrition 2:507-516.

KHASAWNEH, F. E., SAMPLE, E. C, and KAMPRATH, E. J. (eds). 1980. The role of phosphorus in agriculture. Madison, Wisconsin, USA: American Society of Agronomy. 910 pp.

LAFEVER. H. N. 1981. Genetic differences in plant response to soil nutrient stress. Journal of Plant Nutrition 4:89-109.

LONERAGAN, J. F 1978 The physiology of plant tolerance to low phosphorus availability. Pages 329-343 *in* Crop tolerance to suboptimal land conditions, ed. G. A. Jung. Madison, Wisconsin, USA: American Society of Agronomy.

LUCAS, R E., and KNEZEK, B. D. 1972. Climate and soil conditions promoting micronutrient deficiencies in plants. Pages 265-288 *in* Micronutrients in agriculture, eds. J. J. Mortvedt, P. M. Giordano, and W. L. Lindsay. Madison, Wisconsin, USA: Soil Science Society of America.

MENGEL, K., and KIRKBY, E A. 1979. Principles of plant nutrition. Berne, Switzerland: International Potash Institute 593 pp.

MIKESELL, M. E.. PAULSEN, G. M., ELLIS. R.. JR., and CASADY, A. J. 1973. Iron utilization by efficient and inefficient sorghum lines. Agronomy Journal 65:77-80.

MORTVEDT, J. J., and CUNNINGHAM, H. G. 1971. Production, marketing, and use of other secondary and micronutrient fertilizers. Pages 413-454 *in* Fertilizer technology and use, eds. R. A. Olson, T. J. Army, J. J. Hanway, and V. J. Kilmer. Madison, Wisconsin, USA: Soil Science Society of America.

MUHSI, A., and LANGSTON, R. 1975. Growth characteristics and nutrient levels of genetically related grain sorghum varieties resistant and susceptible to chlorosis. Indian Journal of Agricultural Science 45:219-223.

MURPHY. L. S.. and WALSH. L. M. 1972. Correction of micronutrient deficiencies with fertilizers. Pages 347-387 *in* Micronutrients in agriculture, eds J. J. Mortvedt, P. M. Giordano, and W. L. Lindsay Madison, Wisconsin, USA: Soil Science Society of America.

OLSON. R. A., ARMY, T. J., HANWAY, J, J., and KILMER. V. K. (eds.) 1971. Fertilizer technology and use. Madison, Wisconsin, USA: Soil Science Society of America.

PITTA. G. V. E.. SCHAFFERT, R. E., and BORGONOVI, R. A. 1979a. Evaluation of sorghum parents and hybrids to high acidity soil conditions—preliminary study for type of inheritance, (in Portuguese). Page 127 *in* Proceedings of 12th Brazillian Maize Sorghum Review, Goiania, Goias, Brazil.

PITTA. G. V. E.. SCHAFFERT, R. E.. BORGONOVI, R. A., VACONCELLOS, C. A., BAHIA, A. F. C, and OLIVEIRA, A. C. 1979b. Evaluation of sorghum lines to acid soil conditions, (in Portuguese). Page 128 *in* Proceedings of 12th Brazillian Maize Sorghum Review, Goiania, Goias, Brazil.

PITTA. G. V. E., TREVISAN, W. L.. SCHAFFERT. R. E., DEFRANCA, G. E., and BAHIA, A. F. C. 1976. Evaluation of sorghum lines under high acidity conditions—preliminary note (in Portuguese). Pages 553-557 *in* Proceedings of 11th Brazillian Maize Sorghum Review, Piracicaba, Sau Paulo, Brazil.

RANDHAWA, N. S., TAKKAR, P. N., and VENKATA RAM, C. S. 1974. Zinc deficiency in Indian soils. Pages 1-8 inZinc in crop nutrition. New York, USA: International Lead Zinc Research Organization and Zinc Institute.

RAO, S. K., GUPTA, A. K., and BAGHEL, S. S. 1979. Variation in some mineral nutrient accumulation and their association with yield and maturity in grain sorghum. Indian Journal of Plant Physiology 22:109-115.

SANCHEZ, P. A. 1976. Properties and management of soils in the tropics. New York, USA: John Wiley and Sons, Inc., 618 pp.

SANCHEZ, P. A., and UEHARA, G. 1980. Management considerations for acid soils with high phosphorus fixation capacity. Pages 471-514 *in* The role of phosphorus in agriculture, eds. F. E. Khasawneh, E. C. Sample, and E. J. Kamprath. Madison, Wisconsin, USA: American Society of Agronomy.

SCHAFFERT. R. E., FERNANDES, F. T., LEITE, L. C, MARRIEL, I. E., PITTA, G. V. E. and WAQUIL, J. M. 1978. Trends in sorghum production in Brazil and recent research advances at the "Centra nacional de pesquisa de milho e sorgo" (CNPMS/EMBRAPA). Pages 67-71 *in* Proceedings of International Reunion of Sorghum. Buenos Aires, Argentina.

SCHAFFERT, R. E.. MCCRATE, A. J., TREVISAN. W. L, BUENO, A., MEIRA, J. L. and RHYKERD. C. L. 1975. Genetic variation in *Sorghum bicolor* (L.) Moench for tolerance to high levels of exchangable aluminum in acid soils of Brazil. Pages 151-160 *in* Proceedings of Sorghum Workshop, University of Puerto Rico, Mayaguez.

SHUKLA, U. C. 1975. Influence of genetic variability in a crop on its response to zinc deficiency in soils. Indian Journal of Agricultural Chemistry 8:63-67.

SHUKLA. U. C, ARORA, S. K., SINGH, Z.. PRASAD, K. G., and SAFAYA, N. M. 1973. Differential susceptibility in some sorghum *[Sorghum vulgare)* genotypes to zinc deficiency in soil. Plant and Soil 39:423-427.

SMITH, F. W. 1979. Tolerance of seven tropical pasture grasses to excess manganese. Communications in Soil Science and Plant Analysis 10:853-867.

USDA (U.S. Department of Agriculture). 1980. Agricultural Statistics. Washington, D. C, USA: U.S. Government Printing Office.

VAN WAMBEKE. A. 1976. Formation, distribution, and consequences of acid soils in agricultural development. Pages 15-24 *in* Plant adaptation to mineral stress in problem soils, ed. M. J. Wright. Ithaca, New York, USA: Cornell University Agricultural Experiment Station.

WILLIAMS, E. P., CLARK, R. B., YUSUF. Y„ ROSS, W. M. and MARANVILLE, J. W. (In press). Variability of sorghum genotypes to tolerate low iron. Journal of Plant Nutrition.

YUSUF, Y. 1980. Differential responses of sorghum *[Sorghum bicolor* (L.) Moench] genotypes to iron nutrition. Ph.D. Dissertation, University of Nebraska, Lincoln, Nebraska, USA. 187 pp.

YUSUF, Y„ and CLARK, R B. 1979. Screening sorghum for iron efficiency. Page 27 *in* Proceedings of 11 th Grain Sorghum Research and Utilization Conference. Wichita, Kansas, USA..

Session 3 Factors Reducing Sorghum Yields Environmental Stress

N. C. Turner* Discussant—1

Stress is any factor that disturbs the normal functioning of an organism, in the present context, this definition can be reduced to those perturbations that reduce yield. Moreover, my task is to discuss only those yield reducing environmental stresses reviewed in the last four papers: namely, nutrient stress, temperature stress, and water or drought stress. My primary focus will be on the last of these. I do not apologize for this. Drought is the major factor limiting yields in most of the sorghum-growing areas of the world (Seetharama et al. in press). It must therefore be a subject of primary concern for sorghum production workers in the next decade. It is incidentally my principal research interest and hence the environmental stress with which I am most familiar.

My perspective is that of a crop physiologist. Stress physiology aims to bring enlightenment to both breeding and management on the physiological and metabolic basis of yield reduction by stress. Ten yeas ago, Maunder (1972) said "the concern of the physiologists that plant breeding is too empirical may provide the stimulus to move off the present yield plateau". One of my aims in this paper is therefore to review progress in stress physiology over the past decade and to propose improvements for the future.

Perspectives

The symposium "Sorghum in Seventies" (Rao and House 1972) did not have a section on the role of environmental stress in yield reduction, although the role of heat and drought stress was discussed in the section on 'Physiological Aspects of Sorghum Production' and major and minor nutrients were discussed in the section on 'Production Technology'. The past decade had witnessed the move of stress physiology from the laboratory to the field, thereby gaining greater relevance for crop production and greater respect from the field practitioners, i.e., the breeders and agronomists. It has also seen the incorporation of crop physiologists as full-fledged members of the production team in several crop improvement programs. It is therefore not surprising that the role of environmental stresses on yield reduction takes its place as one of the major themes in this symposium.

As suggested by the organizers of the symposium the authors of the four papers in this section have concentrated on the individual effects of water, temperature and nutrient stress on sorghum production. The sorghum crop is, however, a managed ecosystem in which the environmental stresses interact and these, in turn, interact with diseases and predators considered in later chapters. Environmental physiologists must be aware of these interactions in order to avoid incorrect interpretations. The interaction and integration of environmental stresses on yield is therefore my first point of discussion.

When challenged by stress, heritable and nonheritable modifications can develop in plants that alleviate or reduce the harmful effects of the stress. Although the phenomenon of stress hardening has been known for many years, the acclimation and adaptation to stress is a subject that has received increasing attention by environmental physiologists over the past decade (Turner and Kramer 1980). As the ability of plants to harden is important when considering methodologies of water stress, I shall discuss this further.

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum. 2-7 Nov 81. Patancheru, A.P.. India Patancheru. A.P. India: ICRISAT.

With resources limited, it is important to identify important research priorities for the future. As some of my own work gives some pointers for the future, I shall finally report on this.

Interaction of Environmental Stresses

The common association of water and high temperature stresses in drought prone areas is acknowledged in the earlier papers by Peacock (1982) and Jordan and Sullivan (1982). But as Jordan and Sullivan (1982) and Sullivan and Ross (1979) show for sorghum, and as Blum and Ebercon (1981) show for wheat, heat and desiccation tolerance are not necessarily correlated. Although heat stress may be an important factor in drought-prone areas, in for example seedling establishment, it is inappropriate to use heat stress to select for both heat and drought tolerance as suggested by Peacock (1982). Desiccation tolerance, which bears the closest resemblance to heat tolerance, is only one facet of the complex known as drought resistance and appears to be important only for survival of extreme stress (Turner 1979). Although survival mechanisms are clearly important for production in marginal areas in which drought can become severe, subtle effects of drought, such as a reduction in leaf area, may have a much greater effect on overall sorghum yields (Turner 1979). Emphasis to reduce the catastrophic effect of heat and drought stress of a few farmers should not take precedence over a program to alleviate the subtler, but nevertheless detrimental, effects of drought for the major water-limited environments in which sorghum is grown. Furthermore, it has been argued that because heat tolerance has been positively correlated with yield (Sullivan and Ross 1979), the heat tolerance test is "one of the few examples where results from a basic laboratory test have been extended to field situations with positive results" (Jordan and Sullivan 1982). However, I submit that the positive results cited by Sullivan and Ross (1979) should not go unchallenged. The published results were obtained with a range of M35-1 conversion hybrids: since the yields of control plants not subjected to heat stress are not given, it is possible that the yields obtained were the potential yield of the hybrids in the absence of stress and that the correlation with heat tolerance is fortuitous.

A second interaction between heat and drought stress is also of consequence. The role of stomata in controlling water loss has received considerable attention over the past two decades. The early hope that stomatal-closing antitranspirants would improve water-use efficiency and reduce the detrimental effects of drought has not been borne out in practice because the beneficial cooling of transpiration was not taken into account. The improvements reported in water-use efficiency from the use of antitranspirants were obtained with gas exchange methods in which leaf temperature was held constant (Shimshi 1963; Slatyer and Bierhuizen 1964). In nature a reduction in transpiration leads to an increase in leaf temperature, especially in broad-leaved plants, and therefore to an increase in the leaf-to-air vapor pressure deficit, thereby largely annulling any improvement in water-use efficiency (Cowan and Troughton 1971). Gas exchange studies have likewise shown that leaf wilting improves the water-use efficiency of crops (Rawson 1979), but whether such benefits occur in the field remain to be shown. This suggests that mechanisms of drought tolerance that maintain high water potentials by reducing transpiration (Turner 1979) may achieve little saving in water loss and may make plants vulnerable to high temperature stress: certainly stomatal closure did not prevent a continued decrease in leaf water potential in maize (Turner 1975). A corollary to the above is that heat tolerance may be greater in those species and lines that close their stomata at high leaf water potentials.

Water and nutrients also interact in several ways. Myers and Asher (1982) have pointed out that sorghum yields in northern Australia increased with nitrogen fertilization up to 150 to 200 kg/ha in a year with average rainfall, but were lower overall and decreased at fertilization rates above 22 kg/ha in a dry year (Fig. 1). Although Myers (1978) in the original report did not investigate the reasons for the decline in yield in dry years, two reasons can be suggested. First, in the dry year the majority of the nutrients may have remained in the dry upper soil profile in which water and nutrient uptake was limited. Garwood and Williams (1967) have shown that in a dry year, injection of nutrients particularly nitrogen, into the subsoil substantially increased dry matter production of grass swards over that in which the fertilizer was applied to the surface. A similar phenomenon in sorghum could account for the

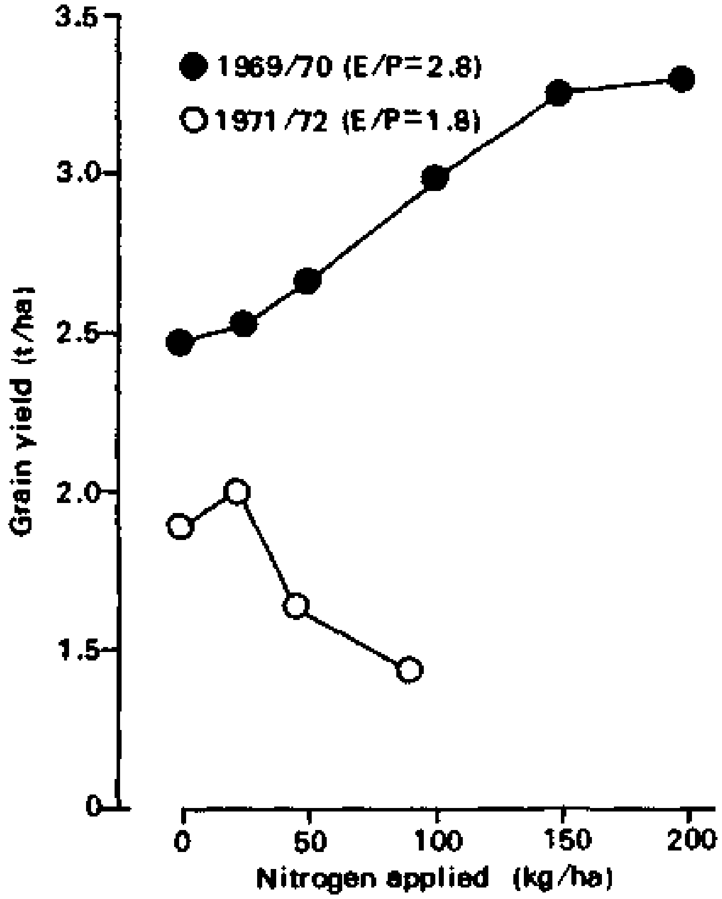

Figure 1. Relationship between grain yield of sorghum and amount of nitrogen fertilizer applied in a season with average rainfall (o) in which pan evaporation (E) exceeded precipitation (P) by a factor of 1.8, and in a season with below average rainfall (•) in which E/P = 2.8. (From data in Myers 1978.)

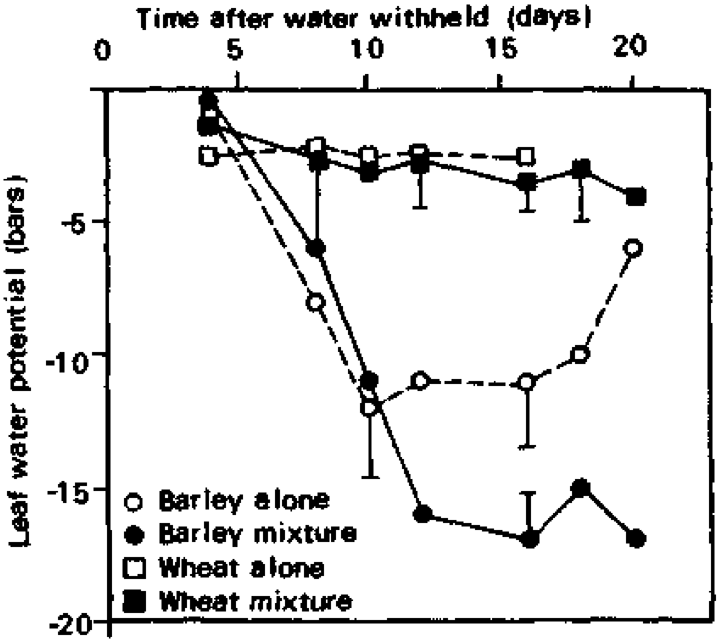

Figure 2. The change with time after water was withheld in predawn leaf water potential of barley (o, •) and wheat (□, ■) plants growing alone (o, □) or in a 1:1 mixture (•, ■) in an acid soil in which the surface was limed but the subsoil was left unlimed. The barley but not the wheat roots were restricted to the limed surface soil. Bars denote + or - one standard error of the mean: errors less than 1 bar omitted for clarity. (Data from Spurway 1979.)

overall reduction in yield in the dry year. Second, the reduction in yield at higher levels of fertilization may have arisen from stimulation of early leaf growth and early depletion of soil water to the detriment of grain filling.

Aluminum toxicity, as pointed out by Clark (1982), reduces root growth. By reducing the soil-root volume, this can have detrimental effects on plant water relations in dry environments. This was shown recently for barley by Spurway (1979). When grown in an acid soil, barley roots failed to penetrate unlimed portions of the soil, whereas the roots of an aluminum-tolerant wheat grew happily. Figure 2 shows the predawn leaf water potential of the wheat and barley in monoculture and in a 1:1 mixture of the two species when grown in the unlimed soil overlain by limed soil and surface droughted for 20 days. The leaf water potential decreased markedly in the barley, particularly in the mixture, as the surface soil water was depleted, but continued high throughout in the deep-rooted wheat. Similar studies have not been undertaken in sorghum, but they emphasize the importance of aluminum toxicity in increasing the susceptibility to drought in water limited environments, particularly if sorghum is intercropped with an aluminum tolerant species.

Because of the many interactions between the environment and crop growth, researchers frequently resort to developing computer simulation models in order to understand the responses of plants to environmental factors and to predict the plant responses in a range of environments. It is ultimately hoped that this approach will reduce the need for extensive yield testing in a range of environments and years. However, because of the need to determine the influence of a drought resistance mechanism on a plant's phenology, physiology and morphology and because of the ability of plants to acclimate to stress, as discussed below, the use of computer simulation models has limited utility in crop breeding programs at the present time. Nevertheless, they are useful in defining the available soil water in a range of environments and years from soil and weather characteristics, and therefore in defining the type of drought resistance characteristics that may be required in a particular location.

Acclimation and Adaptation to Environmental Stresses

The acclimation of plants to both low and high temperatures has long been recognized. Recently Bjorkman et al. (1980) showed variation among species in the ability to acclimate to temperature and showed that low temperature acclimation was correlated with the capacity of specific rate-limiting enzymes whereas high temperature acclimation involved changes in the stability of the thylakoid membranes.

Acclimation to water deficits also occurs in a wide range of species, including sorghum. A range of mechanisms of adaptation or acclimation have been suggested by Turner (1979), and identified in sorghum by Jordan and Monk (1980). One mechanism of acclimation that has received considerable attention over the past decade is that of osmotic adjustment (Turner and Jones 1980). Turner et al. (1978), Jones and Turner (1978), and Stout and Simpson (1978) have all shown that sorghum lowers its osmotic potential in response to water deficits due to an accumulation of a range of solutes (Turner et al. 1978; Stout and Simpson 1978; Jones et al. 1980). Figure 3 shows the change in osmotic potential with decrease in leaf water potential in the sorghum cultivar RS 610 at predawn and in the early afternoon. This form of presentation shows that, contrary to the situation in sunflower (Turner 1982), sorghum does not fully maintain turgor as leaf water potential decreases, but nevertheless the accumulation of solutes lowers the predawn leaf water potential at which zero turgor is reached from about -11 bars to about -17 bars. The difference between the predawn and early

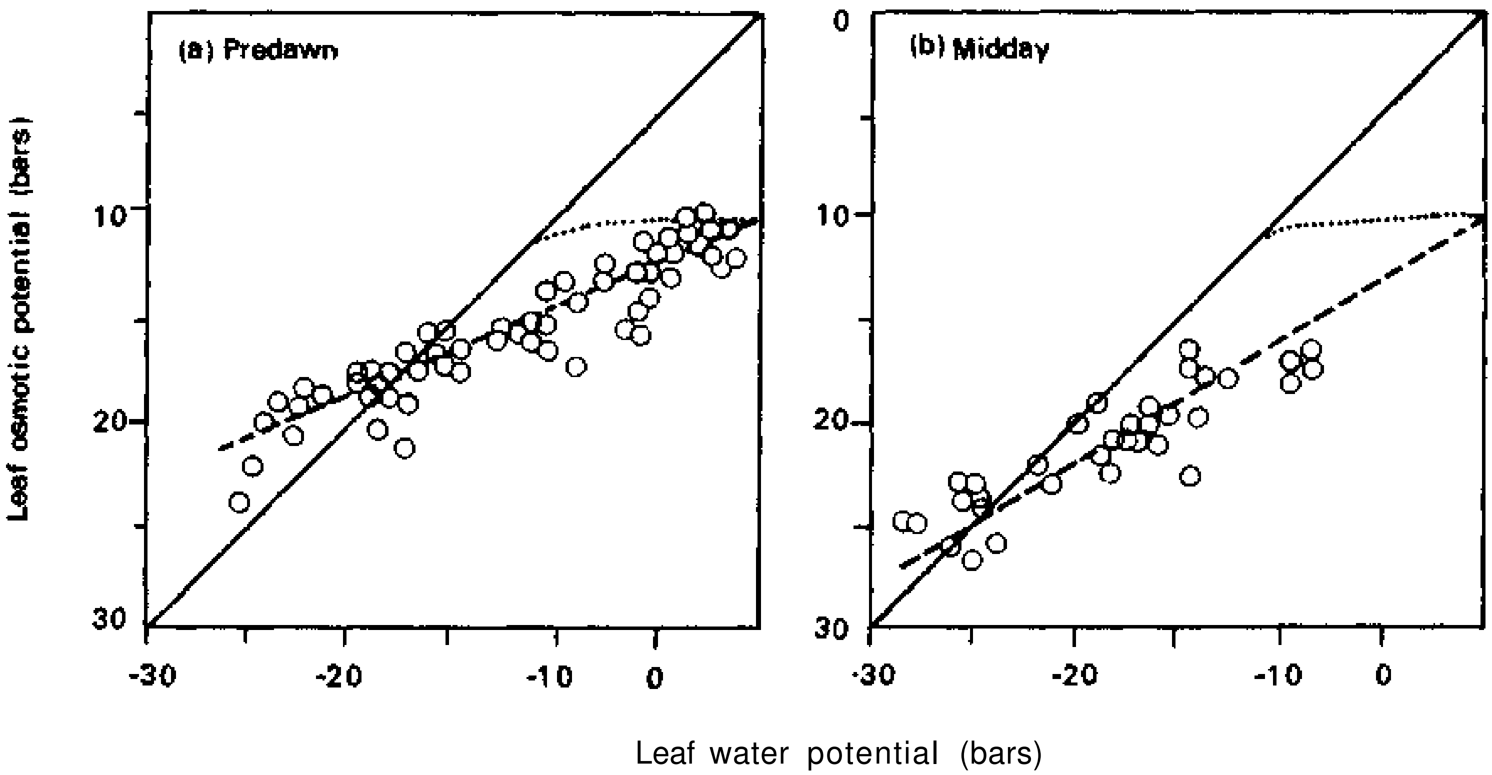

Figure 3. Relationship between the leaf water potential and leaf osmotic potential at (a) predawn and (b) midday in sorghum (cv RS 610) grown in the glasshouse. The solid line gives the 1: 1 relationship, the dashed line the fitted linear regression, and the dotted line the expected Boyle-van't Hoff relationship for the osmotic values measured at predawn. The Boyle-van't Hoff relationship was calculated using the moisture release curve obtained by Turner and Long (1980) for sorghum in the same glasshouse. (Data from Jones 1979.)

afternoon values suggest that there is considerable accumulation of solutes diurnally, thereby lowering the leaf water potential at which zero turgor is reached during the day. Turner et al. (1978) showed that osmotic adjustment lowered the leaf water potential at which stomata closed and Jones and Rawson (1979) showed that it also lowered the leaf water potentials at which low rates of photosynthesis were obtained. Jones and Rawson (1979) used slow rates of stress to induce osmotic adjustment and prevented its inducement by imposing rapid rates of stress. The results are shown in Figure 4. When osmotic adjustment occurred, the leaf water potential at which net photosynthesis reached 50 ng CO_2/ cm^2/s or leaf conductance reached 0.1 to 0.2 cm/ s was about 6 bars lower than in rapidly stressed plants in which osmotic adjustment did not occur.

Jordan and Miller (1980) have pointed out that osmotic adjustment to the degree observed in sorghum will only delay the onset of the low physiological activity accompanying stress by a few days at reasonable rates of transpiration. However, there is evidence that osmotic adjustment also allows the continued growth of roots, thereby enabling the plants to explore a larger soil volume. However, Jordan and Miller's analysis does suggest that other ways of adapting to water deficits will be required if the stress is prolonged and particularly if deep soil water is unavailable.

Water Deficit and Crop Productivity

The yield of a grain crop such as sorghum is a function of the solar energy captured and utilized to convert carbon dioxide and water to carbohydrates that are ultimately stored in the grain. Crop

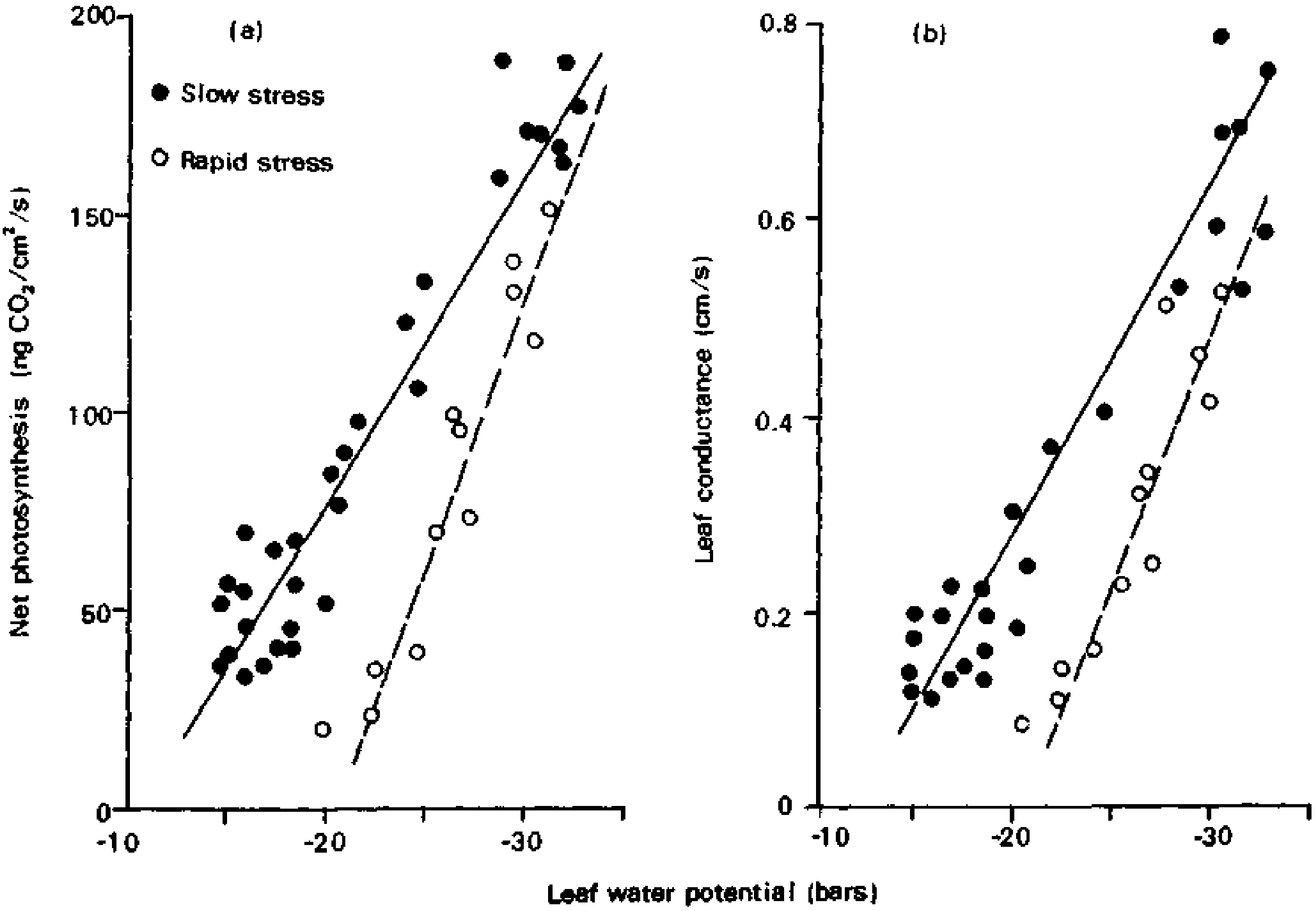

Figure 4. Relationship between (a) net photosynthesis and leaf water potential, and lb) leaf conductance and leaf water potential in sorghum (cv RS 610) at heading to anthesis. The plants were either slowly stressed over 21 days by growing them in 45 kg of soil and withholding watering (•). or rapidly stressed over 3 days by growing them in 7 kg of soil and withholding watering (o). (Redrawn from Jones and Rawson 1979.)

productivity is therefore a function of the leaf area development, the rate of photosynthesis per unit leaf area and the distribution of the assimilates between grain and stover (Turner and Begg 1981). Several analyses recently have suggested that water deficits have a greater effect on leaf area than on photosynthetic rates per unit leaf area (Turner and Begg 1978; Legg et al. 1979; Turner 1982). Our own studies suggest that this is true for sorghum also. Figure 5a shows that over an 18-hr period leaf extension in sorghum was reduced by 60% in unirrigated compared with irrigated plants when the difference in leaf water potential during the day was less than 2 bars. Under similar conditions $^{14}CO_2$ photosynthesis was unaffected. The cumulative effect of this mild stress was to reduce the leaf area index from 2.1 to 1.5 by reducing the area of the upper leaves, as shown in Figure 5b.

At more severe levels of stress, photosynthesis per unit area is also reduced. This is shown in Figure 6 in which the profiles of quantum flux density, leaf conductance and $^{14}CO_2$ photosynthesis are presented for irrigated and nonirrigated sorghum. In the irrigated sorghum the leaf water potential did not drop below -15 bars, but in the nonirrigated sorghum the leaf water potential decreased to -21 bars at midday and maximum rates of photosynthesis were observed at 0800 h and decreased thereafter. However, my conclu-

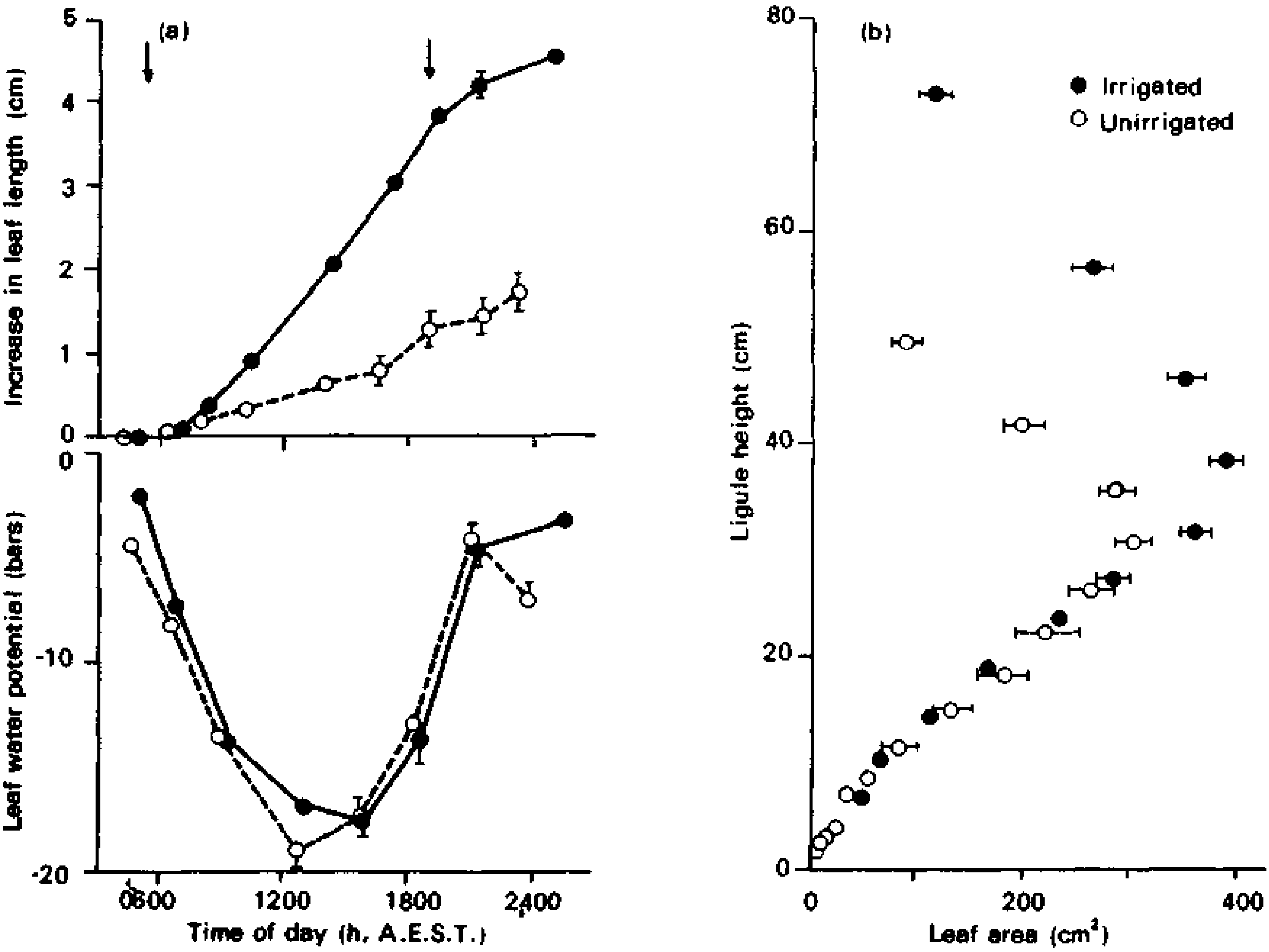

Figure 5. (a) The diurnal change in leaf water potential and increase in leaf length in the late vegetative phase and (b) the leaf area profile at anthesis in irrigated (•) and unirrigated (of crops of sorghum (cv RS610) at the Ginninderra Experiment Station, near Canberra, Australian Capital Territory. Bars denote ± one standard error of the mean, the arrows in (a) denote the times of sunrise and sunset, andA.E.S. T: is Australian Eastern Standard Time. Errors less than 0.1 cm, 0.5 bars, and 10 cm' omitted for clarity.

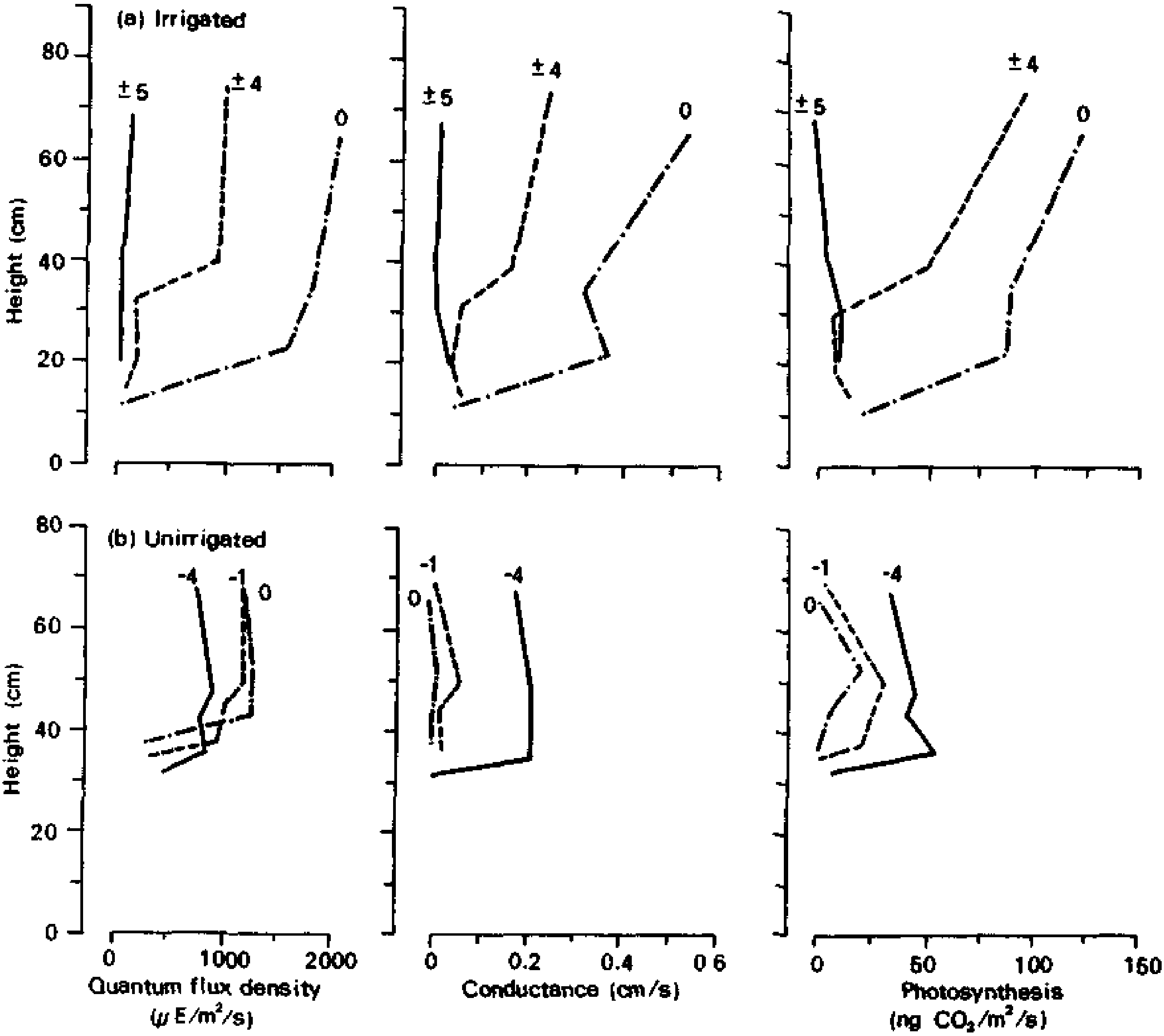

Figure 6. Vertical profiles ofquantum flux density, leaf conductance, and $^{14}CO_2$ photosynthesis at three times of day in (a) irrigated and (b)unirrigated crops of sorghum (cv RS610) at the Lockwood Farm, Hamden, Connecticut (USA). The numbers denote the intervals in hours from noon, American Standard Time. For experimental details see Turner and Incoll (1971).

sion after 10 years of working with sorghum is that the primary effect of water stress is in reducing the leaf area and hence intercepted radiation. Since water use in sorghum decreases proportionally as the leaf area index decreases below three when the soil surface is dry (Ritchie 1974), the reduction in leaf area is a powerful mechanism for conserving soil water and as a consequence, reductions in photosynthesis per unit area occur only rarely and then only at severe stress levels.

Prospects

Priorities for the Future

The primacy of drought in limiting sorghum yields in Africa and Asia leads me to suggest that it receive top priority in the next decade. Since the total dry matter production is largely a function of the water that passes through the plant in transpiration (Fischer and Turner 1978), quick gains may be made in the first instance from improvements in agronomic practice that enable the plants to use more of the water available in the soil in transpiration rather than being lost as soil evaporation or that add to the total water available in any one season or location. Turner and Begg (1981) have suggested a range of such management practices (Table 1). Although suggested as possible management practices for regions with a Mediterranean climate, they are also appropriate to the semi-arid tropics: details are given in Turner and Begg (1981) and are not repeated here.

Concurrent with improvements in agronomic practice a program aimed at improving the drought resistance of sorghum should be maintained. Elsewhere I have outlined the basic features of such a program (Turner 1979; Turner 1981; Turner, in press). The first requirement is the characterization of the droughts experienced and expected in the sorghum growing areas of the world. This must be followed by the identification of characters that will confer benefits under each expected drought regime. Jordan and Monk (1980) have suggested 14 and Seetharama et al. (in press) have suggested 22 phenological, morphological and physiological attributes that may confer drought resistance in sorghum. Clearly not all are equally important in each drought environment and in fact characters that confer an advantage in one environment may be disadvantageous in another. Thus identification of the important attributes in each environment is a necessary second step: Turner (1981a; 1982) has attempted to do this for three different soil water availability patterns.

Table 1. Management practices for improving yields in drought-prone areas.

1. By maximizing the proportion of precipitation that passes through the crop:
   - Weed control
   - Tillage practices to increase infiltration and decrease soil evaporation
   - Mulching
   - Rapid crop establishment by appropriate seeding and fertilizer techniques

2. By increasing the water available to the crop:
   - Fallowing
   - Runoff farming
   - Supplemental irrigation
   - Antitranspirants.

Such a program is clearly long range. However, one lesson learned in the past decade is that there are no shortcuts to yield improvement under drought. Keys such as proline accumulation and heat or desiccation tolerance that promised to unlock the variability in drought resistance with a simple biochemical or physiological test, I believe have all floundered in the laboratory because of the complex rather than simple nature of field drought resistance. Nevertheless, experience over the past decade has also pointed to several areas of high priority for the next decade.

Begg (1980) has argued on evolutionary grounds that greater improvement is likely from selection for morphological mechanisms of adaptation to drought than from selection for physiological mechanisms. Likewise I have tried to point out above that our own research and that of others has highlighted the adaptive importance of leaf area development and senescence, rather than stomatal behavior or photosynthetic rate per unit area, in drought resistance. I suggest that an understanding of the role of leaf expansion and leaf senescence in relation to water deficits and water use, and their variability across the germplasm, is of utmost importance and should have high priority in any crop improvement program.

A second priority area and one that has received little attention in the past decade is the influence of water deficits on the distribution of assimilates. Water deficits generally increase the proportion of assimilates in the roots and crowns relative to that in the shoot (Wardlaw 1968) and decrease the proportion of dry matter in the grain relative to that of the total crop (Donald and Hamblin 1976). Radioisotope techniques for studying the detailed distribution of assimilates are tedious and difficult to apply in the field and therefore it is not surprising that they have not made the leap from the laboratory to the field. However, measurement of the proportion of total dry matter in the grain, i.e., the harvest index, is straightforward and its lack of use probably reflects its lack of enchantment by breeders and physiologists. Moreover, most yield increases under favorable conditions have been achieved by increases in harvest index. Since there is a good correlation between the harvest index of spaced plants used in early generation selection and the harvest index of the crop grown in the field (Donald and Hamblin 1976) and since yield and harvest index appear to be independently inherited, studies of this character under drought are urgently required.

Earlier it was pointed out that the credibility of the physiologist rose sharply in the eyes of the breeder and agronomist when the physiologist moved from the laboratory to the field. This step was made possible by the development during the late 1960s of portable techniques such as the pressure chamber, diffusion porometer and "CO, methods for the measurement of leaf water status, stomatal conductance and photosynthesis, respectively, in the field and the development of simple laboratory tests such as heat and desiccation tolerance that can be applied to field samples. Elsewhere I have evaluated the ease of screening drought resistance characters (Turner 1982). Continued progress with the incorporation of drought resistant characters into sorghum will depend on the development of simple techniques for the field evaluation of other characters such as leaf expansion, leaf senescence, assimilate distribution and osmotic adjustment. Earlier I expressed criticism of the heat or desiccation tolerance test as a screen for drought resistance. However, challenge stresses such as the heat and desiccation tests could provide a measure of the acclimation to heat and drought. Sullivan (1972) showed that samples taken from the field during a month of high average temperature had higher heat tolerances than samples taken from the field during a month of low average temperature. Similar tests on the desiccation tolerance of sorghum allowed to adjust to water deficits may also distinguish cultivars that acclimate to drought. Since the degree of osmotic adjustment is difficult to ascertain in a wide range of germplasm, if it correlates well with the desiccation test, the latter could provide a simple means of assessing its importance and heritability in sorghum.

Even the portable techniques used for screening for drought resistance are generally not suited to large field breeding programs. A summary by Turner (1981b) showed that the number of observations per hour for physiological processes associated with plant water status was in the region of 10 to 100 per person. Subsequent experience has shown that use of an automatic porometer and a pressure chamber that can take three samples per occasion can increase the number of observations for these instruments to 100 per team of two people per hour (Turner, in press). With the possibility of measurement for only a few hours per day, the number of observations is clearly only sufficient to screen advanced breeding lines. There is therefore a need to develop suitable visual techniques such as leaf rolling, wilting or tip bum for screening large populations. The role of the stress physiologist will be to relate these visual techniques to parameters of plant water status. Jones,H. G. (1979) provides an example of this. He demonstrated that the visual score for drought resistance based on leaf rolling was linearly related to the leaf water status of rice, but that the relationship differed depending on whether the material being scored was of upland or lowland origin. His work points to the utility of visual techniques within the rice races, but shows that it would have little benefit in screening crosses between upland and lowland rice for drought resistance.

Finally, there is a necessity for the development of suitable methodologies for screening for drought resistance. Where a crop is naturally grown on stored soil moisture in the absence of precipitation it may be relatively easy to reproduce the drought conditions from year to year. However, where drought is unpredictable in terms of timing or severity, a suitable screening regime is difficult to define and even more difficult to implement. In order to ensure some measure of stability in the incidence of drought from year to year, some investigators use out-of-season plantings to screen for drought resistance. Such methodologies need to be employed with care to ensure that characteristics of benefit in the dry season, such as low humidity response of stomata, but which may not be beneficial in rainy-season droughts, do not become incorporated into the selected germplasm. To overcome some of the difficulties of imposing drought conditions in an unpredictable climate, rainout shelters have been developed that automatically shelter the crop from rain (Arkin et al. 1978). The smallness of the area that can be covered, however, limits their use in breeding programs in which many lines need to be screened.

A technique that has gained considerable importance in recent years as a screening tool for drought resistance is the line source sprinkler (Hanks et al. 1976). The technique is currently being used to screen sorghum (Seetharama et al., in press), rice (Puckridge and O'Toole 1981), range grasses (Johnson 1980) and cowpeas (Turk et al. 1980). Its use is restricted to regions in which there is a definite dry season or for generating different degrees of water stress during dry periods. Apart from the hazards of unanticipated rain (Puckridge and OToole 1981) and wind during operation, I question whether the type of stress imposed by the line source sprinkler is appropriate in many cases. Apart from the disadvantages of out-of-season use mentioned above, the line source sprinkler, as usually used, applies different quantities of water but at the same frequency. In practice, irrigation is often applied weekly or even more frequently. Thus plants near the edge of the plots are supplied with frequent but small amounts of water whereas those at the center are supplied with frequent and abundant water. This is very different from drought sequences in nature in which crops have to grow on initially different amounts of stored soil moisture or with infrequent but relatively abundant rainfall. The frequent but small amounts of irrigation applied at the edge of the plots is likely to lead to high losses of water by soil evaporation compared with that occurring with less frequent rainfall events. Where water-use efficiency is determined as the ratio of dry matter production or grain yield per unit of evapotranspiration, this could lead to low water-use efficiencies compared with crops grown with normal rainfall events. Thus differences in water-use efficiency obtained with line source sprinklers, as described by Sullivan et al. (1980) and represented by Garrity et al. (in press) and Jordan and Sullivan (1982) must be accepted with caution.

The Role of the Physiologist

With average yields in Africa and Asia being less than 900 kg/ha (Seetharama et al., in press) and as low as 200 kg/ha in parts of the Sahel (Bein 1980). largely as a result of drought, considerable scope for improvement in sorghum production still remains. In this paper I have tried to point out the phenological, physiological and morphological characteristics that are likely to be useful in a drought improvement program. There is clearly a role for the stress physiologist in such a program.

As Passioura (1981) has pointed out, physiology is judged primarily on how enlightening it is and whether this enlightenment provides leads or tools for breeders and agronomists. Thus the stress physiologist concerned with improving crop productivity must interact closely with both breeders and agronomists. The physiologist must therefore be part of the crop improvement team of agronomists, soil scientists, meteorologists, entomologists, pathologists, and plant breeders. Moreover he must be an integral part of the team, involving a two way interaction, for two reasons. Firstly, disciplinary powers tend to pull the physiologist into studying processes in more and more fine detail so that ultimately he is of little use to the breeder or agronomist. Secondly, he needs access to the tools and products of the breeder and agronomist. Too frequently the breeder demands to know whether a characteristic of, say, drought resistance is beneficial and then requests a simple screening technique without himself providing the tools to test whether the characteristic is indeed beneficial. Frequently, to determine unequivocally whether the character is beneficial or not, the physiologist will require of the breeder isogenic lines with and without the character of concern. This need is urgent and requires the collaboration of physiologist and breeder in establishing isogenic lines and suitable screening methodologies: this will necessitate the release of a breeder from the production of varieties.

Role of the International Institutes

It is clear that a sorghum improvement program such as the one being undertaken at ICRISAT can and must draw on the expertise developed by sorghum physiologists and agronomists from developed countries such as those represented by the authors of the papers in this section. Indeed, with the constraints on research funds both within the developed countries and the International Institutes, greater rationalization and cooperation will be necessary in the future. Much can be achieved by conferences, symposia and exchange of staff.

But the different resources in the two spheres should be used to the mutual benefit of both. The International Institutes such as ICRISAT have relatively abundant land and labor, and a broad germplasm—resources that are difficult or impossible to obtain or maintain in developed countries. On the other hand, research workers in developed countries have access to sophisticated equipment and expertise in a broad range of disciplines—resources that are hard to achieve and/or maintain in a developing country. Thus cooperative or contract research between the two types of organization should be more widely developed over the next decade. Hopefully, the establishment of the Centre for Agricultural Research for Developing Countries by the Australian Government, will make such cooperation between researchers in ICRISAT and Australia easier.

Although cooperation between the International Institutes and research workers in the developed countries of the world should be encouraged, the primary clients of the International Institutes must continue to be the national programs. Since not all of the national programs in the developing countries can or ought to have a stress physiologist as part of the team, stress physiologists at the International Institutes must act as resource people for agronomists and breeders in the national programs. Conferences such as the recent one at the International Rice Research Institute on "Principles and Methods of Crop Improvement for Drought Resistance: With Emphasis on Rice" (IRRI, in press) that brought together breeders and agronomists concerned with drought resistance in rice from both developed and developing nations and a sprinkling of stress physiologists working with rice and other crops, are one method of increasing and maintaining scientific exchange at this level, and are to be recommended.

References

ARKIN. G. F., RITCHIE, J. T.. THOMPSON. M., and CHAISON, R. 1976. A rainout shelter Installation for studying drought stress. Agronomy Journal 68:429-431.

BEGG, J. E. 1980. Morphological adaptations of leaves to water stress. Pages 33-42 *in* Adaptation of plants to water and high temperature stress, eds. N. C. Turner and P. J. Kramer. New York, USA: Wiley-Interscience.

BEIN, F. L. 1980. Response to drought in the Sahel. Journal of Soil and Water Conservation 35:121-124.

BJORKMAN, 0., BADGER, M. R., and ARMOND, P. A. 1980. Response and adaptation of photosynthesis to high temperatures. Pages 233-249 *in* Adaptation of plants to water and high temperature stress, eds. N. C. Turner and P. J. Kramer. New York. USA: Wiley-Interscience.

BLUM, A., and EBERCON, A. 1981. Cell membrane stability as a measure of drought and heat tolerance in wheat. Crop Science 21:43-47.

CLARK, R. B. 1982. Mineral nutritional factors reducing sorghum yields: micronutrients and acidity. These Proceedings: ICRISAT.

COWAN, I. R.. and TROUGHTON, J. H. 1971. The relative role of stomata in transpiration and assimilation. Planta 97:325-336.

DONALD, C. M.. and HAMBLIN, J. 1976. The biological yield and harvest index of cereals as agronomic and plant breeding criteria. Advances in Agronomy 28:361 -405.

FISCHER, R. A., and TURNER, N. C. 1978. Plant productivity in the arid and semiarid zones. Annual Review of Plant Physiology 29:277-317.

GARRITY, D., SULLIVAN, C. Y„ and Ross, W. M. (In press). Alternative approaches to improving grain sorghum productivity under drought stress. *In* Principles and methods of crop improvement for drought resistance: with emphasis on rice. Los Banos, Laguna, Philippines: IRRI.

GARWOOD, E. A., and WILLIAMS, T. E. 1967. Growth, water use and nutrient uptake from the subsoil by grass swards. Journal of Agricultural Science 69:125 -130

HANKS, R. J., KELLER, J., RASSMUSSEN, V. P., and WILSON. D G 1976. Line source sprinkler for continuous variable irrigation-crop production studies. Journal of the Soil Science Society of America 40: 426-429.

IRRI (International Rice Research Institute). (In press). Principles and methods of crop improvement for drought resistance: with emphasis on rice. Los Banos. Laguna, Philippines: IRRI.

JOHNSON, D. A. 1980. Improvement of perennial herbaceous plants for drought-stressed western rangeland. Pages 418-433 *in* Adaptation of plants to water and high temperature stress, eds. N. C. Turner and P. J. Kramer. New York, USA: Wiley-Interscience.

JONES, H. G. 1979. Visual estimation of plant water status in cereals. Journal of Agricultural Science 92:83 -89.

JONES, M. M. 1979. Physiological responses of sorghum and sunflower to leaf water deficits. Ph.D. thesis, Australian National University, Canberra.

JONES, M. M„ and RAWSON, H. M. 1979. Influence of rate of development of leaf water deficits upon photosynthesis, leaf conductance, water use efficiency, and osmotic potential in sorghum. Physiologia Plantarum 45:103-111.

JONES, M. M., and TURNER. N. C. 1978. Osmotic adjustment in leaves of sorghum in response to water deficits. Plant Physiology 61:122-126.

JONES. M. M.. OSMOND, C. B., and TURNER. N. C. 1980. Accumulation of solutes in leaves of sorghum and sunflower in response to water deficits. Australian Journal of Plant Physiology 7: 193-205.

JORDAN, W. R., and MILLER, F. R. 1980. Genetic variability in sorghum root systems: implications for drought tolerance. Pages 383-399 *in* Adaptation of plants to water and high temperature stress, eds., N. C. Turner and P. J. Kramer. New York, USA: Wiley-Interscience.

JORDAN, W. R., and MONK, R. L. 1980 Enhancement of drought resistance of sorghum: progress and limitations. Pages 185-204 *in* Proceedings of the 35th Annual Corn and Sorghum Research Conference. Wichita, Kansas, USA: Grain Sorghum Producers Association.

JORDAN, W. R. and SULLIVAN, C. Y. 1982. Reaction and resistance of grain sorghum to heat and drought These Proceedings: ICRISAT.

LEGG, B. J., DAY. W., LAWLOR. D W., and PARKINSON, K. J. 1979. The effect of drought on barley growth: models and measurement showing the relative importance of leaf area and photosynthetic rate. Journal of Agricultural Science 92:703-716.

MAUNDER, A. B. 1972. Objectives and approaches to grain and forage sorghum improvement in the Americas. Pages 60-100 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi. India: Oxford and IBH Publishing Co.

MYERS, R. J. K. 1978. Nitrogen and phosphorus nutrition of dryland grain sorghum at Katherine, Northern Territory. I. Effect of rate of nitrogen fertilizer. Australian Journal of Experimental Agriculture and Animal Husbandary 18:554-563.

MYERS, R. J. K. and ASHER, C. J. 1982. Mineral nutrition of grain sorghum: Macronutrients. These Proceedings: ICRISAT.

PASSIOURA, J. B. 1981. The interaction between the physiology and the breeding of wheat. Pages 191 -201 *in* Wheat science—today and tomorrow, eds. L. T. Evans, and W. J. Peacock. Cambridge, UK: Cambridge University Press.

PEACOCK, J. M. 1982. Response and tolerance of sorghum to temperature stress. These Proceedings: ICRISAT.

PUCKRIDGE, D. W., and O'TOOLE, J. C. 1981. Dry matter and grain production of rice, using a line source sprinkler in drought studies. Field Crops Research 3:303-319.

RAO, N. G. P., and HOUSE, L. R. (eds). 1972. Sorghum in seventies. New Delhi, India: Oxford and IBH Publishing Co

RAWSON. H, M. 1979. Vertical wilting and photosynthesis, transpiration, and water use efficiency of sunflower leaves. Australian Journal of Plant Physiology 6:109 -120.

RITCHIE, J T. 1974. Atmospheric and soil water influences on the plant water balance. Agricultural Meteorology 14:183-198.

SEETHARAMA, N., SUBBAREDDY, B. V., PEACOCK. J. M., and BIDINGER, F. R. (In press) Sorghum improvement for drought resistance. *In* Principles and methods of crop improvement for drought resistance: with emphasis on Rice. Los Banos. Laguna, Philippines: IRRI.

SHIMSHI. D 1963. Effect of soil moisture and phenylmercuric acetate upon stomatal aperture, transpiration, and photosynthesis. Plant Physiology 38:713-721.

SLATYER. R. O., and BIERHUIZEN. J. F. 1964. The influence of several transpiration suppressants on transpiration, photosynthesis, and water-use efficiency of cotton leaves Australian Journal of Biological Sciences 17: 131-146.

SPURWAY, R. A. 1979. Root growth and its effect on the supply of water to plants grown in monocultures and 1 : 1 mixtures in an acid soil. Ph.D. thesis, Australian National University. Canberra.

STOUT, D. G., and SIMPSON, G M. 1978. Drought resistance of *Sorghum bicolor.* I, Drought avoidance mechanisms related to leaf water status. Canadian Journal of Plant Science 58:213-224.

SULLIVAN, C. Y. 1972. Mechanisms of heat and drought resistance in grain sorghum and methods of measurement. Pages 247-264 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co.

SULLIVAN, C. Y., and Ross, W. M. 1979. Selecting for drought and heat resistance in grain sorghum. Pages 263-281 *in* Stress physiology in crop plants, eds. H. Mussell and R. C. Staples. New York, USA: Wiley-Interscience.

SULLIVAN. C. Y., WATTS, D. G., GARRITY, D. P., and MAURER, R. E. 1980. Response of sorghum and corn to limited irrigation. Pages 205-218 *in* Proceedings, 35th Annual Corn and Sorghum Research Conference. Wichita, Kansas, USA: Grain Sorghum Producers Association.

TURK, K. J.. HALL, A. E., and ASBELL, C. W. 1980. Drought adaptation of cowpea. I. Influence of drought on seed yield. Agronomy Journal 72:413-420.

TURNER, N. C. 1975. Concurrent comparisons of stomatal behavior, water status, and evaporation of maize in soil at high or low water potential. Plant Physiology 55:932-936

TURNER, N. C. 1979. Drought resistance and adaptation to water deficits in crop plants. Pages 343-372 *in* Stress physiology in crop plants, eds. H. Mussell and R. C. Staples. New York. USA: Wiley-Interscience

TURNER, N. C. 1981a. Designing crops for dryland Australia: can the deserts help us? The Journal of the Australian Institute of Agricultural Science 47 : 29-34.

TURNER, N. C 1981b Techniques and experimental approaches for the measurement of plant water status Plant and Soil 58: 339 366.

TURNER, N. C. (In press). The role of shoot characteristics in the drought resistance of crop plants *In* Principles and methods of crop improvement for drought resistance: with emphasis on rice. Los Banos, Laguna. Philippines: IRRI.

TURNER, N. C, and BEGG, J E. 1978. Responses of pasture plants to water deficits. Pages 50-66 *in* Plant relations in pastures, ed. J. R Wilson Melbourne. Australia: CSIRO

TURNER, N. C, and BEGG, J. E 1981 Plant water relations and adaptation to stress. Plant and Soil 58:97-131.

TURNER, N. C. and INCOLL. L. D 1971. The vertical distribution of photosynthesis in crops of tobacco and sorghum. Journal of Applied Ecology 8:581-591.

TURNER, N. C, and JONES, M. M 1980. Turgor maintenance by osmotic adjustment: a review and evaluation. Pages 87-103 *in* Adaptation of plants to water and high temperature stress, eds N C. Turner and P. J Kramer New York. USA: Wiley-Interscience.

TURNER, N. C, and KRAMER. P. J. (eds.) 1980. Adaptation of plants to water and high temperature stress. New York. USA: Wiley-Interscience 482 pp.

TURNER, N. C, and LONG, M. J. 1980. Errors arising from rapid water loss in the measurement of leaf water potential by the pressure chamber technique. Australian Journal of Plant Physiology 7 : 527-537.

TURNER, N. C, BEGG. J. E„ and TONNET, M. L. 1978. Osmotic adjustment of sorghum and sunflower crops in response to water deficits and its influence on the water potential at which stomata close. Australian Journal of Plant Physiology 5:597-608.

WARDLAW. I. F 1968. The control and pattern of movement of carbohydrates in plants The Botanical Review 34:79-105.

Session 3 Factors Reducing Sorghum Yields Environmental Stress

A. Blum* Discussant—2

Looking at the world map of crop distribution it becomes evident that as plant growth environments deteriorate, the relative frequency of sorghum acreage increases. Sorghum is established as a superior cropping alternative in most stress environments, especially under conditions of drought and heat stress. The problem of environmental stress is therefore inherent to sorghum growing and it is the major limiting factor to yield in most sorghum growing regions.

Although the various types of environmental plant stresses were discussed in one session, a unified approach to plant stress is not deemed possible, even though a proportionally reduced yield is the common result of all types of stress. In the final analysis, each type of plant stress causes specific lesions which may develop at various organizational levels in the plant's physiological or metabolic system. Common to all types of plant stress is our ignorance of the quantified effects of given stress induced lesions on the plant's integrated productive system. We shall return to this question later.

Although a unified approach to plant stress cannot be developed, there are some points where causes and effects of various stresses may cross. For example, salinity-induced osmotic adjustment may confer better resistance to water stress. Or, low temperature stress may cause an increase in cellular solute concentration and thus improve drought tolerance.

The relationships between heat and drought, in terms of injury and resistance, were extensively presented by Peacock in this symposium. Leaf "firing" in the field appears to be a practical integrated measure of heat and drought injury.

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However, the disassociation of the effects of the two stresses requires controlled test conditions. This may be important because limited evidence seems to indicate, for example, that dehydration avoidance could be negatively associated with heat tolerance, across varying genetic materials.

The role of mineral nutrition in affecting plant response to water stress is an intriguing question. Among the various plant processes, translocation is among the most tolerant to water stress. This tolerance may probably be utilized in developing a strategy for plant nutrition under conditions of predictable water stress profiles. Tolerance of the translocation of plant reserves to post-anthesis drought stress is already being utilized in our wheat breeding program. On the other hand, the effect of a given dosage of nutrients, such as nitrogen, on excessive leaf area development and water use, is a matter of record. It can therefore be seen that plant nutrition should be explored as part of the integrated system involving both injury from and tolerance to water stress.

Better knowledge of the interactions among the various environmental stresses may very well lead to a new insight with respect to crop management practices in given ecological regions. It is my own conviction that while crop management practices are probably the most thoroughly investigated topic in agronomy, they have rarely received the appropriate and careful evaluation in the light of our updated knowledge of stress eco-physiology. Most crop management systems are geared to the realization of the full yield potential in favorable seasons, while accepting an inevitably large loss if stress develops. I am not aware of ample evidence that this approach is justified in the long run for all types, levels, frequencies and interactions of environmental stresses. Our most recent experience with wheat management under arid conditions in Israel lends

International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81. Patancheru. A.P.. India. Patancheru, A.P. India: ICRISAT.

support to recognition of a desirable trading off between reduced expectation for potential yield in return for improved buffering of the system if stress occurs. Work by Foale and associates, as cited by Wilson and Eastin at this symposium, is a good example of research that clearly sets the environmental limits, in relation to the long range probabilities, for a given sorghum management system, in the Australian scene.

Turning to the genetic improvement of resistance to stress, it becomes apparent that plant productivity under stress is the breeder's target. However.while yield is the target, selection for yield under any type of stress is inefficient (Blum 1978; Blum 1981). Selection for physiological stress resistance attributes alone is also inefficient, because (a) yield potential of a genotype has its net effect on productivity under stress, and (b) knowledge of the effect of the selected attribute within the plant's productive system is lacking. It therefore remains for an effective breeding program for given stress environments to recombine high yield potential with physiological resistance mechanisms that will buffer the productivity system. A schematic example has been published (Blum 1981} demonstrating the flow of genetic materials across stress and non-stress environments during subsequent generations, with the appropriate multiple selection criteria. Selection criteria depend largely on available screening routines. A working screening routine for stress response must be an en masse technique that will effectively separate genotypes for a given resistance attribute, either directly or indirectly, in a reproducible manner. For example, seed germination in osmoticum is an indirect en masse technique for drought resistance with very poor reproducibility (Blum et al. 1980), which of course makes it useless.

A review of the papers presented at this session demonstrates some useful techniques for suboptimal or supra-optimal temperature tolerance, by measurements on germinating seed, growing seedlings and a test for cellular membrane thermostability. Tolerance to salinity is being screened effectively by monitoring plant growth or survival in saline hydroponic cultures. We can screen for drought (dehydration) tolerance by monitoring plant growth and survival in controlled osmotic media, or by estimating injury to cellular membranes by dehydration in vitro.

Dehydration avoidance (maintenance of "tissue hydration" under drought stress) was considered in this session only via some of its components, i.e., amount of epicuticular wax as a barrier to cuticular transpiration and rooting depth and density as a factor improving water uptake. Indirect screening for complete dehydration avoidance in the field is possible by several methods. Visual scoring of leaf rolling is taken in rice (0' Toole and Cruz 1979) to be a simple and reliable estimate associated with turgor loss. It should be evaluated critically also in sorghum. Remote sensing methods, that can be used in very large nurseries, were adapted to screening work for dehydration avoidance, using the short infrared photographic imaging in sorghum (Blum et al. 1978) and the long infrared thermal sensing in small grains (Blum et al. 1981). The latter method is in routine use in our wheat breeding program, and warrants a thorough evaluation also for sorghum. The line source gradient method, as described here, appears to be a useful integrated method, limited only by physical and economical constraints.

The Role of Crop and Stress Physiology in Increasing and Stabilizing Crop Production

Looking at the 1970s

While the contribution of agronomy and plant breeding to the advancement of crop production is eminent, the contribution of crop and crop stress physiology has not been highlighted, to say the least. The last decade definitely brought it into a clearer focus, in this respect.

Research in crop and stress physiology expanded our understanding of crop responses to the environment. This is not just a lip service, but it consists of a real economic contribution. This understanding—put to use intelligently—has reduced the amount of empirical agronomic research, over space and time. It has increased the efficiency of some agronomic research by eliminating the unproductive repetition of experiments, as required in empirical work. This is easily translated into improved returns per unit investment in agronomic research.

The more direct contributions of crop and stress physiology to agriculture is a matter of record. Following are some examples:

1. Irrigation water-use efficiency was improved by employing simple physiological models of

the system, as well as physiological criteria for irrigation scheduling. New irrigation technologies (such as drip-irrigation) could not have evolved without a recognition of the plant water stress dynamics in the field. This recognition also improved the utilization of saline and brackish water in agriculture.

2. Expanded knowledge of the plant water regime and water stress processes in given agricultural ecosystems was responsible for the development of stress-adapted management systems, such as new planting configurations in sorghum and wheat.
3. Research into the physiology of mineral nutrition, together with soil chemistry, was responsible for improving the efficiency of fertilizer utilization in many crops.
4. Physiological knowledge has contributed to the development of a plant ideo-type concept and thus affected the efficiency of breeding programs (including the drought response complex). The efficiency was improved in terms of the time saved and the reduced carryover of useless genetic materials during subsequent generations.
5. Relevant screening procedures for heat and drought stress—reasonably tested in breeding programs—are available. Their utilization is only a question of the breeder's initiative, interest and available resources.
6. The new discipline of "genetic engineering" could not have evolved without the physiological basis for this technology.

In addition to these examples, more can be pointed out by almost any agronomist and plant breeder, as based on his own experience.

Looking at the 1980s

There is no doubt in my mind that crop and stress physiology will have an even greater impact on agricultural research and production, in the next decade.

It is my impression that a greater proportion of leaders in the agricultural sciences accept crop physiology as an important independent or interactive discipline.

Empirical agronomic research will be reduced to the margins and be replaced by in-depth intensive research. Crop physiology will then be used as an interactive part of the agronomic research. It will be employed as a tool for validization and explanation of research results and will predict interactions with the environment—instead of empirical repetition of work over locations and years.

Finally, may I be so bold as to suggest a list of some of the important topics of research in crop and stress physiology in the 1980s.

1. Research into the physiology and metabolism of hybrid vigor, as a convenient private case of the genetic physiology of high yield.
2. Re-evaluation of most of the commonly accepted management systems (especially in stress environments) with the appropriate physiological validization.
3. Improve and develop physiological and management-oriented models, primarily as a tool in research, and hopefully as a tool in farming in the 1990s.
4. Intensify research on the various aspects of plant nutrition, with regard to the variation in the plant's water regime, and in relation to the genetic improvement of yield.
5. Develop the technical abilities to use cell and tissue cultures as a substrate for selection for stress tolerance.
6. Research into the application of remote sensing technology as a tool in agronomy, plant breeding and crop physiology, as well as a tool for decision-making in farming.
7. Establish research in sorghum (as already being developed in barley, cowpeas and soybeans) to determine the interactions between given drought resistance mechanisms and crop productivity under stress and potential environments.
8. Explore additional possible mechanisms of environmental stress tolerance, followed by the development of proper rapid screening technology.
9. Invest in "pilot projects" that will perform breeding for stress tolerance, with strict and committed physiological guidance, in order to learn from success or failure.

References

BLUM, A. 1978. Genetic improvement of drought resistance in crop plants: a case for sorghum. Pages 430-445 *in* Stress physiology in crop plants, eds. H. Mussell and R. C. Staples. New York. USA: Wiley-Interscience.

BLUM, A. 1981. (In press). Breeding programs for improving crop resistance to water stress. *In* Crop reactions to water and temperature stresses in the humid temperate climates, eds. P. J. Kramer and C. D. Raper, Jr. Duke University. Durham.

BLUM. A., SCHERTZ. K. F., TOLER, R. W., WELCH. R. I., ROSENOW, D. T., JOHNSON. J. W.. and CLARK, L. E. 1978. Selection for drought avoidance using infra-red photography. Agronomy Journal 70:472-477.

BLUM, A.. MAYER, J., and GOZLAN, G. 1981. (In press). Infrared thermal sensing of plant canopies as a screening technique for dehydration avoidance in wheat. Field Crops Research.

BLUM, A.. SINMENA, B., and Ziv, 0.1980. An evaluation of seed and seedling drought tolerance screening tests in wheat. Euphytica 29:737-736.

O'TOOLE, J. C. and CRUZ. R. T. 1979. Response of leaf water potentials, stomatal resistance and leaf rolling to water stress. Plant Physiology 65:428-432.

Session 3 Factors Reducing Sorghum Yields Environmental Stress

Discussion

Asher

The question has been raised as to whether or not we should be attempting to produce genotypes more suited to existing soil conditions as an alternative to the traditional agronomic methods of modifying unfavorable soil environments with fertilizers and soil amendments to suit existing genotypes. As a previous speaker has pointed out, the maximum number of characters for which the selection is practised at any one time is very small, perhaps three. Hence if we choose to select for nutritional characters, progress in this direction will necessarily be at the expense of progress that might have been made in some other direction. Consequently we need to be reasonably sure that this is worthwhile.

My own view is that the steep rises in the costs of manufacturing and distributing fertilizers which occurred during the 1970s have already placed them beyond the reach of the poorer farmers in the poorer countries and the situation seems likely to become worse rather than better in the years ahead. Indeed it is questionable to what extent poor nations without their own means of fertilizer manufacture will be able to spare valuable foreign exchange for the importation of expensive fertilizer materials. Consequently I believe that the time has arrived for a careful investigation of gains that might be made through breeding for selected and carefully defined nutritional characteristics.

I believe that this research will show that differences in ability to absorb nutrients present in relatively insoluble mineral forms are likely to be more important in the majority of cases than differences in the efficiency of distribution or utilization within the plant. It is for this reason that I believe that prospects for finding "nitrogen efficient" genotypes are less favorable than those for finding genotypes and adapted to soils deficient in other elements. However differences in the total volume of soil exploited or differences in ability to form associations with free living nitrogen fixing microorganisms could be important.

Quite apart from the question of possible genotypic differences as associated with nitrogen fixation, I believe that we have to look towards biological nitrogen fixation to lessen the need for costly nitrogen fertilizers in the sorghum production systems of the poorer nations.

H. G. Jones

I agree with Professor Asher in that we need to put more emphasis on the genotype alterations capable of withstanding nutrient deficiencies. This may come out further during discussion.

Nicou

The speeches of this morning dealt solely with breeding to solve the problems of drought resistance, temperature, mineral deficits and toxicities. The breeders will be asked to develop plants resistant to every harmful factor including diseases and pests. I feel that we should not demand too much from the breeders. Certain agronomic methods exist which can control drought. A few of them are used in Australia, others have been developed in West Africa or in India. Similarly, there are some agronomic techniques to control mineral deficits and toxicities. For example, some regions exist in Upper Volta where acidification is so high that sorghum does not grow. I do not suppose it is possible to develop resistant varieties to such high acid conditions. I regret that different speakers have not described means other than that of breeding to solve the problems of mineral deficits and toxicities. I think that we should not depend only on one possibility but have at our disposal, all possible and useful means to control the factors responsible for loss of sorghum yields.

Clark

This is a response to the comment by Dr. Nicou about adding more demands on the already heavy-burdened plant breeders for inclusion of water (temperature and drought) and mineral stress traits into their breeding programs. We all recognize that scientists are busy and have important programs. My experience has been that plant breeders, unless the job description states that his/her emphasis will be on environmental stress, have been far more reluctant to help a physiologist than the physiologist to help a breeder. I attended a recent international symposium in which many physiologists working on mineral stresses would love to reach out to help plant breeders, but breeders were not available or hesitant to reach out to include the physiologist. I wonder if this may be because of the conservative nature of plant breeders and their reluctance to move away from traditional plant breeding methodology. I find myself learning more genetic techniques to help relieve some of the load on our sorghum breeder, and he is willing to help me. Because of this. I think we are making progress, we are making a close working relationship, and a greater excitement is being noted from both of us. I think we need to rethink our attitudes, inhibitions, or reluctancies and bring the physiologist and breeder closer together in plant improvement programs.

Another item that has not been used and improved, but could help breeders is information banks. If genotype response differences to drought, temperature and mineral stresses for many genotypes are put into information systems, these can be used to help plant breeders better evaluate the germplasm he/she is using or ought to consider using. Information banks should and ought to be set up, kept current, and used.

Bapat

Are there any character associations observed for heat tolerance—for example the glossy leaf trait which imparts tolerance to shoot fly?

Jordan

We have not looked at the glossy trait per se, but we have evaluated wax loads on many lines. It is interesting to note that M35-1, a glossy line, has high wax in nearly all environments. We have not investigated either the chemistry or structure of epicuticular waxes. M35-1 is also heat tolerant and drought tolerant, but a cause-effect relation of glossy to these traits has not been investigated.

Bapat

High temperature conditions reduce grain number; is this due to nonfiling of grains or reduced number of spikelets?

Peacock

How temperature stress influences grain number will depend on the severity and timing of the stress in relation to the stage of growth of the sorghum plant. It is well documented that high temperatures at floret differentiation will lead to a severe reduction in final grain number.

Parameswarappa

Dr. Peacock, you mentioned genetic differences in plumule length at germination, but we observed that the plumule length varied in the same variety depending on the age of the seeds used in the test. For example, freshly harvested seeds produced longer plumules.

Soman

The rate of growth and length of plumule do not depend on only one factor. Age of the seed is thought to be related to the metabolic state of the tissue. Therefore, it is possible for such a relation. However, in our studies we used seeds harvested in the same season and stored more or less under the same conditions. Besides the genotype, the other important factor is temperature. Biochemically, the rate of growth depends on the rate of respiration (turnover of soluble components) which changes as a function of time.

K. N. Rao

What is the level of acidity under which the scoring for acid tolerance in sorghum is done to identify genotypes suitable for acid soils?

Clark

In nutrient solutions, sorghum will grow very well at pH near 4. Thus, pH per se may not be the limiting factor. In soils, Al, Mo, and Fe toxicities and other acidity factors may become limiting to plant growth at higher pH values (usually at about 5.5 or below). Thus, the pH at which sorghum may grow in acid soils will depend on many factors.

Muchena

Dr. Jordan mentioned that there is no difference between tall and short cultivars of sorghum in root size. This is contrary to our observations in pearl millet. We found that while some isogenic lines showed no difference between tall and dwarf counterparts there were some which showed differences, the dwarf being superior. I wonder if there is not an analogous situation in sorghum. Did you examine a wide enough range of lines in the work you quoted?

Jordan

We examined only isolines of kafir and milo sorghum in our studies. Even though height differences between isolines were about 1 m, we observed no root differences that could not be explained from small differences in leaf area. The results were consistent for both growth in large soil boxes and in solution culture.

Parameswarappa

Dr. Clark mentioned about the toxicity of aluminum on cytoplasm. May I know the different types of cytoplasms tested? Or was it one and the same cytoplasm in all the male-sterile lines you tested?

Clark

The cytoplasm materials we used were of different sources prepared by Dr. W. M. Ross. They are described by W. M. Ross and K. D. Kofoid, Crop Science 19: 267-270. Those used in our study were KS34. KS35. KS36. KS37, KS38 and KS39.

Sinha

Given a particular environment and the uncertainties of available water, what should be the level of yield under drought conditions as compared with irrigated conditions that would be satisfactory? Is it likely that in some situations we already have such types which have satisfactory yield potential? Is it possible to define the yield potential in relation to the amount of available water?

Blum

I am fortunate to work within an agricultural system that will accept varieties earmarked as adapted for growing under defined environments. We can therefore release varieties designed for growing in stress environments. These varieties may lack in their potential yield but will perform better than others under stress. I do not feel that the probabilities for recombining very high yield potential with high levels of drought resistance are good.

Soman

Dr. Clark, your technique with solution culture to screen for Al toxicity is interesting. I wonder about the response of these materials when planted in the soil. Did you try to transplant the material (say tolerant ones) to a soil medium or the field and observe its performance?

Clark

We are now in the process of doing this. For the most part, nutrient solution responses are close to field responses. Some differences have occurred. One item that has become apparent in field trials versus nutrient solution trials is that we may have to screen in solution at Al concentrations that more closely fit soil conditions. For example, we had one genotype that was very tolerant at our usual Al level for screening. When we increased Al two-fold, this genotype responded very poorly to Al while others that did not do so well in the initial Al level looked as good or better than our so-called tolerant one. Under the field conditions that our Al tolerant genotype was grown, it did not grow well. I realize that any nutrient screening method must relate to field responses; we are now trying to do that. If they do not, we are trying to find out why and adapt the methods so that they will. Soil conditions may have other problems besides Al, thus the nutrient solution screening is for Al toxicity, not Mn, Fe, etc.. toxicity which may also be a problem, in the soil.

Maiti

Drought occurs at different stages of growth. There may be a necessity to screen genotypes for drought resistance at different stages. Dr. Jordan, do you think that drought resistance at the seedling stage is in any way related to drought resistance at the adult growth stages? If so, could seedling resistance predict the performance at the adult stage? Our work at ICRISAT gave an indication to this effect.

Jordan

There may be a possibility of seedling resistance related to resistance to adult stage but we have not made any study in this direction.

Asher

Dr. Myers drew attention to the need for an illustrated handbook of nutritional disorders of sorghum, preferably containing information about critical tissue concentrations for nutrient deficiencies and toxicities. ICRISAT has substantial expertise in the publication and dissemination of technical material in the SAT. and would, in my opinion render a great service to sorghum researchers if it were to undertake the production of such a handbook. Some of the information needed is available already. I would suggest that the task of obtaining the additional data might be handled most effectively through collaboration with other institutions which already have the necessary specialized facilities and expertise.

Bunting

We have not, I suggest, sufficiently disentangled heat stress effects from those due to water shortage. They have been confounded in the methods of measurements.

Sorghum is grown in two quite different water regimes which are the mirror images of each other. In temperate regions, the growing season starts with the profile full of water which is drawn upon during the season because the rate of evaporation is greater than the rate of precipitation. Water stress is rare in the seedling stage; it is often important during the later part of the summer. In the semi-arid tropics, the growing season starts with the profile empty, and it tends to fill from the top as the rate of precipitation increasingly exceeds the rate of evaporation. In some soils with restricted percolation (Vertisols, pans and compact layers) a temporary water table may lie near to the surface, to fall later as the precipitation falls below the rate of evaporation. The period of wet conditions may damage roots and oblige the crop to rejuvenate new roots in order to exploit the water in the profile. Drought risks are most severe at the start and end of the season. These contrasted water regimes are so different that we cannot safely transfer ideas about drought resistance, tolerance or evasion or plant materials alleged to possess these attributes from one to the other.

In the tropical regime, moreover, nitrogen is mobilized in the surface soils when they are wetted by early showers, and is free to be leached by the more substantial rains which follow as the wetting front moves down the profile. On the other hand, leaching is unusual during the growing season in the temperate water regime.

H. G. Jones

Before closing this session, I want to make a quick comment to emphasize what the speakers have said earlier. They have clearly brought out the role of physiologists in sorghum improvement programs and how important cooperation is going to be in the future.

We would admit that so far physiology has made quite an outstanding advance in knowledge but its application has been relatively limited to date. The reasons for this have been outlined by Drs. Turner and Blum.

Further, it was also clear that we need a team approach including the breeders, physiologists and agronomists. For rapid progress, we must go beyond the pure empirical approach and I am optimistic that this is a technique for the 80s.

Insect Pests

Chairman: A. N. Pitre
Co-Chairman: F. Gilstrap

Rapporteurs: H. C. Sharma
S. L Taneja

Pest Losses and Control of Damage on Sorghum in Developing Countries — The Realities and the Myths

J. C. Davies*

There have been significant advances in sorghum research and considerable increases in world sorghum grain production and yield in the past decade. However, the sobering fact is that, with the notable exception of India, there has been only a minimal improvement in overall production from the countries where sorghum is used primarily in human food (Kanwar and Ryan 1976) and indications are that production trends will be negative before long in many countries (Ryan, personal communication). This is a situation that can be ignored only at our peril. It is a situation for which something can be done, but only if we take an objective look at our ideas—many of which are preconceived. We must realize that the solutions proposed and results obtained in the sorghum research field in developed countries, must be examined very critically before being adopted or utilized as blueprints for attacking the serious and urgent problems of increasing sorghum production, particularly in Africa. I make no apology, therefore, for 'slanting' my remarks today on entomology, towards the developing world situation. Even a brief scan of the sorghum literature shows that the developed world is exceptionally well catered for, both by the amount and quality of information being produced on sorghum in all scientific disciplines, including entomology. However, I suspect that in the 10 years since the last sorghum symposium, the number of research and development workers, who are able to devote their full time to the sorghum crop in Africa and the developing world has not increased to anywhere near the extent needed, to cope with the well documented problems of feeding their rapidly expanding populations. Indeed the number of sorghum research workers in the developing world may well have decreased!

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I also make no apology for taking a rather simplistic approach and for not delving into the more fascinating scientific aspects of pest problems on the crop in the developing countries and the more esoteric proposals for tackling them.

Sorghum as an Insect Food

Sorghum must rate as one of the most favored plants, cultivated by man through the ages, as a host for pest insects. Numerous lists have been produced cataloging well over 150 species as pests or potential pests of sorghum (Jotwani et al. 1980; Seshu Reddy and Davies 1979). Fortunately, it remains a truth, that the actual number of species which can be considered of *major* importance are no greater now than they were when the last distinguished scientific gathering assembled for the Sorghum in Seventies Symposium. As at that time, the most ubiquitous and serious in worldwide terms probably remains the sorghum midge, *Contarinia sorghicola* (Harris and Harris 1968; Harris 1976)—a pest which we should discuss a little later in the context of the realities and difficulties facing us as entomologists. Many pests are of regional importance including the various armyworms, e.g., *Spodoptera exempta* (Brown and Dewhurst 1975) and the locusts, *Schistocerca gregaria, Locusta migratoria* and *Nomodacris septemfasciata,* particularly in the African context. These days, we tend to relegate locusts to the status of pests of the past—but I suspect that in the context of political upheaval and consequent problems of control strategy and the logistics of both aerial and ground survey and control, we would do well to keep a very jaundiced eye on their activities. The spectacular losses and damage, which can be caused quickly by both armyworms and locusts, could possibly

International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum. 2-7 Nov 81, Patancheru, A.P., India. Patancheru, A.P. India: ICRISAT.

be more important for the peoples of Africa even now than the more insidious enemies, which annually take their toll—the shoot fly, *Atherigona soccata,* the lepidopterous stem borers, *Chilo partellus, Busseola fusca,* the *Sesamia* spp and *Eldana saccharina.* The latter appears to be relatively more important in Africa now than it was in the early 1970s (Girling 1978).

The omnivorous termite species take a steady, if unspectacular toll, but the true effect on yields is not assessed. Since the last conference we have made, as entomologists, little or no progress in determining the identity *or* extent of damage caused by the many hemipterous species found in the heads, although Bowden in 1965 drew attention to their possible importance. Certainly, there is no doubt that the last decade in India has seen *Calocoris angustatus* appear as a more than occasional pest locally, but we appear to know very little of the reasons for sudden population increases. While the importance of aphid species has been seriously viewed in the cooler temperate countries (Schuster and Starks 1973), in the developing countries the exact status of the various species has been little researched. Certainly, here at ICRISAT, late season attacks with high aphid counts in the head and associated honey dew and consequent mold growth, make them an object of speculation, if not of research.

With the introduction of the tighter panicle, the importance of the many lepidopterous head worms both in India and Africa has changed—but this change has not been quantified in terms of damage. As early as the late 1950s, Doggett (1954) among others, was commenting on the numbers of *Heliothis arimigera* larvae in tight and protected panicles, possibly due to discouragement of predation by birds, but possibly also to the increased protection afforded against insect and arachnid predation or improved habitat for survival. While increased *Heliothis* numbers may not in themselves have much effect on sorghum yields, we should be looking at the overall effects of such observations on the pest spectrum and yields of a range of crops, in view of the mixed cropping situation which the small farmers of the SAT use to spread their risk. The situation is one which is completely different from that in a developed agricultural economy, where even height and good panicle conformation are important, and harvesting and drying machinery are readily available to handle such cultivars in monoculture.

As entomologists, we can look back on the last decade as one where the sorghum crop has not suffered the entomological equivalent of the Southern leaf blight disaster of the 1970s on maize in the USA or the downy mildew "epidemic" on pearl millet of the mid 1970s in India. I hope that we are all convinced that this was cold calculation and not luck—I do believe that screening techniques are surer in the developed world and contribute to safety margins in released cultivars, but there is room for considerable improvement. I view with wariness the tendency to believe that quick solutions to production problems for human food sorghum are possible by the transfer of established lines—commercial or otherwise—to developing countries. We are only at the very early stages of the incorporation of insect resistances into better agronomic and higher yielding types fully adapted to the SAT. Our screening capability in these situations is inadequate at the national level. The finance to improve this vacuum is lacking. A great deal remains to be discovered about the biology of the pest species range on sorghum in the developing world. A glance at the impressive lists will convince even the most skeptical that there is a potential, or actual, pest for every stage of the sorghum plant from seedling till after storage in almost all situations—climatic, edaphic and cultural. Additionally, we have been singularly fortunate in that the potentials of several insect species for disease transfer appear to have been relatively unutilized in sorghum.

Pest Attack and the True Loss Factor

The references to significant pest losses in crops, and these probably included the progenitors of modern sorghum, are ancient and impeccable, and are mentioned in the Bible in Exodus 10 and Joel 1. While the potential losses in the high plains of Texas to midge *are* well quantified (Bottrel 1971), there are however, far less readily available sound data on losses from developing countries, where sorghum is a significant food crop. In these countries, particularly those of the semi-arid tropics with a rainfall of 600-1000 mm per annum, where sorghum is an important human food, the yields generally quoted are pitifully low—500 -700 kg/ha. A major reason given for this is pest attack. Certainly these yields compare very unfavorably with yields from the same cultivars on research stations within the SAT, which are frequently three or four times as high. These statistics are meaningful to governments and planners who must consider the total production in feeding strategies for their populations—but how meaningful are they as statistics on which to base entomological research proposals? Most of us who have toured extensively in these areas "know" that yields on well-grown, timely-sown sorghum on farmers' fields are more, by a factor of 3 or 4, than the average and "know" the level of inaccuracy inherent in the average estimates in official statistics—even the ones widely quoted yesterday. Clearly, a great deal could be done by the introduction of improved agronomic practices even with existing cultivars and known research information and techniques.

Possibly one of the few pests on which some firm evidence on losses for developing countries exists is the sorghum midge. As early as 1960, Nye (1960) commented that in Eastern Africa, it was a severe pest only on research stations and this is certainly so, at present, in some areas of West Africa. I do not think that the situation in East Africa has been looked at objectively since the 1960s.

The situation in Nigeria appeared to be very different (Harris 1961). Extensive surveys there in the late 1950s indicated a 4% loss on some 250 000 acres (equivalent at that time to almost 2 million pounds sterling). Even within West Africa, the situation is far from uniform, however Bowden (1965) noted that in Ghana infestations (as opposed to losses) are seldom above 10-15% and that quoted losses to midge are compounded by losses due to the head infesting hemiptera. The observation was reported to be possibly due to the cultivar being grown which had a relatively compact head, but also possibly to the higher rainfall. In India, midge is often serious at research centers and undoubtedly important in "endemic areas" (Venugopal et al. 1975; Jotwani 1978) particularly where plantings are staggered, but from my own observations, it appears that in some endemic areas, the head infesting hemiptera may also be important contributory factors to the losses quoted.

Actual data on losses due to shoot flies and stem borers are hard to ascertain. Fields badly damaged by shoot fly are spectacular when observed, but what do they mean in terms of yield loss to a whole area, or country, in a particular season? This cannot be said to have been accurately assessed. Clearly, early sown crops are but lightly damaged, in all but a few seasons. Attempts to gauge the economic threshold levels for shoot fly, using insecticides, in limited and 'blanket' applications, tend to show that increments of yield in sorghum produced are often not significant nor economic on research stations with the higher yield levels relevant to these (Ingram 1959; Davies and Jowett 1970). Assessments of losses from the various insidious stem borer species in sorghum are even more difficult to quantify. Ingram (1958) commented that in Uganda, despite heavy attacks by *Busseola fusca* and *Chilo partellus.* sorghum yielded well. A similar suspicion was echoed by Harris (1962) for West Africa, and subsequently supported by his further work (Harris 1964), where the use of insecticides for control gave conflicting results with regard to yield increments. Increases in yield per stand were obtained from bored stands. This was presumably a function of either extra tiller production or selection of potentially higher yielding stems for attack by borers. Evidence has been produced quoting correlations between length of tunnelling and yield loss. However, there are several reports of disconcerting positive correlations between stem tunnelling, or number of borers per stem, and yield. This feature, which presumably is a reflection of the sampling methods or cultivar used, does not appear to have been seriously researched. It might be postulated that with the dynamic biological systems with which we are dealing, compensatory reactions from plants and discriminatory mechanisms on the part of insects are operating.

So where does this put the pest problem in relation to the scheme of yield loss and in relation to other yield reducers such as poor plant establishment and final plant population, drought, disease, parasitic weed and possibly most important of all, birds? It is important to know this at times of fund constraint and scarce resource allocation. The evidence of loss, except for the recorded catastrophic "invasion" years when massive or a localized very severe pest attack is recorded, is pitifully poor. There is little reliable clearcut information on "normal" pest attack on "normal" crops. In relation to insect attack, it is suprising how often late-sowing is commented on as a factor in increased pest attack, but then late sowing or serial sowing is becoming more and more recognized as a small farmer technique (and an apparently realistic one at that), for the avoidance of risk—be it from hail, extended rain or pointed massive pest attacking migratory pests. Do we have to balance losses in late sown crops against the insurance factor for those important years when these late sown crops are the ones which, even though poor, give the only sustenance in disaster years to 'on farm' families? The small farmer systems are clearly, and rightly, far more sophisticated than those of large-scale farmers, where modem technology has provided risk evading mechanization to assist in times of crisis, be it supplemental irrigation, spray planes, harvesters or crop driers or, in the developing country situation, cash reserves from other sources which are available to buy in food in years of scarcity.

My conclusion from a study of the currently available loss data is, that if these were presented in a court of law, while the circumstantial evidence for pest loss is very strong, there is insufficient evidence to convict. Clearly, we cannot extrapolate the situation, as we know it with regard to pest loss, from the high farming situations of the developed world to developing country and particularly small farmer agriculture. We are, to quote a gentleman who must be justly famous, "in a different ballgame". In my view, as a basis for our forward strategy in sorghum for the 80s we have a responsibility as entomologists to evaluate, rather more carefully than we have, the losses actually suffered in local cultivars in the existing farmer situation, given current methods of production and agronomy. We also have to assist in projecting, realistically, what can be achieved in increasing production by introduction of new cultivars and their impact on both pest loss and pest status of the many insect species recorded from the crop. Shifts of pest status on cereals are not numerous, but some have been observed in the developed world; they are not well documented in the developing world on sorghum, but have been seen even in the last decade on millet in West Africa *(Vercambre* 1978). There is evidence from Latin America, Africa and India, of some species increasing in relative importance in the last decade.

Summing up on pest loss, I would ask, do we really know the economically damaging pest species in the developing world other than in very localized or short term circumstances? We should not overlook the fact that even an insect such as sorghum midge was repeatedly missed by trained biologists in the past and the damage it caused had been variously reported as ranging from hail damage to blight. Do we really know the effects of the various pest or potential pest species on crop establishment, for instance, in small farmer situations? Could the losses in plant population caused by shoot fly be more important than those of borer in the stem, for instance? Do we have real estimates of the loss in the developing country situation as opposed to fancied extrapolated losses from developed country data? There is a school of thought that believes such research is not required—do we subscribe to this? I believe schemes already exist that could take on this task immediately and let us have reliable information speedily. A part of this excercise must be to arrive at more reliable production and average yield per hectare figures.

An important point already commented on in this workshop, in this context, is the fact that currently in developing countries, little of the sorghum produced enters established trade channels—it is mainly consumed on the farm—so how accurate are the means for loss on which we justify our projects? Let me hasten to say that. I believe, the losses are real and the situation particularly with regard to 'invasive' pests very delicately balanced. Perhaps in any case, the disaster year information more than justifies all entomological input—which is so slight in developing countries.

Control Strategies for the Developing World

The utilization of resistance as a control strategy in the developing world is one which has enormous practical relevance and additional emotional appeal. Like many others in this room, I have worked with insecticides on both cash and food crops and with the latter, at the end of the day, the sheer magnitude of the problem of infrastructure and delivery of crop protection products to the small farmer and the crop, aside from questions of economic or socioeconomic practicality, force one to the view that the only thing that can be guaranteed is that the small farmer will plant a seed at the earliest posible time for his particular situation, in a particular season. Thereafter, he is at the mercy of forces often completely out of his control.

However, we *are* all a little euphoric about the very real problem of incorporating and utilizing the identified resistances from germplasm sources in the seed which will eventually go to the farmer. The goal of pest resistant sorghum can only be achieved by a very concerted and dedicated effort, to integrate the workings of the many scientific disciplines involved in the effort to achieve final success. It is regrettably not a perfect world, and a true multidisciplinary approach does not come easily—all of us in our individual disciplines "know" and the fact of 'knowing' and the very real pressures of the systems in which work is carried out. with its emphasis on results and quick solutions, mitigates against true fully integrated effort. There are, in developed countries, increasingly strong economic and commercial forces driving and fueling true multidisciplinary effort. However, in most developing countries, the restricted availability of trained staff places almost impossible strains on true multidisciplinary effort. Often the men are not available to place in a team to tackle just the needs of sorghum: the breeder is often concerned with a range of food crops and the entomologist or pathologist has to give second or third priority to the crop. As a general rule, physiologists are not available and agronomists cover an impossibly large range of crops and the glamor field is farming systems, not sorghum agronomy. In the circumstances, it is not surprising that the necessary close contacts and time for integration of knowledge, ideas and work plans are not satisfactory.

It is also significant that knowledge obtained in one discipline or one country is often not available to another for a variety of reasons. As an example of what I mean, currently not far from here, another look is being taken at the desirable sorghum head type for the semi-arid tropics, and in particular, the advisability of more lax headed types than those generally preferred in recent years. Yet from the 1950s, there was considerable evidence, at least in Africa, that lax headed types were less susceptible to hemipterous head bugs and afforded more easy access to birds for predation of lepidopterous head worms. There was also evidence that grain molds were less of a problem in wet years, in situations where end-of-season rains were frequent, because of the relative speed of drying after rainstorms. It must be conceded that lax heads do not conform to current ideas of a desirable head types—which are largely conditioned by concepts derived from high input mechanized agriculture—but our target clientele are the small farmers, whose objective is to produce more grain, more reliably, with reduced risk, to feed their increasing families.

As ever more gloomy forecasts are made about the shortfalls in cereals in developing countries in Africa over the next two decades, we must be concerned. I wonder if Dr. Blum, who is in our audience today, feels that the situation in 1981 is significantly better than it was when he attended the last conference, with the sorghum for the decade theme, and said "Plant breeders in general appear to lack an understanding of insects with regard to their hosts and tend to regard the insect population as a fixed environment parameter, with all the consequent implications" (Blum 1972). I believe we are moving educationally in the correct direction, but I also believe that there is a current danger of too much emphasis on the heritable resistance characteristics at the expense of the investigation of the overall entomological implications of the very complex characteristics of crop production in relation to agroclimatic and ecological factors and dynamic insect biology. I would perhaps extend the sentiment of Blum's statement to incorporate workers in the interdisciplinary areas of relevance to the successful breeding of the sorghum crop to withstand insect attack, and not to confine the statement merely to plant breeders.

In the context of cross discipline understanding, further thought needs to be given to the use of modern insecticides in resistance breeding programs. Their use appears to be a valid tool early in breeding programs to ensure transfer of desirable characteristics for yield and for good agronomic traits. However, excessive or prolonged use of insecticides into late generation breeding material is potentially dangerous, if we are endeavoring to produce suitably robust material with insect resistance for use on farmers' fields. It is sobering to reflect on Pradhan's (1971) forebodings about utilization of insecticidal "umbrellas" in breeding and the fact that release of 'superior', but otherwise insect susceptible varieties, in the tropics will not really achieve anything. This is a very real possibility and must be guarded against. The products of breeding programs must be viable for existing farmers' conditions, while having the potential for increased yields in improved or moderate to high input situations.

The concept of chemical control of sorghum pests is a relatively recent introduction in North America (Jotwani and Young 1972). The concept was based on a rapid expansion of sorghum acreage and the development of high yielding hybrids in moderately high input conditions of fertilizer usage and mechanical plowing, using harvesting and drying techniques of high sophistication. I believe some of these concepts have a place in the developing world—particularly in Africa, if a serious food shortage is to be avoided. There are areas where, after a minimal amount of adaptive work, existing sorghum cultivars could be grown in riverain irrigated areas on deep black soil rainfed plains with assured rainfall, to produce large amounts of food. Rapid adaptation of existing pest control strategies to suit SAT situations may be possible to protect such mass and exotic material—but little work on efficient application techniques has been done to date.

The situation with reference to chemical control in developing countries outlined by Jotwani and Young at the last conference has not materially changed. Generally, the favorable results obtained in the work done on the sorghum areas of the developed countries have been followed by testing of the successful insecticides in the developing countries (Barry 1972; Sepswadi et al. 1971; Jotwani, 1978; Vedamoorthy et al. 1965). Many of the results have been good under research station and supervised conditions and spectacular increases in yields have been claimed. I am a little concerned that, to an extent, the use of insecticides has caused an upsurge of work which detracted from effort on the entomology of the crop. This was certainly so in the early 1970s. In general, there is little convincing evidence of the economic soundness of some of the recommendations made for insecticide use on sorghum, in developing countries, except in special high input. or at least high fertility, and possibly assured water situations. Many insects in the developing country situation, particularly midge, and possibly stem borers, are not easily controlled economically with existing techniques. Certainly in the SAT areas, where water is such a problem, some of the spray volumes recommended for use are beyond the ability of the socioeconomic framework to supply. Answers must be found which utilize simpler application techniques involving either no water usage or at the least, minimal quantities. Dusts and granules have their own particular problems with regard to transport. storage and application techniques in the tropics.

The words of caution stated by Jotwani and Young (1972) at the last conference, with reference to the numerous instances of failure to control pests and the importance of developing long range strategies, which do not rely entirely on insecticides, but integrate all the various methods—cultural, mechanical, biological, and resistance—are as true today as they were then. Progress has been made in India in education on the value of cultural methods and early sowing of sorghum, and plans have been made for detailed studies in the West African areas that could lead to integrated pest management. There is clearly however, in much of the developing world, a dearth of information on which to base these strategies and further a lack of any real conception of whether these are possible to apply, or indeed are acceptable at the small farmer level, given the scarcity of resources and number of qualified extension staff.

Novel Methods of Control of Pests

Much has been written and speculated about the use of more novel methods of control worldwide, but despite the rapidly increasing level of understanding and the detailed and intricate work on insect produced chemicals—pheromones, juvenile hormones and chemically produced sterilants —the promise remains largely unfulfilled, as far as the less monetarily valuable crops such as sorghum are concerned. Several of the important pheromones of stem borers—*Chilo Partellus* (Nesbitt et al. 1979) and *Busseola fusca* (Hall et al. 1981)—have been identified and field tested with success. They appear, at this stage, to be at best useful research tools and at the worst possible eye catching glamor areas for research which could divert funds and scarce scientific talent from the difficult problems of pest control on the sorghum crop in developing countries. This, to a greater or lesser extent, also applies to the use of hormones and sterilants. In the area of insect physiology and feeding behavior, chemical content of sorghum cultivars and related chemical constitution of sorghum, very significant strides have been made over the past decade. Clearly, this work has direct relevance to the problems of breeding for insect resistance and the potential payoff is great, if simple field screening for identified chemicals can be developed (Fisk 1981; Woodhead et al. 1980).

The research area of insect physiology with possibly greatest significance to lepidopterous pest carryover between seasons, is aestivation and diapause behavior. Some pioneering work on this has been done in Kenya by Scheltes (1978), but much remains to be done. The complexites of the interrelated chemical and water balance factors are areas for fruitful research effort. At ICRISAT, some preliminary studies were done and this work must be expanded. Here is a fruitful area for collaboration with developed country institutions with their sophisticated equipment and techniques.

Related to some of these chemical and physiological studies are the cultural methods of control. These are, by and large, worked out for many pest species in the developing world (Harris 1964; Nye 1960; Ingram 1958). Refinements have been proposed in the last few years (Adesiyun 1980). The extent to which many of these are acceptable to small farmers will be a task for the workers in the field of integrated pest management to determine.

In closing, may I say that I have been deliberately provocative in places because I feel that the time left to show real impact on the sorghum food situation in developing countries is running out. The progenitors of the sorghums which will help us to overcome the problems should already be in "the system " or at least be there within the next 5 years—given the 10-12 year lead time needed to get a proven line widely used by farmers. There has been an alarming increase in food imports into most West African countries in the last few years. The World Bank estimates suggest that while population has grown 2% a year throughout the area, food crop production has stagnated and in several countries, decreased. We need to examine, very seriously, some of our straightforward interpretations of developed country results on monocrop shorter-term sorghums and their applicability to the erratic rainfall, poor soil, intercrop situations so prevalent in the sorghum areas of developing countries. In situations such as in India with a reasonable infrastructure, high land usage and high human populations, there have been striking advances in the 1970s resulting in grain surpluses using transformation strategies. However, even these conditions do not hold good for much of the area which ICRISAT was built to serve. I would particularly draw attention in this context to the relative neglect of red sorghums in our breeding programs, when they are so readily utilized in large areas of Africa where a good brew is a food and where populations have learnt to use them satisfactorily. These sorghums have several useful characteristics: entomological, pathological, and birdwise, when compared with some of the white grained types, which are favored in current breeding programs.

We should come away from this conference with a realistic assessment of what is needed, what the real constraints to progress on the ground in these countries are and how we can contribute to overcoming them. The number of scientists working in the field on sorghum in developing countries is inadequate and the number of entomologists even fewer. It is useless to encumber these few with work on materials or ideas, which are of marginal importance to sorghum pest control and ultimately to sorghum production. What is needed are plans developed on a multidisciplinary basis, to tackle the priority problems. These should be reassessed at this time with realism and urgency.

References

ADESIYUN. A. A., and AJAYI, 0. 1980. Control of sorghum stem borer, *Busseola fusca.* by partial burning of the stalks. Tropical Pest Management 26:113-117.

BARRY. D. 1972. Chemical control of sorghum shoot fly on a susceptible variety of sorghum in Uganda. Journal of Economic Entomology 65:1123-1125.

BLUM, A. 1972. Breeding for insect resistance in crop plants with special reference to sorghum. Pages 398-410 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co.

BOTTRELL, D. G. 1971. Grain sorghum research in Texas. Texas Agricultural Experimental Station PR 2940. College Station, Texas. 35 pp.

BOWDEN, J. 1956. New species of African stem boring agrotidae (Lepidoptera). Bulletin of Entomological Research 47:415-428.

BOWDEN. J. 1965. Sorghum midge, *Contarinia sorghicola* r(Coq.) and other causes of grain sorghum loss in Ghana. Bulletin of Entomological Research 169-189.

BRENNIERE. J. 1970. Economic problems caused by insects which infest sorghum in West Africa. Pages 1-8 *in* IRAT Seminar on Sorghum and Millet.

BROWN, E. S. 1970. Control of the African armyworm *Spodoptera exempts* (Walk.)—an appreciation of the problem. East African Agriculture and Forestry Journal 35:237.

BROWN. E. S., and DEWHURST. C. F. 1975. The genus *Spodoptera* (Lepidoptera: Noctuidae) in Africa and the Near-East. Bulletin of Entomological Research 65:221 -262.

DAVIES. J. C, and JOWETT, D. 1970. The control of sorghum pests with insecticides in Eastern Uganda. East African Agriculture and Forestry Journal 35: 414-421.

DOGGETT, H. 1954. Progress reports from experiment stations, season 1952-53. Tanganyika Territory, Lake Province Empire Cotton Growing Corporation, London. 20 pp.

FISK, J., BERNAYS, E. A., CHAPMAN, R. F.. and WOODHEAD, S. 1981. Report of studies on the feeding biology of *Peregrinus maidis.* Report Core Project 27, Centre for Overseas Pest Research. 33 pp.

GIRLING. D. J. 1978. The distribution and biology of *Eldana saccharina* Walker (Lepidoptera: Pyralidae) and its relationship to other stem borers in Uganda. Bulletin of Entomological Research 68:471-488.

HALL. D. R.. BEEVOR, P. S.. CORK, A.. LESTER. R.. NESBITT BRENOA, F., NYIRENDRA. G. K. C, PHIRINOTA. D. D.. BLAIR. B. W.. and TANNOCK. J. 1981. The female sex pheromone of the maize stalk borer *Busseola fusca* (Fuller) Lepidoptera: Noctuidae. Identification and initial field trials. Zimbabwe Journal Agricultural Research 19.

HARRIS, K. M. 1961. The sorghum midge, *Contarinia sorghicola* (Coq.) in Nigeria. Bulletin of Entomological Research 55:233-247.

HARRIS, K. M. 1962. Lepidopterous stem borers of cereals in Nigeria. Bulletin of Entomological Research 53:139-171.

HARRIS, K. M. 1976. The sorghum midge. Annals of Applied Biology 84:114-118.

HARRIS, K. M.. and HARRIS ELIZABETH 1968. Losses of African grain sorghums to pests and diseases. Pest Articles and News Summaries 14:48-54.

INGRAM, W. R. 1958. Stalk borers associated with Gramineae in Uganda. Bulletin of Entomological Research 49:367-383.

INGRAM, W. R. 1959. Experiments on the control of stalk borers on sorghum in Uganda. East African Agricultural and Forestry Journal 25:184-187.

JOTWANI, M. G. 1978. Investigations on insect pests of sorghum and millets with special reference to host plant resistance. Final Technical Report (1972-77). Research Bulletin of the Division of Entomology, IARI, New Delhi, India. 114 pp.

JOTWANI, M. G., and SUKHANI 1968. Seed treatment of sorghum for the control of shoot fly *(Atherigona varia soccata* Rond.) Pesticides Oct, 40-41.

JOTWANI, M. G., and YOUNG, W. R. 1972. Recent developments in chemical control of insect pests of sorghum. Pages 377-398 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi: Oxford and IBH Publishing Co.

JOTWANI, M. G.. YOUNG, W. R., and TEETES. G. L. 1980. Elements of integrated control of sorghum pests. FAO Plant Production and Protection paper, FAO. Rome. 159 pp.

KANWAR, J. S.. and-RYAN, J. G. 1976. Recent trends in world sorghum and millet production and some possible future developments. Paper presented at the Symposium on Production, Processing and Utilisation of Maize, Sorghum and Millets, Dec, CFTRI, Mysore, India.

NYE, I. W. B. 1960. The insect pests of gramineous crop in East Africa. Booklet Colonial Research Studies No. 31. London, UK: Her Majesty's Stationery Office. 48 PP

ROME, R. E., and PADGHAM, D. E. 1980. Report on sorghum stem borer. Ecology and behaviour 1977-78. Core Program Project 27. Centre for Overseas Pest Research, London 52 pp.

SCHELTES, P. 1978. Ecology and physiological aspects of aestivation. Diapause in the larvae of two pyralid stalk borers of maize in Kenya. Published Thesis, Landbouwhoge School, Wageningen.

SCHUSTER, D. J., and STARK. S. K. J. 1973. Greenbugs components of host resistance in sorghum. Journal of Economic Entomology 66:1131-1134.

SEPSAWADI. P.. MEKSONGSEE. B.. and KNAPP, F. W. 1971. Effectiveness of various insecticides against sorghum shoot fly. Journal of Economic Entomology 64:1509 -1511.

SESHU REDOY. K. V.. and DAVIES. J. C. 1979. Pests of sorghum and peart millet and their parasites and predators recorded at ICRISAT Center, India up to August 1979. Progress Report. Cereals Entomology No. 2. ICRISAT.

TEETES. G. L, and JOHNSON. J. W. 1973. Damage assessment of the greenbug on grain sorghum. Journal of Economic Entomology 66:1181-1186.

VEDAMOOHTHY, C. THOBBI, V. V., MARTI, B. H., and YOUNG, W. R. 1965. Preliminary studies with seed and seed furrow application of insecticides for the control of the sorghum stem maggot *Atherigona indica* Maltoch (Anthomyiidae). Indian Journal of Agricultural Science 35:14-28.

VENUGOPAL, M. S., SUBRAMANIAM, T. R., and MEENAKSHI. K. 1975. Assessment of damage by sorghum midge, *Contarinia sorghicola* (Coq.) to certain sorghum lines. Sorghum Newsletter 18:65.

VERCAMBRE, B. 1978. *Raghuva* spp et *Masalia* sp Chenilles des chandelles du Mil en zone Sahelienne. I'Agro. Trap. 33, 1:62-79.

WOODHEAD. S., PADGHAM, D.. and LEATHER. E. 1980. Insect feeding preferences and plant chemistry in sorghum cultivars. Report Core Project 27, Centre for Overseas Pest Research, London. 36 pp.

Sorghum Insect Pest Management—I

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Mechanized sorghum production in the Western Hemisphere, particularly in the United States, Mexico and areas in South and Central America, continued to increase during the decade of the 70s. This growth in large part occurred because of previous significant research breakthroughs in shortening the plant, developing a practical way of using hybrid vigor and developing disease resistant hybrids, as well as the technology required to handle, store, process and utilize the grain and forage. The crop, however, has not been without production constraints, and rarely if ever reaches its maximum yield potential. One of the major constraints has been insect pests. As is so often the case in a rapidly expanding agriculture, intensified insect pest problems paralleled increased sorghum production. Vast monoculture cropping of hybrid sorghums with increased fertilizer use and in some cases irrigation, created an environment that favored new insect pests and increased the severity of old ones. The higher obtainable yields also increased the farmer's income and permitted him to use more insecticides. Consequently, insect control became a regular production practice by farmers in many areas in the 1970s.

Insecticide use on sorghum increased dramatically during the 1970s compared with the 1960s. In Texas, for example, only 2% of the harvested acreage was treated for insect control in 1965, while in 1976, 60% of sorghum acreage was treated (Table 1). The majority of the insecticide use on sorghum in most years was directed at the greenbug. In 1975. sorghum replaced cotton as the major insecticide use crop in Texas. Producer reliance on insecticides is not currently as deeply entrenched in sorghum production philosophy as that of cotton. Hopefully it will not be, mainly because of the low profit margin of sorghum, the expense of insecticides and their application, and the ecological disruption that follows insecticide use.

Although insect pests continue to plague sorghum production, some strides in developing sound sorghum insect/mite pest management strategies were made during the 1970s. The amount of literature on sorghum entomology during the last decade reflected the increase in attention given the insect pests of the crop. Several excellent reviews or book chapters that address the sorghum insect/mite complex were published during the early 1970s (Young 1970; Doggett 1970; Bottrell 1971; Jotwani and Young 1972). These articles provided descriptions of the state of the art in regard to pest biologies, nature of damage and control at the time. More recent reviews reflected some advancement in the level of sorghum insect pest management as a result of accelerated research, especially in the USA after the invasion of the greenbug in 1968. These reviews summarized the greatly increased

Table 1. Insecticide use trend! on sorghum in Texas.

Statistics	Year 1966	Year 1976
Acres harvested (1000)	5 566	5 800
Percent harvested acres treated one or more times	2.0	59.0
Mean no. applications per treated acre	1.1	1.5
Pounds insecticide used (1000 lbs a.i.)	219	4 043
Total insecticides used in crops in Texas (1000 lbs a.i.)	14 862	12 038
Percent used on sorghum	1.5	33.6

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum. 2-7 Nov 81. Patancheru, A.P., India. Patancheru, A.P. India: ICRISAT.

volume of sorghum entomology literature and reflected the increase in research needed to allow progress in the development of sound IPM programs for sorghum (Young and Teetes 1977; Teetes et al. 1979; Teetes 1979; Jotwani and Davies 1979; Teetes 1980). A common element among these reviews is the increased emphasis on developing insect resistant sorghums as an integrated pest management (IPM) control component.

Since a number of recent sorghum entomology reviews exist, it will not be the intent here to review specific research accomplishments of the past decade, but rather to provide an overview of the state of the art of sorghum insect pest management as we enter the decade of the 80s. A look to the future (the next decade) would appear to have more value.

Current Level of Sorghum IPM

Focal consideration of sorghum insect pest management in Texas is made here as the state is a leader in the production of sorghum, and growers must contend with a complex of serious insect/mite pest species. Methods to deal with this insect/mite complex, which annually cost USA sorghum growers $80 million in yield loss alone, not counting the cost of control measures, will provide a description of the current level of sorghum integrated pest management.

Sorghum insect/mite pests are currently managed in Texas by the integration of multiple direct control tactics used in combination to formulate an optimum production strategy. The system is supported by essential ancillary information on pest biologies, population dynamics and economic injury levels.

The strategy revolves around the key pests of sorghum. The greenbug is a key pest in most of the Great Plains sorghum growing area. The sorghum midge is a key pest in the southern, humid parts of the USA and in South and Central America. The fall armyworm is a key pest of sorghum in the southeastern USA and in Central and South America. Spider mites, especially the Banks grass mite, and perhaps the corn earworm, are considered secondary pests. The many other pests which sometimes injure sorghum are in the pest status category of occasional pests.

Methods used to control sorghum insect pests and the level of use of the various IPM control components are shown in Table 2.

Key Pests

The greenbug first became an economic pest of sorghum in 1968. Research rapidly provided control tactics to deal with the pest, but initially, high dosage rates of persistent, broad spectrum insecticides were used. Currently, economic threshold levels, resistant hybrids, minimum effective insecticide dosage rates and conservation of naturally occurring predators/parasites are tactics effectively used by producers to minimize losses by greenbug. Greenbug resistant sorghum lines identified and developed by public institutions were released to commercial concerns that made resistant hybrids available to producers in 1976. These hybrids are being planted on over 50% of the Texas acreage, but in other areas where the hybrids are adapted, they are being planted on over 80% of the sorghum acreage. The occurrence in 1980 of greenbug biotype E, which is capable of severely injuring biotype C resistant sorghums, has reduced the value of these hybrids in some areas; but sources of resistance to biotype E have been identified and will soon be available to farmers. These new sources are resistant to biotypes C and E.

The use of green bug resistant sorghum hybrids, in conjunction with natural biological control, has reduced the dependence on insecticides and has proven to be a viable management system. Economic threshold levels exist for greenbug susceptible and resistant hybrids. When greenbug density or damage reaches the economic threshold level, ecological selectivity of commonly used organophosphates is achieved by extremely low dosage rates to preserve natural enemies and prevent greenbug resurgence.

A native parasite, *Lysiphlebus testicipes* (Cresson) along with other entomophagous species such as coccinellids, contribute to a general lowering of greenbug density. This is an important, but generally unrecognized, benefit of the natural enemy complex. Parasite abundance generally lags behind greenbug abundance such that they do not reliably provide economic control of greenbugs in all situations. The use of selective, low rates of insecticides is used to shift the prey/parasite ratio in favor of the parasite. Greenbug resistant hybrids also act to shift the prey/

Table 2. Control tactics now smployad against insect pasts of sorghum In Texas.

	Control Methods											
	Biological[b]			Cultural					Chemical			Sampling
Pest	Plant resistance	Conservation	Microbial	Sanitation	Eliminating hosts	Crop rotation	Planting date	Water management	Soil	Seed	Foliar	Monitoring
Soil pests												
White grub	1	1		2	2	2	2		3	1	1	2
Wireworms	1	1		2	2	3	2		2	3	1	1
Rootworms	1	1		2	2	3	2		3	3	1	1
Aphids												
Greenbug	3	2		1	1	1	2		1	1	3	3
Yellow sugarcane	1	1		1	1	1	1		1	1	3	2
Corn leaf	1	2		1	1	1	1		1	1	2	2
Armyworms												
Fall armyworm	1	1		1	1	1	3		1	1	2	1
Beet armyworrr	1	1		1	1	1	1		1	1	2	1
Stem borers												
Southwestern corn borer	1	1		3	1	2	2		1	1	1	1
Sugarcane borer	1	1		3	1	2	3		1	1	1	1
Sugarcane rootstock weevil	1	1		2	1	2	1		2	1	1	1
Chinch bug	2	1		1	2	1	2		1	1	2	2
Banks grass mite	1	1		1	1	1	2	3	1	1	3	3
Panicle pests												
Sorghum midge	1	1		1	1	1	3	1	1	1	3	3
Sorghum webworm	1	1		1	1	1	3	1	1	1	3	2
Corn earworm	1	2		1	1	1	3	1	1	1	2	2
False chinch bug	1	1		1	2	1	1	1	1	1	2	2
Stink bugs	1	1		1	1	1	2	1	1	1	2	1
Leaffooted bug	1	1		1	1	1	1	1	1	1	1	1
Stored grain pests	1	1	1	2	1	1	2	1	1	2	1	2

a Control methods: 1 = little or no use; 2 = some use; 3 = major use.

b. Reflects estimated value of naturally occurring parasites, predators, and microbial agents in suppressing respective pest populations. Inundative or supplemental releases of parasites are not presently used to effectively control damaging pest populations.

parasite ratio in favor of the parasite because of the tolerance resistance mechanism.

Losses caused by sorghum midge are reduced by the cultural practice of early, uniform, regional planting of sorghum that allows sorghum flowering to occur before damaging midge infestations develop. This approach takes advantage of the seasonal abundance profile of the pest. The insect has a facultative diapause and spring emergence begins when temperatures exceed 16°C, and is greatest when temperatures are from 20 to 30°C and moisture and hosts are available. Early generations develop in johnsongrass before sorghum flowers. At least two generations occur in johnsongrass. Subsequently, midge density increases on early flowering sorghum. By about the fourth generation, midge density is at damaging levels. Therefore, the basis of the cultural control tactic is to have sorghum flower before midge density reaches damaging proportions. Unfortunately, this escape tactic is not always possible, and inevitably some midge damage occurs regardless. If it were possible to adequately control johnsongrass, it is conceivable that the practice would reduce midge density. However, in most areas where the midge is a very severe pest, johnsongrass is so abundant that eliminating the weed does not appear to be a feasible approach at this time.

The only control approach available to growers when cultural control tactics are inadequate is insecticidal control. However, this approach also has some inadequacies which are a result of the biological habits of the midge and sorghum developmental processes.

Chemical control applications are directed at adults, a noninjurious stage, which oviposit in sorghum spikelets when they are flowering. The larva, which is the damaging stage, develops cryptically with the spikelet and is protected from insecticide applications. Also, because of the lack of discrete generations, the short life duration of adults, and continuously emerging new adults, there is continuous reinfestation. These control difficulties that arise from midge biological habits are further complicated by the flowering habits of sorghum. An individual sorghum panicle may require 6-9 days to flower while a field of sorghum may require 2 weeks or more to flower. The principle of chemical control is to protect flowering sorghum by killing adult midges and preventing them from laying eggs during the time sorghum is susceptible, that is, during flowering. Because of the short residual properties of chemical insecticides and the reinfestation capabilities of the midge, the chemical control approach is expensive, requiring multiple applications and is usually only relatively effective.

Currently, the suggested methodology of chemical control of midge is to base treatment need on the economic threshold level of one adult per panicle. Adult density is determined by visually inspecting panicles or by using a plastic bag or wide-mouth jar to capture egg-laying adults beginning when 25-30% of the plants in a field are flowering. Repeated applications are required throughout flowering if adult midge density is one adult or more per panicle. A major problem with chemical control is knowing what interval of insecticide application to use. Simply, this depends on midge density; but more commonly applications are made at 3-5 day intervals, which are largely based on economics, not effectiveness.

It seems obvious that there is a need for additional control tactics that formulate a more dependable and effective integrated control scheme for sorghum midge. One such tool soon to be available for use is sorghum midge resistant hybrids. Sources for midge resistance were identified in 1972 (Johnson et al. 1973), agronomicaly improved, and released to private industry. Midge resistant sorghum hybrids are to be available commercially in 1982. The role that these hybrids will play in sorghum insect pest management is discussed later in this article.

Secondary Pests

The Banks grass mite prevents sorghum production in the western regions of Texas and threatens economical production of sorghum throughout the Great Plains. Entomophagous species provide some natural control but biological control, either in the form of importation, augmentation or conservation is not being employed against this pest at present. Tactics used in attempts to manage spider mites in sorghum have been a combination of cultural and chemical control. Manipulating planting time and irrigation are generally the only available cultural control tactics. The efficiency of miticides used against spider mites on sorghum has been erratic because of pesticide resistance and inadequate coverage of the infested plant parts with conventional application techniques.

Management tactics for the occasional pests of sorghum, including the fall armyworm which is likely a key pest in some tropical areas and the com earworm which acts as a secondary pest in some areas, have been cultural practices (especially early planting) and insecticide use. Economic threshold levels are available for most occasional pests and are the basis for insecticidal control. Sorghums with loose-type panicles are usually less infested by panicle caterpillars than compact-type panicles and enhance insecticidal and biological control.

In summary, the present control strategies for sorghum insect/mite pests include integration of insecticide use, cultural methods, resistant sorghums, and natural biological control, reinforced by a knowledge of supportive tactics of pest biologies, population dynamics and economic injury levels. The progress made during the 70s in developing control tactics for use in IPM systems is encouraging. However, by a review of the data presented in Table 2, there is certainly room for improvement. A cursory examination of the level of use of many of the control tactics shows that presently most tactics have little or no use against most sorghum insect pests.

Future IPM Strategies

Control strategies in the 1980s for sorghum insect pests will most likely be a combination of the refinement of existing control components and the implementation of control tactics presently being developed. The greatest opportunity appears to be in the development of resistant varieties and classical biological control. More precise economic threshold levels for both insect resistant and susceptible sorghums must be developed to ensure judicious use of insecticides.

Indications are that future control strategies will lessen the dependence on insecticides. Obviously, insecticides will remain a management component, but their use will have to be directed in a manner that optimizes benefit-risk and cost-profit ratios. This can be accomplished by their use in a selective manner and based on refined economic threshold levels. Greenbug resistant sorghum hybrids are presently available and will progressively increase in use as a management component. The incorporation of greenbug resistance into region adopted lines with resistance to several diseases will greatly increase the geographic range of this vital control component within the next few years. Sources of sorghum midge resistance have been identified and improved agronomically. The commercial availability of midge resistant hybrids will add a new and significant control component.

Although natural and conservation biological control of sorghum pests has proved to be an important IPM control component, there is an even greater opportunity in classical biological control. Importation of exotic predators and parasites of sorghum pests holds tremendous possibilities in sorghum insect pest control, as most pests are introduced species. This control tactic is in its infancy and its implementation may require 10-15 years.

Cultural control tactics are expected to change as additional tactics and conservation tillage are added to crop production strategy. Rotation of sorghum will continue to be an important weed and disease control practice, but must also be used to lessen stand loss caused by wireworms, since the effective chlorinated hydrocarbon insecticides used for seed treatment are being banned from use. Planting time for sorghum will remain an important control component. Early planting will remain critical in the humid areas to avoid a multitude of late-season pests. However, delayed planting of sorghum in the drier areas is likely, as the tactic often reduces spider mite severity.

In the future, the integration of the abovementioned control tactics will be aided by systems modeling. As additional knowledge is gained, such an approach will be required to take full advantage of the viable approaches.

A sorghum plant model will provide an important focal point for pest models in the future. Development of models for the sorghum midge will be difficult due to the biological sampling and data collection problems. A sorghum midge model will have major use in testing control strategies mathematically. A greenbug model will undoubtedly be developed as research data and funding are available. This insect is so important on sorghum and small grains, that a good population model will be very likely. Crucial factors in a greenbug model will be the plant and greenbug interaction effects and the role of biological control agents. These must be approached with large, intense research efforts before advanced model use can be made in pest management.

Modeling of minor economic pests and beneficials will also be needed to complete a more comprehensive ecosystem model. Migration data on all pests and major beneficials should be collected since migration from johnsongrass, small grains and cotton have major effects on these systems.

Control and Support Tactics

Role of Sampling, Modeling and Economic Thresholds

The computer will play an important role in future pest population monitoring and decision-making in sorghum production. Computer models will be able to predict pest outbreaks and efficacy of natural enemies. However, field sampling will be needed to update the models at specific time intervals during the year. Light traps, pheromone traps, visual plant examination, mechanical sampling and remote sensing will likely be used to provide data for developing and updating computer models.

In areawide pest management programs, some decisions concerning the need to take management actions may be made by computer. However, until computer predictions reach high levels ot accuracy, field by field pest management sampling will be essential. Constant sized samples will become obsolete and will be replaced by techniques having a variable sample size, sequential sampling. Techniques which do not rapidly assess the statistical risk of an incorrect decision will be replaced by techniques able to assess this risk. Thus, rapid, reliable and reproducible decisions will be made with a known level of risk.

A very important future development will be the establishment of economic thresholds by computer. These threshold models will contain subroutines for crop economics, crop development, pest dynamics and dynamics of pest enemies. Economic thresholds generated by these models will optimize decision making in order to insure optimum profits, yields, prevent environmental contamination and conserve energy. Sampling based on erroneous economic thresholds results in erroneous decisions regardless of reliability of the sampling technique. Thus, improved economic thresholds and sampling techniques are both essential.

Computer simulation and modeling should be considered as a new and important tool. The main advantages are that it can be used to evaluate individual and integrated aspects of complex problems and allow one to piece available research together into a concise, logical framework.

Computer simulation will be used to screen new control strategies. Models will be used in conjunction with field sampling to make customized control decisions. New uses of models will be developed as models become more reliable and experience with them is gained.

More complete insect models and additional pest models will be developed. These will be incorporated into ecosystem models which will be used for a more thorough understanding of the whole ecosystem.

Role of Insecticides

Recognizing the gap between theory and practice of chemical insecticides, their use must remain an important tactic in future pest control strategies and be given special consideration. It is ironic that chemical control has fallen into public ill repute although we are still dependent upon it. The respectability of chemical controls must be reestablished in the public mind, and, second, the pesticide industry needs to be convinced that investments in pesticide development are justified. The first, public acceptance, is a prerequisite for the second. It has become a national pastime to belittle chemical control. Companies are reluctant to combat adverse public opinion and to hurdle the registration obstacle course, in addition to all other calculated risks involved in the multi-million dollar investment and development of a single pesticide. The combination of adverse factors has left the pesticide industry in a demoralized state. Many laboratories are operating on a standby basis and it will be some years before the impact of this disruption is fully felt. Also, the chemical industry must pursue the development of selective chemicals.

Role of Biological Control

If a policy is implemented which adequately supports foreign exploration, laboratory propagation, release and evaluation, partial to complete biological control of the greenbug could be expected. Also there is good likelihood for biological control of stalk borers, panicle caterpillars and other sorghum pests. Past history shows that some degree of success has been obtained in 50% of the attempts. One out of five attempts has resulted in complete biological control of the target pest. One-fourth of these successes has occurred in annual, row crops where classical biological control has been given a low probability of success.

With the possible exception of cultural control, biological control (primarily the importation approach) has proven to be the most successful single tactic for nonchemical crop protection. A study by the National Academy of Science (1975) shows that the cost effectiveness of biological control is $15 return for every $1 invested. This compares to an $8 and $2-$4 return on research in plant resistance and chemical insecticides, respectively.

Role of Plant Resistance

The addition of greenbug resistant sorghum hybrids as a management component in sorghum during the 70s illustrated the utility of plant resistance. This tactic holds great promise in future integrated pest management strategies. However, there are at least three key issues that must be addressed.

Firstly, although plant resistance has some theoretical base, its development has proceeded up to now largely on an empirical base without much understanding of the basis or causes of resistance, particularly the biochemical aspects. Combined genetic material of unknown details inferring resistance has commonly been sought and incorporated into crop varieties through extensive challenges imposed at high pest densities. By trial screenings, resistant types are preserved and backcrossed into agronomically adapted types. The problem has been to find resistance, preserve it, and make it available. "Success" has been achieved by this archaic approach, but the rate of success has no comparison with a more scientific approach. This is a challenge for the future.

Secondly, although many agree that insect resistant crops are important in IPM, there is often expressed reluctance by farmers in the developed world at the deployment phase. This has resulted because of the misconception that resistance implies a total lack of insect infestation or damage, and because of the insecticide crutch. For resistant crop varieties to be fully accepted and exploited by growers, there must be a change in understanding and attitude about the use of resistant varieties. Consequently, it appears mandatory that less emphasis be placed on definitions to explain resistance of plants, and plant to insect and insect to plant responses. Alternatively, it will be necessary to encourage the establishment of economic threshold levels for insect resistant cultivars as a means of unification of the principles behind the use of plant resistance in integrated pest management.

Thirdly, there must be efforts at developing multiple-pest resistant cultivars.

There is a multitude of ways that plant resistance relates to integrated pest management as a control tactic. IPM in application is the use of a variety of pest suppression measures that favor crop production and adversely affect pest density and damage. Attention is given to taking advantage of "weak links" in the pest insect's life or seasonal cycle, or removing favorable environmental conditions. Since the crop is a basic unit in the agroecosystem under consideration in IPM, it should draw much attention. If the crop is the foundation on which the IPM system is built, then an insect resistant cultivar operates as a control tactic at an intrinsic level. Ideally, resistant plants would provide complete and permanent control. However, such high levels of resistance rarely exist and often speed the development of insect biotypes able to injure previously resistant varieties. Also, a cultivar may be resistant to one pest species, but susceptible to others. In spite of its intrinsic nature, plant resistance must be considered "an adjunct" to other control measures.

In relation to the economic threshold level (ETL) concept (pest density at which control measures are applied to prevent an increasing pest density from reaching the level that causes economic damage), an insect resistant cultivar results in a lowering of pest density or raising of the economic injury level (lowest pest density that causes economic damage). The economic threshold concept is graphically illustrated in Figure 1. The effect of a resistant cultivar on pest density or the economic injury level is dependent upon the mechanism or type of resistance. Antibiosis and nonpreference result in a lowering of pest density. Tolerance type resistance acts to raise the economic injury level and thus the economic threshold level. In most cases, however, resistant cultivars possess at least two and usually all three resistance mechanisms.

Antibiosis is a type of resistance that adversely affects the biology of an insect. Consequently, a cultivar whose resistance is expressed as an antibiosis mechanism would tend to reduce pest density by inducing a constant level of suppression on each pest generation. It reduces the rate of pest population increase and retards population density growth. The economic injury level is therefore unattained or reached at a later point in time (Fig. 2) depending on the level of resistance. For some insect species this would mean that the economic threshold level would not change. Whether the economic threshold level changes or not depends upon what the economic threshold level is based. If the ETL is based upon the life stage of the pest that causes damage, the ETL would likely remain the same. However, if the ETL is based upon a noninjurious stage (adult or egg) the ETL may in fact rise. Also, if the ETL is based upon plant damage rather than pest numbers, it would not change.

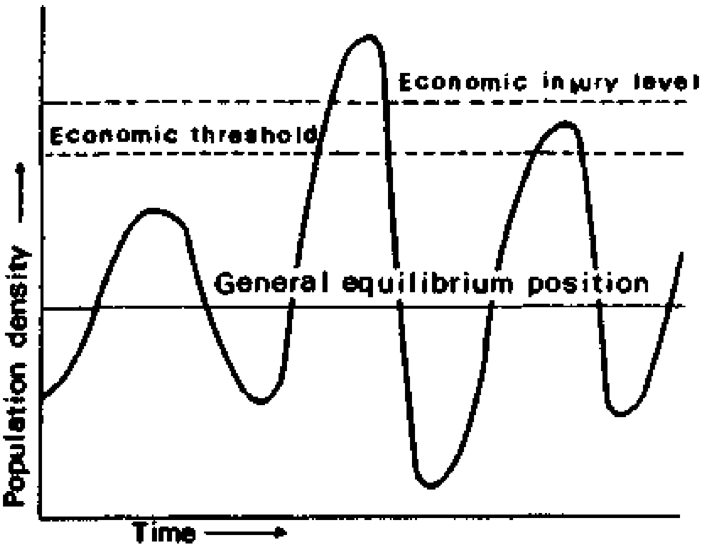

Figure 7. Schematic illustration of the fluctuations of theoretical insect population densities in relation to their general equilibrium position, economic thresholds, and economic injury levels.

If all the crop area is planted to a resistant variety, the reduction in pest numbers will be cumulative over time, and numbers within the area should become smaller each succeeding year. The impact of even a moderately resistant variety on the population dynamics of a pest may be demonstrated conceptually by using simple insect models of the type devised by Knipling (1964) as shown in Table 3.

The effects of sorghums resistant to greenbug and those resistant to sorghum midge on economic threshold levels provide real examples of the

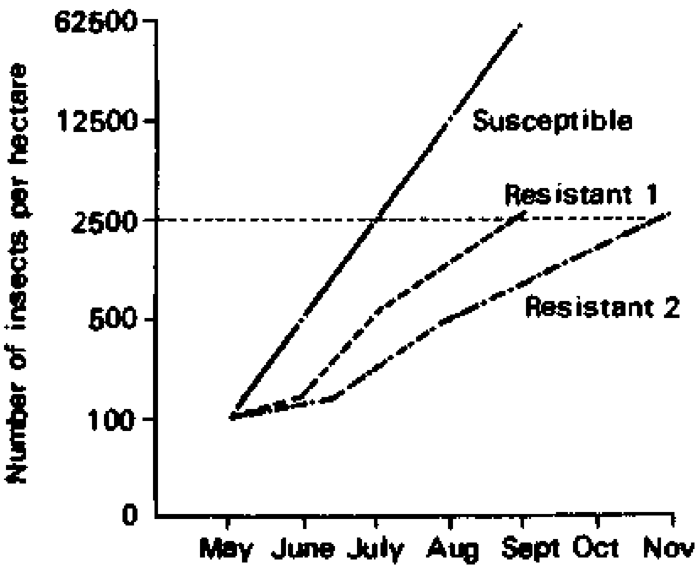

Figure 2. Theoretical population trends of a hypothetical insect population on susceptible variety, resistant variety 1, and resistant variety 2 (Adkisson and Dyck 1980).

Table 3. Theoretical rate of increase by a hypothetical insect population on a susceptible and a resistant variety that reduces population size by 50% in each generation. Assume fivefold rate of increase per generation (Adapted from Knipling 1964).

	Number of insects/hectare	
Generation	Susceptible variety	Resistant variety
First year		
Parent	100	100
F,	500	250
F_2	2 500	625
F,	12 500	1 563
F_4	62 500	3 906
Second year[a]		
Parent	1 625	105
F,	8 125	263
F_2	40 625	656
F_3	203 125	1 641
F_4	1 015 625	4 102

a Assume 10% of F_3 and 50% of F_4 are diapausing individuals of which only 5% survive the winter concept. Greenbug resistance is a tolerance type and the economic threshold is based on number of leaves killed by the aphid. Midge resistance is primarily an antibiosis type and the economic threshold level is based on the noninjurious adult stage (one ovipositing adult/susceptible, flowering sorghum panicle).

Data presented graphically in Figure 3 illustrates the difference in numbers of leaves killed by various greenbug densities on susceptible and resistant sorghum hybrids. Fewer leaves are killed on a resistant hybrid than on a susceptible hybrid by an equal aphid density. This would increase the ETL were it based on aphid numbers. Data presented in Figure 4 illustrates the disparity in yield loss caused by equal aphid densities on a susceptible and a resistant hybrid. However, leaf injury (the basis for the economic threshold) compared with yield loss is the same for resistant and or susceptible sorghums (Fig. 5). Consequently, the economic injury level of greenbug-resistant sorghum hybrids is the same as for greenbug susceptible hybrids.

The hypothetical influence of genetic resistance to sorghum midge in sorghum hybrids on the economic threshold is graphically illustrated in Figure 6. Addition of the resistance character not only increases the economic injury level (assumed tenfold) it also delays the time when that level is reached.

These brief examples are presented as a means of illustrating the utility of using economic threshold levels as an integral part of insect resistant cultivar deployment and subsequent acceptance by growers, as a viable adjunct with

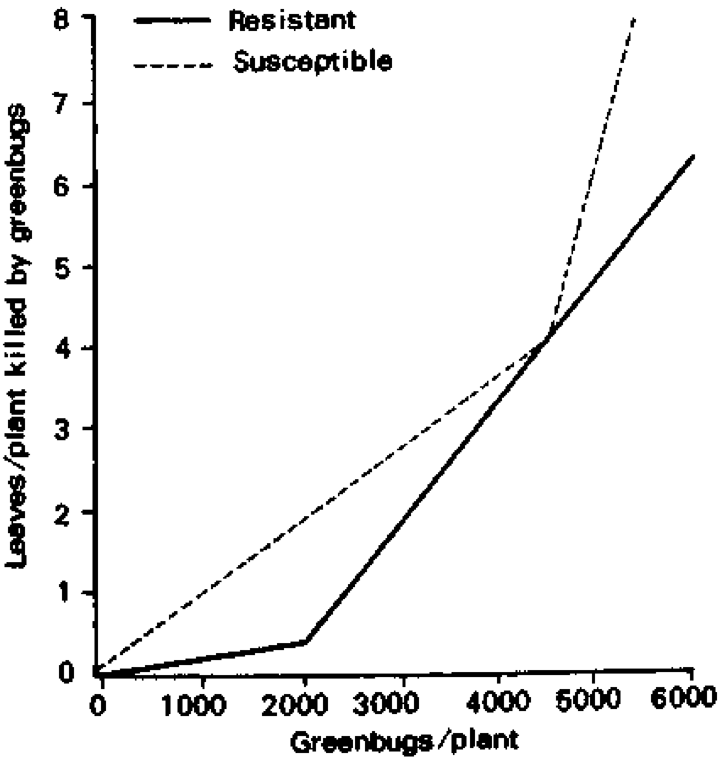

Figure 3. Relationship between numbers of leaves per plant killed by greenbugs on resistant and susceptible sorghum.

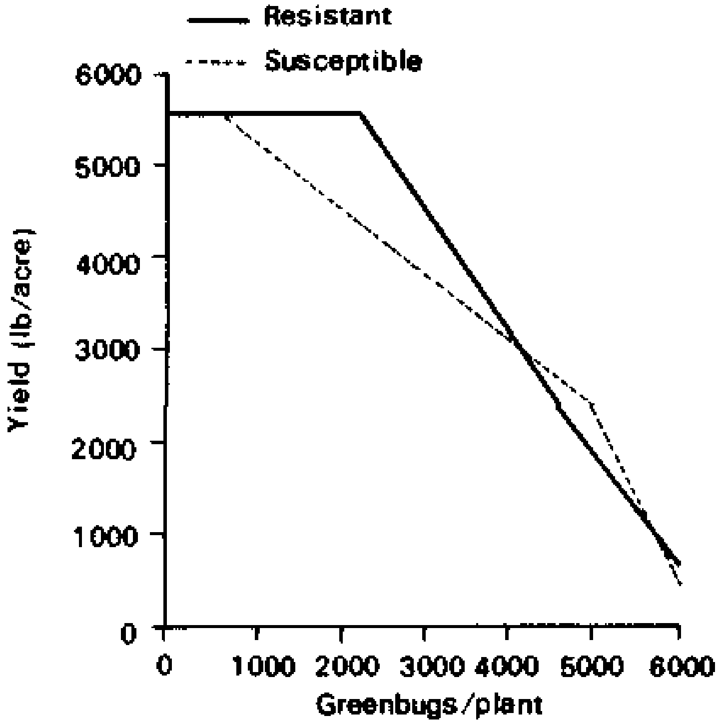

Figure 4. Relationship between yield loss and greenbugs per plant on resistant and susceptible sorghum.

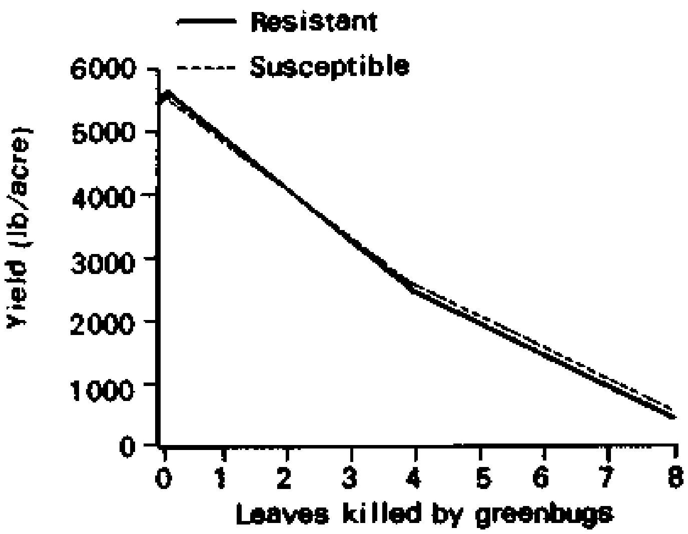

Figure 5. Relationship between yield loss and number of leaves per plant killed by greebugs on resistant and susceptible sorghum.

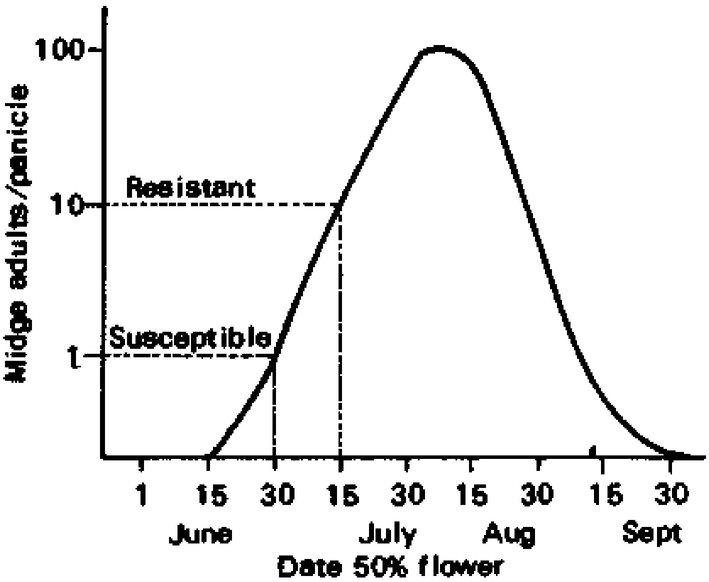

Figure 6. Hypothetical illustration of the influence of genetic resistance to sorghum midge on the economic threshold level in relation to sorghum flowering date and midge density.

other available control tactics. For the greenbug these would include the use of available natural control and a selective insecticide. For midge these would include early, uniform planting and insecticide use.

Role of Future Pest Management Delivery Systems

The adoption and success of sorghum pest management systems in the next 10-15 years will depend directly upon available technology and an effective producer education program. As the basic management tactics are developed for use in a systems production approach previously discussed, an optimum pest management strategy will evolve. Some of these systems may or may not require a full range of component input. However, once an optimal system is determined in any specific time frame, an appropriate educational delivery system must be developed to convey and assimilate the IPM technology.

Pest management systems are viewed as changing and evolving systems. However, there are technologies that will remain somewhat stable and be viewed as the basic component within a sorghum IPM system. Tactics such as cultural practices, chemical control, and sampling to determine the action levels to control pests, are currently the most familiar and frequently used components within present IPM systems. The method and type of chemical control will no doubt undergo change, as will sampling and recommendations for cultural management. However, these factors comprise the main thrust of IPM at present.

Resistant varieties loom on the horizon as an excellent opportunity to be included in a sorghum IPM system. Currently, greenbug and sorghum midge resistant sorghums offer a tremendous advantage in minimizing exposure to late-season, high-density insect pest problems. As resistant genotypes are added and become commercially available, the entire method of sorghum IPM will alter substantially. As these various components are developed, the methods of delivering this new technology to the agricultural producing areas will have to be intensified.

Current delivery systems through State Agricultural Extension Services have been established 1n the sorghum producing areas of Texas. Additional positions and manpower will be required in order to deliver the necessary technology in the next 10 years. The delivery systems that are set in place today are sufficiently flexible to allow for infusion of new knowledge. The organizational structure that has been set up for pest management programs in Texas has been used as a prototype in other production areas in the USA. Area Extension Specialists and County Extension Specialists, backed up by State Extension Specialists, have developed a method of communicating current technology to producers as rapidly as it is developed by the respective research agencies. As manpower is permitted to increase, this delivery system will be capable of accommodating a greater flow of new information.

Most sorghum IPM programs in Texas have previously focused major attention on insect control. The activity in the management of weeds and diseases is presently receiving more attention and expansion. It is important that entomologists, plant pathologists and weed scientists, along with other areas of agricultural production, link to form interdisciplinary pest management teams. It is realized that the methodology for integrated pest control may not be equally developed or available in all disciplines. However, as the methodology is developed, it should flow smoothly into the State Extension and private pest management delivery systems.

The most effective methods of delivering the principles and technology of integrated pest management to growers will likely remain comparable to what they are today, i.e., pest management result demonstrations, workshops, short courses, mass media releases, newsletters and, most importantly, personal communications with individuals and groups of agricultural producers. Personal communication has proved to be the most effective method of teaching the philosophy and practice of IPM. In-the-field experience by extension specialists, working directly with the farmer in making crop production decisions utilizing data collected by and through a field monitoring system, is still the best approach. In the past, producers have relied on others to some extent to make their decisions for them. It is time they either begin to make decisions themselves or hire competent private personnel that can make these critically important decisions.

References

ADKISSON, P. L, and DYCK, V. A. 1980. Resistant varieties in pest management systems. Pages 233-251 *in* Breeding plants resistant to insects, eds. F. G. Maxwell and P. R. Jennings. John Wiley Publishing Co.

BoTTRELi. D. G. 1971. Entomological advances in sorghum production. Texas Agricultural Experimental Station PR - 2940: 28-40.

DOGGETT, H. 1970. Sorghum. Chapter 13. London: Longmans and Green. 403 pp.

JOHNSON, J. W., ROSENOW, D. T., and TEETES, G. L. 1973. Resistance to the sorghum midge in converted exotic sorghum cultivars. Crop science 13:754-755.

JOTWANI, M. G., and DAVIES, J. C. 1979. Insect resistance studies on sorghum at international institutes and national programs with special reference to India. *In* Biology and breeding for resistance to arthropods and pathogens in agricultural plants, ed. M. K. Harris. Texas Agricultural Experiment Station. MP-1451:224-236.

JOTWANI, M. G.. and YOUNG, W. R. 1972. Recent developments on chemical control of insect pests of sorghum. Pages 377-398 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co.

KNIPLING, E. F. 1964. The potential role of the sterility method for insect population control with special reference to combining this method with conventional methods. U.S. Department of Agriculture ARS 33-98 : 54 pp.

NAS (National Academy of Science). 1975. Contemporary pest control practices and prospects: The Report of the Executive Committee. Vol. 1. NAC. Washington 506 pp.

TEETES, G. L. 1979. Overview of pest management and host plant resistance in U.S. sorghum. *In* Biology and breeding for resistance to arthropods and pathogens in agricultural plants, ed. M. K. Harris. Texas Agricultural Experiment Station. MP-1451 :181-223.

TEETES, G. L. 1980. Breeding sorghums resistant to insects. Pages 457-485 *in* Breeding plants resistant to insects, eds F. G. Maxwell and P. R. Jennings. John Wiley Publishing Co.

TEETES, G. L, YOUNG, W. R„ and JOTWANI, M. G. 1979. Insect pests of sorghum. Chapter 4 *in* Elements of integrated control of sorghum pests. FAO Plant Production and Protection Paper 19:17-40.

YOUNG, W. R. 1970. Sorghum insects. Pages 235-287 *in* Sorghum production and utilization, eds. J. W. Wall and W. M. Ross. Westport, Connecticut, USA: AVI.

YOUNG, W. R., and TEETES, G. L. 1977. Sorghum entomology. Annual Review of Entomology 22:193 -218.

Pest Management in Sorghum—II

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Wheat, rice, maize, sorghum, and millet constitute the major cereals for food and feed in the world. The last three named cereals are called the coarse grains and are considered to be the main staple for the world's poorest peoples. Sorghum *(Sorghum bicolor* Moench) is grown on nearly 42 million hectares of land in different parts of the world with India alone cultivating over 17 million hectares (FAO 1980). Generally, sorghum grain yields on peasant farms are low, ranging from 500 to 800 kg/ha and one of the major factors that affects these yields is insect pests. In general, control of sorghum pests exclusively by insecticides, by small-scale farmers is uneconomical and not practical. Under certain circumstances, some insecticides fail to ensure control, and increase the pest incidence instead. Therefore, management of pests by other methods, limiting the use of insecticides, deserves particular attention.

Sorghum in Africa, Asia, Australia, Europe, South America, and United States is subject to attack by a large number of insect pests (Young and Teetes 1977). In India alone, more than 120 pests species have been recorded, most of them being of minor or local importance (Seshu Reddy and Davies 1979). The major pests of sorghum on a global basis are the shoot fly, several species of stem borers, green bug, Banks grass mite, midge, and head bugs. The present paper attempts to review the current situation regarding the management of shoot fly, stem borers, and head bugs of sorghum in the world.

1. Shoot Fly: *Atherigona soccata* Rondani (Muscidae: Diptera)

Sorghum shoot fly is a widespread pest in Asia, Africa, and Mediterranean Europe, but is absent from the America and Australia. Damage is mainly confined to young sorghum seedlings. The larva of the pest causes a dead heart and in some instances seedlings are killed. Damage is especially severe if sowing is delayed, or if resowing is necessary owing to unfavorable weather conditions. The following are the management measures that have received research emphasis:

(1) Cultural Methods

Cultural practices can greatly affect the level of attack by shoot fly. In particular, it is known that sowing date exerts a very great influence on the damage by the pest. Investigations on seasonal incidence of shoot fly carried out in different parts of India, Southeast Asia and Africa showed that fly incidence is lower in areas where a single crop of sorghum is grown annually and when sowing is timely at the break of the rainy season. Wheatley (1961) from Kenya reported that losses in yield were negligible in timely sown sorghum, while the late sown sorghum suffered moderate losses. Sowing immediately after the break of rains, possibly within a period of two weeks in any area, is therefore recommended. This cultural method is effectively used in Israel and other countries (Young 1981).

A commonly recommended age-old cultural practice is sowing sorghum with a high seed rate (10-15 kg/ha) and later thinning out the infested plants. Infested seedlings should be well buried after they are removed. This method has been successfully demonstrated in India (Ponnaiya 1951a; Vedamoorthy et al. 1965) and has been recommended for Africa by Breniere (1972). The thinning method may be recommended only when the infestation levels are not high and the tabor for thinning is cheap. However, experimental results from Mowafi (1967) and Davies and Seshu Reddy (in press) show that a higher plant

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International Crops Research Institute for. the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum. 2-7 Nov 81. Patancheru. A.P., India. Patancheru. A.P. India: ICRISAT.

density increases numbers of shoot flies, eggs laid and plants attacked. The density of plants has a significant effect on oviposition by the fly.

Removal of Alternative Hosts

Sorghum shoot fly has been reared from 17 wild and 5 cultivated host plants (Davies and Seshu Reddy 1981). But very few of these appeared significant as host plants for carryover or for multiplication of the fly in India. In Kenya, *Sorghum arundinaceum* was found to be preferred for oviposition to a highly susceptible sorghum hybrid, CSH-1 (Delobel and Unnithan, in press). However, in China, Shie et al. (In press) reported that the damage by the shoot fly on the two wild hosts, *Digitaria sanguinalis* and *Sorghum propinquum* ranged from 10 to 20%. Removal of wild sorghums may therefore be an useful strategy in some circumstances.

During the dry seasons, volunteer or irrigated fodder sorghum appears to be the principal source of carryover. Davies and Seshu Reddy (In press) suggested that attempts should be made to discourage growing summer sorghums.

(2) Control by Trapping

Attractant traps have been mostly used in surveying or for monitoring population density. The use of fish meal and detergent water in such traps has been shown to be a simple and reliable means of effecting this (Seshu Reddy et al. 1981). Fish meal traps should, however, be considered as a tool for the fly management and have been recommended in Thailand (Meksongsee et al. 1981). Purification of the attractant from fish meal derivations at the Max Planck Institute, Munich, is under way and may improve the efficiency at this method. (J. C. Davies, ICRISAT, personal communication).

(3) Biological Control

Many parasites and predators have been recorded at different life stages of the shoot fly. However, they have not been utilized for biological control. Egg, larvae and pupae parasites of the sorghum shoot fly in Asia, Africa and Europe have been listed by Jotwani (1978) and Seshu Reddy and Davies (In press). Jotwani observed a maximum of 15% parasitism by *Aprostocetus* sp in September 1975, and 35.3% parasitization by several species of parasites in August 1977. In Nigeria, the numbers of parasites and predators of the shoot flies recorded were insignificant when compared with the extent of damage and the numbers of shoot flies bred (Adesiyun 1981).

In Kenya, shoot fly eggs are parasitized by a chalcid, *Trichogramma kalkae* (the rate of parasitism may reach 55-60% during the cool season), and they are actively fed upon by adults of the coccinellid beetle, *Scymnus tepidulus.* Second and early third instar larvae are parasitized by *Tetrastichus nyemitawus,* but the rate of parasitism always remains lower than 10% (A. G. L. Delobel, ICIPE, personal communication). There is need for more work on the possible biological control of the sorghum shoot fly.

(4) Chemical Control

In general, insecticide application to the foliage has not given effective control of the shoot fly, but the use of certain systemic insecticides on the seed or in the soil is more effective. Pasalu and Narayana (1975) found that sevidol and lindane were as good as phorate in controlling the shoot fly and increasing the yields. Several trials with systemic insecticides, e.g., furadan applied as a seed dressing or as a soil treatment, were successful and its use has been recommended in India and elsewhere (Jotwani and Young 1972; Young 1981). Soil application of fensulfothion and isofenphos at 1-1.5 kg, a.i./ha also provided satisfactory control even at higher levels of shoot fly infestation (Srivastava and Jotwani 1981). Counter R. a soil systemic insecticide has been found to be effective in controlling the fly in Thailand (Meksongsee et al. in press). Shie et al. (1981) in China, reported success with rogorto kill the adult shoot fly. The use of insecticides is not economically justified with peasant farmers in most instances owing to low yields and health hazards. However, in a number of countries, furadan is being used commercially on high yielding cultivars and seed production plots with success.

(5) Host Plant Resistance

Screening Techniques and Sources of Resistance

In 1970, Starks found in Uganda that the application of fish meal increased the sorghum shoot fly infestation in experimental plots. Using this finding, the All India Coordinated Sorghum Improvement Project (AICSIP) and ICRISAT developed a cheap and reliable field screening technique by utilizing a combination of sowing dates, spreader rows and fish meal on the material under test. Subsequently the source of resistance was identified by the two above mentioned institutions and by Soto and Laxminarayana (1971) and Soto (1972). The identified resistant lines have been included in the breeding programs to incorporate resistance in agronomically acceptable high yielding sorghum cultivars.

Mechanism of Resistance

The primary mechanism of resistance to shoot fly has been observed to be mainly nonpreference for oviposition and a low level of antibiosis to the larva (Soto 1974). There appears to be a definite link between nonpreference for oviposition and the presence of trichomes (minute hairs) on the leaf lamina (Maiti et al. 1980). These trichomed cultivars have distinctive characteristics, which are evident only in the first three weeks. The leaves tend to be more erect and narrower, with a yellowish green glossy appearance which is referred to as "glossy trait". Ponnaiya (1951b) observed that the shoot fly resistant and susceptible cultivars differed in the occurrence of irregularly shaped silica bodies in the 4th to 7th leaf sheaths. Blum (1968) found that resistant cultivars were characterized by a distinct lignification and thickness of the walls of cells enclosing the vascular bundle sheaths within the central whorl of young leaves at the three leaf stage. Also the resistant varieties possessed a much greater density of silica bodies in the abaxial epidermis at the base of the first, second and third leaf sheaths. It was observed by Raina et al. (In press) that some cultivars possessed strong antibiosis for the shoot fly in which mortality among the first instar larvae was very high while growth of the surviving larvae was significantly lower and the longevity of the female was significantly reduced. Thirumurthi and Subramanian (1976) reported that there was no relationship between HCN content in the plant and shoot fly resistance.

The other resistance mechanism first observed by Doggett and Majisu (1966) is termed recovery resistance, in which the killing of the early main shoot results in rapid tillering of the plant and subsequent survival of heads produced by the tillers so that yield is not significantly affected.

Genetic Basis of Resistance

Rana et al. (In press) reported that the shoot fly resistance was polygenic in nature and was governed by additive genes. They suggested that the resistance showed partial dominance under low to moderae shoot fly infestation and this relationship could shift under heavy infestation levels.

Breeding for Shoot Fly Resistance

It has been convincingly established that shoot fly resistance can be transferred from the donor parents and maintained in the successive segregating generations. Rao et al. (1978) have stated that due to superiority of the hybrids over the parents and the additive nature of the inheritance of the shoot fly resistance, it can be advantageously utilized in hybrid breeding as well as in line development. They have also concluded that the resistance is due to a gradual accumulation of desirable alleles rather than due to the presence of one or two major genes.

It is evident that reliable screening techniques and a number of sources of resistance have been developed. Therefore, the call for speedy development of the shoot fly resistant, yet high yielding, cultivars for the farmer's use is of immediate concern to the researchers in the field.

2. Stem Borers

It is generally accepted that a range of moth borers constitute the most widespread and serious group of insect pests of sorghum in the sorghum growing areas of the world. These include *Acigona* sp, *Busseola* spp, *Chilo* spp, *Diatraea* spp, *Eldana* sp, *Ostrinia* sp, *Sesamia* spp. The borers cause damage by feeding on the leaves and in the leaf whorls of plants, and on tunnelling inside the stem they cause deadheads.

(1) Control by Cultural Practices

(a) Seedbed Preparation

In several of the sorghum growing areas of the world for at least part of the year, severe climatic conditions involving a hot dry season or a winter of three or more months are experienced. Under these conditions, borers, such as *Chilo, Busseola. Eldana* and *Diatraea* undergo diapause in the stubbles. A good early plowing of land to be used for sowing sorghum is useful in exposing or burying larvae or pupae present in stubbles and residues. Rough plowing of the field at the end of crop season enables very early plowing just after the break of the rains to be carried out. thus ensuring timely sowing which reduces attack (Nye 1960; Harris 1962; Anonymous 1979; Seshu Reddy and Davies 1980).

(b) Destruction of Crop Residues

Sorghum stalks and stubbles left standing in the fields are an imporant source of initial populations of several stem borer species. Therefore, destruction of stubbles and disposal of stems before sowing the new crop should be recommended.To control *B. fusca* in Nigeria, it is recommended to burn the stalks completely after the grain has been harvested to kill larvae or to spread them thinly in the field to expose the larvae to the full effects of adverse weather conditions (Harris 1962; Ajayi 1978). However, Adesiyun and Ajayi (1980) reported that the farmers are not adopting the above practices in Nigeria, as the stalks are used for building, fencing, and as fuel. They suggested partial burning of stalks (to cure them for use as firewood) immediately after grain harvest. This produces a 95% destruction of the larvae without damaging the stalks.

In East Africa, both Ingram (1958) and Nye (1960) stressed the importance of good crop hygiene. The use of untreated crop residues to mulch the next crop should be avoided.

(c) Early Sowing

Timely sowing is usually an important factor in reducing pest attack in many crops, as it is the case with sorghum stem borers.

(d) Crop Rotation

Rotation to nonhost crops also forms an important control practice for the stem borers. This practice has been recommended in Texas for *Diatraea* complex (Anonymous 1979).

(e) Removal of Deadheads

In small areas removal of the affected plants showing the deadhearts with the larvae at a time when they are about 25-40 cm height may also help reduce the incidence in the growing plants.

(f) Removal of Volunteer and Alternative Host Plants

Several of the stem borers harbor in graminaceous wild hosts (Ingram 1958; Nye 1960). Wherever possible, volunteer cereal hosts, wild sorghums and other graminaceous wild hosts should be removed together with their stubbles and be burnt as they will form an important source of carryover.

(2) Biological Control

There is no doubt that several parasites and predators exert an important regulatory influence on stem borers particularly in noncrop season carryover populations. A number of natural enemies of the stem borers have been reported (FAO 1980; Rensburg and Hamburg 1975; Appert and Ranaivosoa 1970; Mohyuddin and Greathead 1970). Considerable progress could be made by the full utilization of these natural enemies through their mass multiplication and release in the areas where the stem borers are more prevalent.

(3) Use of Light Traps

In areas where regular occurrence of the stem borer months is noticed, light traps could be used for both attraction and destruction of the moths.

(4) Role of Pheromones

Pheromones or sex attractants have a high biological activity, so they could provide a relatively inexpensive method of insect control. As control agents, they have a low mammalian toxicity and are less likely to lead to the development of resistant strains than insecticides.

With the isolation of a pheromone of *C. partellus* and its subsequent synthesis by the Tropical Products Institute, London, successful field trials were carried out in India (Nesbitt et al. 1979). Some work has also been carried out on the sex pheromones of *Diatraea saccharalis* (Long and Hensley 1972).

The use of pheromones on a large scale for the reduction of the pest population is still at the research and development stage. Work should be pursued actively for the development of synthetic pheromones of the stem borer species and their utilization in reducing the population.

(5) Chemical Control

Based on insecticidal trials in India for the control of *C. partellus.* endosulfan 4% or lindane 1% or malathion 10% granules have been recommended for high yielding hybrids and varieties. Granules in general, gave better control against borers than sprays and resulted in higher yields (Jotwani and Young 1972). They further recommended that two applications of carbofuran or cytolane could be applied; one at the time of sowing, and the other side-dressed 25-30 days after germination for effective control against shoot fly and stem borer, with the possibility of controlling other leaf-eating insects simultaneously. Little work has been done on the insecticidal control of *C. partellus* infesting sorghum in East Africa (Coaker 1956; Nye 1960; Greathead 1971; Girling 1972; Kayumbo 1976). Work carried out in South Africa has shown chemical control of *C. partellus* to be ineffective (Rensburg and Hamburg 1975).

Similarly not much work on insecticidal control has been done in many countries against other borers. There is a need to evaluate more recently developed insecticides against these important stem borers. When cultural and other methods of control have not proved effective, the use of insecticides could be recommended only on high yielding cultivars or seed production plots.

Host Plant Resistance

It is very well recognized that pest resistant cultivars of sorghum offer the most effective way of overcoming the yield losses caused by pests. This attempt is very important particularly with the stem borers since they attack all the stages of the growth of the plant and have more than one generation in each cropping season.

(a) Sources of Resistance

Intensive screening work in India and East Africa has yielded several highly promising resistant lines of sorghum to *C. partellus* (Pant et al. 1961; Swamp and Chaugale 1962; Singh et al. 1968; Starks and Doggett 1970; Pradhan 1971; Jotwani 1978; Seshu Reddy and Davies, unpublished). Initially the screening work was carried out under high levels of natural infestation. Later the promising lines were evaluated by artificially infesting the plants with egg masses. Some work has been done on the artificial rearing of C. *partellus* in India (Dang et al. 1970; Laxminarayana and Soto 1971; Siddiqui and Chatterji 1972). An improved artificial diet for *Chilo* and a modified dispenser for infesting the newly hatched larvae into the test material have been developed. This method has been found to be very rapid and accurate (Seshu Reddy and Davies 1978b). Studies are also being carried out in CIMMYT, Mexico on the artificial diets and dispensing methods for infesting *Diatraea.*

(b) Mechanism of Resistance

Jotwani et al. (1978) confirmed that antibiosis is the major mechanism of resistance to *Chilo* in some of the sorghum varieties by showing that larval mortality was significantly higher in the early stages and larval development slower in the resistant varieties. Swamp and Chaugale (1962) showed that HCN content had no relationship with the resistance of sorghum of *C. partellus.* Woodhead et al. (1980) found that first instar larvae of *C partellus* were deterred by HCN.

(c) Genetic Basis of Resistance

Rana and Murthy (1971) have investigated the genetic analysis of *Chilo* resistance and found that it is polygenetic in inheritance. The F, hybrids were intermediate for primary damage (leaf feeding) but better than midparental values for secondary damage (stem tunnelling). They further concluded that resistance to primary damage was governed by additive and additive x additive gene action, while additive and nonadditive types of gene action were important for secondary damage. They felt that the inheritance patterns of primary and secondary damage were different.

(d) Breeding for Resistance

Jotwani et al. (1974) bred two *Chilo* resistant varieties, i.e., E 302 and E 303. by successfully incorporating the resistance from a local cultivar (BP 53) into two agronomically desirable high yielding lines. Several of the derivatives in the breeding nursery also exhibited high levels of resistance to *Chilo* (Jotwani 1978).

In Uganda, Starks and Ooggett (1970) made significant advances with both breeding methodology and incorporation of resistance characteristics to *Chilo.*

The stem borer resistance breeding work other than *Chilo,* has been limited and therefore attempts should be made to identify the resistance sources for other stem borers of sorghum and to incorporate resistance into adapted, agronomically good high yielding lines. In East Africa there are instances in which all the four stem borer species, i.e.. *C. partellus, B. fusca, E. saccharina,* and *S. calamstis* attack the same host plant; under these circumstances, programs should be initiated to develop sorghum cultivars with multiple resistance to the stem borer complex.

3. Earhead Bugs

Several heteropteran species are known to infest developing sorghum grain in different parts of the world, but their significance in economic terms is unknown.

The earhead bug, *Calocoris angustatus* Leth has long been considered to be a major pest of sorghum in Southern India. The problem seems to be increasing with the introduction of high yielding cultivars. Considerable damage caused by several species of head bugs has been observed in Africa (L. R. House and N. G. P. Rao, personal communication). Yet, little is known of the biology, ecology, population dynamics, carryover or even loss levels caused by the head bug complex.

At the time of heading a large number of adults and nymphs suck the contents from the developing grains and as a result most of the grains or the whole .earhead may become "chaffy". Sometimes the grains become shrivelled and discolored. The seed weight is reduced and the rate of germination may be depressed.

(1) Cultural Practices

(a) Early Sowing

Early uniform sowing of only one cultivar of grain sorghum over a large area should be encouraged so that the flowering period is shortened and thereby the head bug injury is greatly reduced. Thimmaiah et al. (1972) concluded that C. *angustatus* damage increased with the late sowing.

(b) Removal of Alternative and Volunteer Hosts

Calocoris was found feeding on six wild species of sorghum (Seshu Reddy and Davies unpublished) and therefore wherever feasible, the removal of wild, volunteer sorghum and pearl millet host plants should be carried out, before head emergence. This will help in minimizing initial infestation.

2. Biological Control

There appears to be very little work done on the natural enemies of head bugs. Recently an egg parasite of *Calocoris* has been observed at ICRISAT.

(3) Insecticidal Control

Jotwani and Young (1972) have suggested the use of 10% carbaryl + sulphur dust (9:1) or 1.3% Lindane dust at 20 kg/ha for the control of *C. angustatus.* Paul (1976) found that two applications of chlorpyriphos, leptophos, diazinon, and carbaryl as sprays and carbaryl, malathion, quinalphos and BHC as dusts gave significantly lower numbers of *C. angustatus.*

(4) Host Plant Resistance

Attempts are being made to develop screening techniques and identify the sources of resistance to *C. angustatus* at ICRISAT, India. Sowing cultivars of mixed maturities, immediately after the break of the rains, as spreader rows and sowing the test material protected against shoot fly two weeks later has shown promise (Reed et al. 1981). All the cultivars should have a similar maturity for screening purposes or else adjust the sowing to get the test cultivars to come to maturity at the same time. In general, the compact-headed types are more susceptible than open-headed types.

There is an immediate need for developing field screening techniques and resistance sources for the head bug complex. Additional research to develop cultivars with resistance is needed.

Conclusions

A considerable amount of data exist on the management of pests of sorghum in many countries. But. this information is not being properly disseminated to the sorghum growers. It is important, therefore, that farmers be given proper education through demonstrations and mass media communication about the use and advantages of such methods of control.

Host plant resistance offers excellent opportunities for the control of sorghum pests provided the problems are well understood and tackled in a multipronged approach. The ultimate research goal in the 1980s should be more pest resistant sorghum cultivars to be made available to the farmers. The following areas should also receive greater attention during the 1980s.

SHOOT FLY. Although sufficient progress has been made on the identification of sources of resistance, we are still far from providing shoot fly resistant materials for farmers to use. Therefore, concerted efforts should be made to utilize the available germplasm.

HEAD BUGS. The following lines of research need to be given priority for the head bug complex: biology and ecology, refinement and standardization of screening techniques, continued search for the natural sources of resistance, transfer of resistance to agronomically suitable lines, and the subsequent screening of the generated material from the breeding programs.

STEM BORERS. Detailed investigations on the biology and ecology of the stem borer complex should be carried out to the extent necessary to develop reliable and effective screening techniques and identify sources of resistance. Later, breeding programs incorporating agronomically elite materials should be carried out, particularly in the African continent. However, immediate efforts should be made in the utilization of already identified resistance sources in the breeding programs.

MULTIPLE PEST RESISTANCE. Extensive research is needed to identify the multiple sources of resistance to shoot fly and stem borers, as well as to the sorghum midge and earhead bugs and later to incorporate them in the improved materials.

MECHANISMS OF RESISTANCE. Adequate information should be obtained on the mechanisms of resistance including physical and chemical factors to all the major pests of sorghum.

PEST RESISTANCE NURSERIES. Although pest resistance nurseries are in existence for the shoot fly, stem borer *{Chilo partellus)* and midge, international nurseries should be established for the major pests of sorghum for the material emanating from the breeding programs. They should be tested across a range of environmental and pest situations.

BIOLOGICAL CONTROL. First of all, efforts should be made to locate the gaps between countries by properly listing and checking the natural enemies. Then, attempts to reduce the populations of pest species infesting sorghum with natural enemies should be made. This should mostly involve introduction and establishment of exotic parasite species or mass rearing and release of the effective native parasites.

CHEMICAL CONTROL. Because sorghum is a crop primarily for subsistence farmers, emphasis should be on finding safer and cheaper insecticides which are effective against the major pests at low dosages.

PHEROMONES. There is scope for investigations on the pheromones of other species of stem borers and their practical usage in reducing the moth numbers after their emergence from diapause.

TRAINING. Training is an integral part of any research program. Therefore, to achieve more effective pest control programs, it is very essential that the personnel involved with the programs should be given training on the identification of insects, parasites/predators, biology, ecology, screening techniques, and control areas.

References

ADESIYUN, A. A. (In press). Seasonal abundance of the shoot flies infesting sorghum and their natural enemies in Samaru, Nigeria. Insect Science and its Application 2.

ADESIYUN, A. A., and AJAYI, O. 1980. Control of the sorghum stem borer, *Busseola fusca,* by partial burning of the stalks. Tropical Pest Management 26:113-117.

AJAYI, 0. 1978. Control of sorghum, millet, and wheat field insect pests. Samaru Conference Paper 24, Ahmadu Bello University, Zaria. Nigeria.

ANONYMOUS. 1979. Insect and mite pests of grain sorghum—management approaches. Texas Agricultural Extension Service. Texas A&M University, College Station, Texas. B-1220, 24 pp.

APPERT, J., ET RANAIVOSOA, H. 1970. *Sesamia calamistis* Hampson (Lep., Noctuidae) chenille mineuse des graminees. Bulletin de Madagascar 20:633-652.

BLUM, A. 1968. Anatomical phenomena in seedlings of sorghum varieties resistant to the sorghum shoot fly, *Atherigona varia soccata.* Crop Science 8:388-391.

BRENIERE, J. 1972. Sorghum shoot fly in West Africa. Pages 129-136 *in* Control of sorghum shoot fly, eds. M. G. Jotwani and W. R. Young. New Delhi, India: Oxford and IBH Publishing Co.

COAKER, T. H. 1956. An experiment in stem borer control in maize. East African Agricultural and Forestry Journal 21:220-221.

DANG KUMALESH, ANAND MOHINI, and JOTWANI, M. G. 1970. A simple improved diet for mass rearing of sorghum stem borer, *Chilo zonellus* (Swinhoe). Indian Journal of Entomology 32:130-133.

DAVIES, J. C, and SESHU REDDY. K. V. 1977. Insect pests of sorghum and pearl millet and assessment of insect numbers and losses. Presented at the All India Workshop on Assessment of Crop Losses due to Pests and Diseases. 19-30 Sept, University of Agricultural Sciences, Bangalore, India.

DAVIES, J. C, and SESHU REDDY, K. V. (In press). Shoot fly species and their graminaceous hosts in Andhra Pradesh, India. Insect Science and Its Application 2.

DELOBEL, A. G. L, and UNNITHAN, G. C. (In press). Status of *Sorghum arundinaceum* (Desv.) Stapf, as a host of the sorghum shoot fly, *Atherigona soccata* (Rond). Insect Science and Its Application 2.

DOGGETT, H., and MAJISU. B. N. 1966. Record of research. East African Agricultural and Forestry Research Organization Annual Report. 86 pp.

FAO (Food and Agriculture Organization). 1980. Elements of integrated control of sorghum pests. Rome, Italy: FAO. 159 pp.

GIRLING, D. J. 1972. Report on investigations on graminaceous stem borers in East Africa (November 1969 —March 1972). Unpublished Report, Commonwealth Institute of Biological Control (CIBC), East African Station, 55 pp.

GREATHEAD, D.J 1971. A review of biological control in the Ethiopian region. Technical Communication No. 5, Commonwealth Institute of Biological Control.

HARRIS, K. M. 1962. Lepidopterous stem borers of cereals in Nigeria. Bulletin of Entomological Research 53:139-171.

INGRAM, W. R. 1958. The lepidopterous stalk borers associated with graminae in Uganda. Bulletin of Entomological Research 49:367-383.

JOTWANI, M. G. 1978. Investigations on insect pests of sorghum and millets with special reference to host plant resistance. Final Technical Report (1972-1977). Project A7-ENT-120, Indian Agricultural Research Institute, New Delhi. 114 pp.

JOTWANI, M. G., CHAUDHURY, S., and SINGH, S. P. 1978. Mechanism of resistance to *Chilo partellus* (Swinhoe) in Sorghum. Indian Journal of Entomology 40:273 -276.

JOTWANI, M. G., SRIVASTAVA, K. P., and KUNDU, G. G. 1974. Two highly promising stem borer resistant lines of sorghum. Entomologists' Newsletter 4:51-52.

JOTWANI, M. G., and YOUNG, W. R. 1972. Recent developments on chemical control of insect pests of sorghum. Pages 377-410 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co.

KAYUMBO, H. Y. 1976. Incidence of the spotted borer, *Chilo* sp on sorghum in Morogoro region. Tanzania. Presented at the Sixth East African Cereals Research Conference.

LAKSHMINARAYANA, K., and SOTO, P. E. 1971. Technique for mass rearing of stem borer *Chilo zonellus (partellus).* Sorghum Newsletter 14:41-42.

LONG, W. H„ and HENSLEY, S. D. 1972. Insect pests of sugarcane. Annual Review of Entomology 17:147 -176.

MAITI. R. K., BIDINGER, F. R„ SESHU REDDY. K. V.. GIBSON, P.. and DAVIES, J. C. 1980. Nature and occurrence of trichome in sorghum lines with resistance to the sorghum shoot fly. Joint Progress Report—Sorghum Physiology—3/Sorghum Entomology—3 ICRISAT, Patancheru, A.P., India. 40 pp.

MEKSONGSEE. B, CHAWANAPONG. M. SANGKASUWAN. O.. and POONYATHAWO, P. (In press). The biology and control of sorghum shoot fly, *Atherigona soccata* Rondani in Thailand. Insect Science and Its Application 2.

MOHYUDDIN, A. I., and GREATHEAD. D. J. 1970. An annotated list of the parasites of graminaceous stem borers in East Africa, with a discussion of their potential in biological control. Entomophaga 15:241-274.

MOWAFI, K 1967. Preliminary studies on the dura shoot fly *Atherigona indica infuscata* (Emden) (Anthomyiidae: Diptera). B.Sc. Dissertation, University of Khartoum, Sudan.

NESBITT, B. T„ BEEVOR, P. S.. HALL, D. R., LESTER, R., DAVIES. J. C, and SESHU REDDY, K. V. 1979 Components of the sex pheromone of the female spotted stalk borer, *Chilo partellus* (Swinhoe) (Lepidoptera: Pyralidae): indentification and preliminary field trials. Journal of Chemical Ecology 5:153-163.

NYE, I W. B 1960. The insect pests of graminaceous crops in East Africa. Colonial Research Studies No. 31. London, UK: Her Majesty's Stationary Office. 48 pp.

PANT. N C, PATHAK, M. D, and PANT, J. C. 1961. Resistance to *Chilo zonellus* (Swin.) in different host plants. Indian Journal of Entomology 23:128-136

PASALU, I. C, and NARAYANA, K. L 1975. Control of sorghum shoot fly, *Atherigona varia soccata* Rond. (Anthomyiidae: Diptera). Pesticides 9:25-27

PAUL, M D 1976 Evaluation of certain insecticides for control of the earhead bug, *Calocoris angustatus.* Sorghum Newsletter 19:20

PONNAIYA. B. W. X. 1951a. Studies on the genus sorghum I Field observations on sorghum resistance to the insect pest, *Atherigona indica* M. Madras University Journal 21 : 96-177

PONNAIYA. B. W. X. 1951b. Studies on the genus Sorghum. II The cause of resistance in sorghum to the insect pest, *Atherigona indica* M Madras University Journal 21 : 203-207

PONT, A C. 1972 A review of the oriental species of *Atherigona Rondani* (Diptera : Muscidae) of economic importance Pages 27-104 *in* Control of sorghum shoot fly. eds. M G. Jotwani and W R. Young. New Delhi, India: Oxford and IBH Publishing Co

PRADHAN. S. 1971. Investigations on insect pests of sorghum and millets. Final Technical Report 1965 -1970, Indian Agricultural Research Institute, New Delhi. 157 pp.

RAINA. A. K.. THINDWA. H. Z, and OTHIENO. S. M. (in press). Sorghum resistance to shoot fly: Development and fecundity of flies on selected cultivars. Insect Science and Its Application 2.

RANA, B. S.. JOTWANI, M. G., and RAO. N. G. P. (in press). Inheritance of host plant resistance to sorghum shoot fly Insect Science and Its Application 2.

RANA, B. S., and MURTHY, B. R. 1971. Genetic analysis of resistance to stem borer in sorghum. Indian Journal of Genetics and Plant Breeding 31 .521-529.

RAO. N. G. P., RANA, B S., and JOTWANI, M. G. 1978. Host plant resistance to major insect pests of sorghum. Technical Document. International Atomic Energy Agency (IAEA) 215:63-78

REED, W , SESHU REDDY. K. V.. LATEEF, S. S., AMIN, P. W.. and DAVIES. J. C. (In press). Contribution of ICRISAT to studies on plant resistance to insect attack. *In* Current themes in tropical science 2: natural products for innovative pest management

RENSBURG. N J. VAN, and HAMBURG. H. VAN. 1975. Grain sorghum pests. An integrated control approach. Pages 151 -162 *in* the Proceedings of 1 st Congress. Entomological Society of South Africa.

SESHU REDDY, K. V.. and DAVIES. J. C. 1978a. The role of the entomology program with reference to the breeding of pest resistant cultivars of sorghum at ICRISAT. Paper presented at the Symposium on the Strategies for Insect Pest Control through Integrated Methods, August 1978, IARI, New Delhi.

SESHU REDDY, K. V., and DAVIES, J. C. 1978b. A new medium for mass rearing of the sorghum stem borer, *Chilo partellus* Swinhoe (Lepidoptera: Pyralidae) and its use in resistance screening. Indian Journal of Plant Protection 4:48-55

SESHU REDDY, K V., and DAVIES, J. C. 1979. Pests of sorghum and pearl millet and their parasites and predators recorded at ICRISAT Center, India, up to August, 1979 Cereal Entomology Department Progress report-2, ICRISAT, Patancheru, A.P , India 23 pp.

SESHU REDDY, K V. and DAVIES, J. C. 1980. Sorghum stem boer, *Chilo partellus* Swin. — Recent findings at ICRISAT Center. Presented at the All India Coordinated Sorghum Improvement Project (AICSIP) Workshop, 12-14 May 1980, Coimbatore, India.

SESHU REDDY, K V., SKINNER II., J. D., and DAVIES. J. C. (In press) Attractants for *Atherigona* spp including the sorghum shoot fly. Insect Science and Its Application 2.

SHIE-SHIANG-LIN, FAN ZI-DE. and Su ZHON-HUA. (In press). Studies on sorghum shoot fly in China. Insect Science and Its Application 2.

SIDDIQUI, K. H„ and CHATTERJI, S. M. 1972. Laboratory rearing of the maize stem borer. *Chilo zonellus*

Swinhoe (Crambidae: Lepidoptera) on a semi-synthetic diet using indigenous ingredients. Indian Journal of Entomology 34:183-185.

SINGH, S. R., VEDAMOORTHY, G., THOBBI, V. V., JOTWANI, M. G.. YOUNG. W. R„ BALAN, J. S.. SRIVASTAVA, K. P., SANDHU, G. S., and KRISHNANANDA, N. 1968. Resistance to stem borer, *Chilo zonellus* (Swinhoe) and stem fly, *Atherigona varia soccata* Rond. in the world sorghum collection in India. Memoirs of the Entomological Society No. 7. 79 pp.

SOTO, P. E. 1972. Mass rearing of the sorghum shoot fly and screening for host plant resistance under green house conditions. Pages 137-148 *in* Control of sorghum shoot fly. eds. M. G. Jotwani and W. R. Young, New Delhi, India: Oxford and IBH Publishing Co.

SOTO, P. E. 1974. Ovipositional preference and antibiosis in relation to resistance to a sorghum shoot fly. Journal of Economic Entomology 67:265-267.

SOTO, P. E., and LAXMINARAYANA, K. 1971. A method of rearing the sorghum shoot fly. Journal of Economic Entomology 64:533.

SRIVASTAVA, K P., and JOTWANI, M. G. (In press). Recent advances in chemical control of shoot fly. Insect Science and Its Application 2.

STARKS, K J. 1970. Increasing infestations of the sorghum shoot fly in experimental plots. Journal of Economic Entomology 63:1715-1716.

STARKS, K. J., and DOGGETT, H. 1970. Resistance to a spotted stem borer in sorghum and maize. Journal of Economic Entomology 63:1790-1795.

SWARUP, P. V., and CHAUGALE, D. S. 1962. A preliminary study on the resistance to stem borer, *Chilo zonellus* Swin. infestation in sorghum *{Sorghum vulgare* Pers). Current Science 31 :163-164.

THIMMAIAH, G., MUTALIK DESAI, PANCHABHAVI, K. S., and MELIPATIL, M. B. 1972. A note on the effect of late sowing on the incidence of sorghum earhead bug, *Calocoris angustatus* Leth. in North Mysore region. Sorghum Newsletter 15:54.

TIRUMURTHI. S., and SUBRAMANIAM, T. R. 1976. HCN content of sorghum varieties in relation to shoot fly resistance. Madras Agricultural Journal 63 :131-132.

VEDAMOORTHY, G.. THOBBI, V. V., MATAI. B. H., and YOUNG, W. R. 1965. Preliminary studies with seed and seed furrow applications of insecticides for the control of sorghum stem maggot, *Atherigona indica* Malloch. (Anthomyiidae). Indian Journal of Agricultural Sciences 35:14-28.

WHEATLEY, R. E. 1961. The insect pests of agriculture in the Coast Province of Kenya. V. Maize and sorghum. East African Agricultual and Forestry Journal 27 :105 -107.

WOODHEAD, S., PADGHAM, D. E., and BERNAYS, E. A. 1980. Insect feedings on different sorghum cultivars in relation to cyanide and phenolic acid content. Annals of Applied Biology 95:151-157.

YOUNG, W R. (In press). Sixty five years of research on the sorghum shoot fly. Insect Science and Its Application 2.

YOUNG. W. R., and TEETES, G. L. 1977. Sorghum Entomology. Annual Review of Entomology 22:193. -218.

Session 3 Factors Reducing Sorghum Yield; Insect Pests

W. R. Young* Discussant—1

From the papers presented in this session, and the review articles cited by today's speakers, it is clear that much has been learned and documented regarding sorghum insect and mite pests during the past 10 to 15 years. When the first sorghum bibliography was published by George Washington University (1967), covering the 33-year period 1930-1963, there were 177 references listed under the heading Insect Pests, and much of this literature was linked to other crops that shared the same pests. The supplement to this bibliography (Rockefeller Foundation 1973) covering 5 years, 1964-1969, contained 201 references on the same subject. Comparable figures are not available, to my knowledge, for the last decade but we are all well aware of the fact that both the interest in sorghum and the research effort on the crop have expanded tremendously in recent years. We now have much more information on sorghum and its interactions with the physical and biological environment, including the insect pest species that attack it.

The speakers today have reviewed current knowledge on a number of key sorghum pests, including the state of the art in managing these pests, both in the old and new world. As reported by Drs. Teetes and Seshu Reddy we are most knowledgeable about a few major pests, the shoot fly. sorghum midge, greenbug, head bugs, and stem borers. For some of these pests principally the greenbug and sorghum midge in Texas, the elements of integrated pest management systems are in place and operating. In Africa and India, management of shoot fly and midge is occurring in a less directly organized way through adjustment of planting dates. The same is true in Israel.

Today, rather than comment on approaches to controlling individual pests, I would rather draw your attention to more general concerns and developments in the evolution of our capability to effectively manage sorghum pests below the economic injury level. Our future progress in sorghum insect pest control will depend in part on how well we make use of the new tools and processes for pest management that have developed in the last decade. Finally, I would offer a few suggestions as to how the agencies represented here, and the scientists working in them, may effectively organize to add to our basic data bank of sorghum pest information, and also effectively use this information to further advance our management of sorghum pests. While specific effective management procedures for a pest complex in each agro-ecological region are location specific, approaches to developing effective management include general features that apply to all locations.

The contrast between general features of sorghum production, as related to pest control, is apparent between the situations described by Dr. Seshu Reddy, representing Africa and Asia, and Dr. Teetes representing the Americas (North, Central and South America—specifically Texas).

The table below lists these features.

Africa. Asia

(a) Sorghum grown in mixed culture with other crops
(b) Medium to low productivity per unit area
(c) Research input on pest control generally low
(d) Little insecticide use (more natural biological control operating)

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(e) Integrated Pest Management not formally organized, but in some cases operating

The Americas

(a) Sorghum mainly grown as a monoculture
(b) High productivity per unit area
(c) Research input on pest control higher
(d) More insecticide use (less biological control)
(e) Organized Integrated Pest Management advancing rapidly for a few pests

As Dr. Teetes clearly states in his paper, progress has been made during the 70s in developing control tactics for use in Integrated Pest Management systems for sorghum insect/mite pests. These strategies "include integration of insecticide use, cultural methods, pest resistant sorghums, and natural biological control, reinforced by a knowledge of supportive tactics of pest biologies, population dynamics, and economic injury levels" and "in the future, the integration of these control tactics will be aided by systems modeling" aided with the powerful modern computer simulation technology.

The question I would raise is how can we best organize to move ahead in the 80s with a further advancement of sorghum Integrated Pest Management from the present conceptual and preliminary stage to more effective action programs; to programs that will make use of our expanding data base in a modern systems approach to sorghum insect/mite pest control?

What is needed? First, we need more field collected data; data that can be summarized and effectively processed for systems modeling, data on crop, pest, physical-bioecological-socio-economic-interactions with specific emphasis on economic thresholds. Modern tools and techniques are of little use without an effective data base.

Second, we need more efficient collection, collation, processing, and application of these data in pest management programs specifically tailored and organized to fit local situations, and increasing levels of production.

Who is available to participate in this continuing effort to advance and refine sorghum pest management?

1. Scientist teams in local, regional, and national sorghum improvement programs.
2. Scientists in international centers with mandates to advance sorghum improvement such as ICRISAT, in India, and The International Centre for Insect Physiology and Ecology, in Kenya, that is contracting basic research on sorghum pests.
3. Scientists in the agricultural universities in both the "developing" and "developed" countries that can be called upon to provide their expertise and experience to the overall effort.

How should we proceed? A specific example may help to elucidate one possible approach. The group at Texas A&M University and its collaborators in the state have considerable experience and expertise in developing and operating an Integrated Pest Management Program for greenbug. They have devised and refined data collection systems for monitoring greenbug numbers and its parasite and predator populations on greenbug resistant and susceptible cultivars. They are effectively using this information, coupled with economic injury threshold data, to reduce economic injury of greenbug on sorghum in Texas. The net effect also has been a more balanced approach to insecticide use. They also are moving on to a systems modeling approach for greenbug and other key pests. Would it be possible with coordination from ICRISAT, and specific training programs organized at ICRISAT, or at Texas A&M, to transfer the experience that has developed in Texas to scientists working in other country national programs in order to improve the efficiency of data collection and use on other sorghum insect problems in other regions of the world? Could training programs and a library of data collection and systems modeling procedures be developed at ICRISAT?

Stated in a few words, research on sorghum pest control is expanding. More and more information is being collected at many locations with the aim to improve pest management. We have increasingly better techniques to collate and use the information being collected. Since the world is getting smaller, communicationwise, let us put our heads together to explore ways to share information and expertise, and to improve the transfer of technology within our worldwide sorghum improvement network.

It is of course also imperative that we explore sources of support for these types of activity. It would seem to me that rather modest inputs for training, and an accompanying data processing and modeling library would pay large dividends in making much more effective both the resources and expended effort that are now fragmented among many national programs.

I hope in our discussions we may explore ways and means to better organize our efforts aimed toward better management of sorghum pests.

References

GEORGE WASHINGTON UNIVERSITY. 1967. Sorghum—A bibliography of the world literature covering the years 1930-1963. Metuchen, New Jersey. USA: Scarcecrow Press.

ROCKEFELLER FOUNDATION. 1973. Sorghum—A bibliography of the world literature 1964-1969. Metuchen, New Jersey, USA: Scarcecrow Press.

Session 3 Factors Reducing Sorghum Yields
Insect Pests

M. G. Jotwani* Discussant—2

The subject of management of sorghum pests has been dealt with quite exhaustively in the two papers presented by Dr. Teetes and Dr. Seshu Reddy. As has been rightly pointed out by Dr. Lukas Brader in the foreword of the recent FAO publication entitled, *"Elements of Integrated Control of Sorghum Pests (1979)",* the information on practical examples, which can give a solid basis for the pest management program on sorghum, is rather limited. There is a necessity to have more data on some of the important components of pest management.

The key pests in different sorghum growing regions have been identified and briefly described in some of the reviews on sorghum pests (FAO 1979; Young and Teetes 1977). However, there are alarming reports of heavy losses caused by some of the minor pests after the large-scale cultivation of the high yielding varieties. This has been especially noticed in India in the case of sorghum shoot fly *(Atherigona soccata).* midge *[Contarinia sorghicola)* and several species of earhead caterpillars. The increase in activity of these pests is mainly attributed to specific characters of the new plant types and the changes in agronomic practices necessary for growing the high yielding cultivars. Different components of pest management for the three major insect pests, i.e., the shoot fly, stem borers and earhead bug have been reviewed in one of the papers.

Shoot Fly

Use of cultural methods is considered to be of utmost importance in the pest management program. For shoot fly control, date of sowing has been found to be of great significance and data collected from different areas have convincingly shown that by simply adjusting the sowing date, shoot fly damage can be considerably reduced.

The age-old recommendation of using a higher seed rate and removing and destroying infested seedlings was not found to be effective when carried out in small areas under heavy shoot fly infestation conditions (Sukhani and Jotwani 1980). It is felt that this method can succeed only when carried out as a campaign in large areas. Similarly, trials conducted for 3 years at a number of locations showed that plant density, row and plant distances had no effect on the extent of shoot fly damage under heavy population pressure of the fly-

Some work has been done by Davies and Reddy (1980) on alternate host plants of the sorghum shoot fly. Granados (1972) found that the shoot fly could complete development on *Digitaria asandens* and *Brachiara reptans.* Both papers mention that alternate hosts in Gramineae were of minor importance in carry over. Off-season irrigated fodder sorghum seems to be a more important carry-over source (Davies and Reddy 1980).

There is need to carry out more work on alternate hosts and on off-season survival carry over, migration and population dynamics.

Findings on fishmeal acting as a strong attractant for shoot fly adults has a great potential for utilization in control operations. Collaborative work by ICRISAT and the Max Planck Institute, Munich is in progress.

Preliminary work carried out at Navsari (Gujarat, India) has shown that poisoned fishmeal bait applied in leaf whorls of young plants can attract and kill large, number of fly adults. Possibly this method can be tried for suppression of the shoot fly population.

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum. 2-7 Nov 81, Patancheru, A.P., India. Patancheru. A.P. India: ICRISAT.

There is yet another important finding that female flies are attracted to lay more eggs on dark green colored seedlings. Advantage of this behavior can also be taken for trapping the flies.

Several hymenopterous insects have been recorded as egg, larval and pupal parasites of the shoot fly. A few observations taken on these natural enemies show that generally the level of parasitization under natural conditions is very low. *Aprostocetus* sp has been found to be the dominant species in India. There is an urgent need to identify the parasites and predators which can be utilized in the biological control and to develop methodology for their mass multiplication, release and conservation. Imports of exotic parasites from some other sorghum growing countries of Asia and Africa can also be attempted.

Chemical control of shoot fly by conventional methods of foliar application has generally failed to give satisfactory control of the shoot fly even with the most potent insecticides. The cause of the failure of this method has not been properly investigated. Various systemic insecticides applied in the soil at the time of sowing, though effective, are too expensive to be recommended in this risk prone crop. Carbofuran seed treatment has been found to be effective and is being used in India in the shoot fly endemic areas. It has been found that the cost of application of carbofuran can be further reduced by using a 6:4 mixture of treated and untreated seed. The plant stand can be maintained by using the seed mixture at the rate of 9-12 kg/ha. A number of new insecticides are being tested and isofenphos has been found to be promising.

Developing high yielding shoot fly resistant varieties is undoubtedly a highly desirable method of checking shoot fly damage. Some progress has been made in this direction and the change can be seen from the susceptibility level of the first released hybrid CSH-1 as compared with CSH-5, CSH-7R, and CSH-8R. Efforts are being made to increase the level of resistance.

Investigations have been carried out on the physical and biochemical basis of resistance to shoot fly. Studies on the morphological characters showed that thickness of the leaf sheaths was not associated with shoot fly resistance. In the chemical analysis, HCN content of leaves and growing points of susceptible varieties were found to be significantly higher than the resistant varieties. The same trend was observed in the case of chlorophyll and carotenoid contents. It was further found that lysine, an essential amino acid, was present in the leaf sheaths of the susceptible hybrid CSH-1, but was absent in the resistant varieties. The survival and development of the shoot fly was adversely affected when reared on these resistant varieties (Singh and Jotwani 1980a and b).

Stem Borers

Several species of stem borers have been recorded as pests from different sorghum growing regions (Young and Teetes 1977).

It has been mentioned in the second paper that 'tunnelling' inside the stem causes deadhearts. However, it has been found that in sorghum, feeding by the borer larvae on the central shoot inside the leaf whorls results in the deadheart formation. Very often no deadheart formation takes place in spite of severe leaf injury and stem tunnelling.

The cultural method of destroying the main sources of carry over can be very effective if practiced by a large number of cultivators. However, as it has been already pointed out, the harvested stems are not only used as fodder but also for several other purposes like fencing, building and fuel. Thus it becomes difficult to effectively check the carry over population. The hibernating larvae inside the stems kept for fodder purposes can be easily killed by chopping and storing the stems as small pieces.

Early sowing has been recommended for checking the stem borer damage; however, the data available from the north Indian states show that the borer causes more damage in the early sown crop as compared with the late sown crop. This can be explained by the fact that in most of these areas, a summer crop of fodder sorghum is grown during March to June. The borer larvae emerging from hibernation in the month of March get a suitable host plant for rapid multiplication and thus a heavy population builds up by the time the *kharif* crop is sown in early July.

The mechanical method of removal and destruction of deadhearts can prove to be successful only if it is carried out by a large number of cultivators. It may, however, be more effective to remove and destroy central shoots showing early "pin hole" damage symptoms in which there are invariably a large number of young larvae which disperse to adjoining plants at a later stage.

The use of light traps for the control of stem borer, *Chilo partellus* (Swinhoe) was found to be ineffective in the trials conducted in the early sixties. We may have to collect some more data on the type of traps and light intensity before recommending this method to sorghum growers.

Considerable information is available on the natural enemies of stem borers (FAO 1979). However, a systematic program on the biological control of these pests has not been undertaken. Only recently a project has been started on the control of *Chilo partellus* by releasing Barbados, Columbia and Philippines strains of *Trichogramma* in different ecological pockets in India. T. *exiguum* has now been etablished against *Chilo partellus* at Delhi and Nagpur. Various steps are being undertaken for augmentation and conservation of this parasite to increase its efficiency.

The use of pheromones has shown promise against stem borer when used in limited areas; however, large-scale trials on farmers' fields will have to be undertaken to assess the effectiveness of this method. It may be mentioned here that gossyplur, claimed to be a very effective pheromone for pink bollworm, did not give satisfactory results when applied for pink borer control in large cotton growing areas of Haryana (India). However, it has shown some promise for monitoring pink bollworm population.

A number of insecticides have proved to be effective for the control of sorghum stem borer, *C. partellus.* In the earlier trials, it was found that granules applied in leaf whorls were more effective than dust and spray formulations applied on the foliage. In the trials conducted recently it has been found that insecticides like endosulfan, carbaryl, lindane, and phenthoate dusts applied at the reduced dosages of 8-10 kg/ha in leaf whorls can control the borer effectively.

Satisfactory progress has been made in developing varieties showing borer resistance as well as desirable agronomic characters of high yield, early maturity and medium height. Some of these, i.e., E-501, E-502. E-503, E-504, E-601, E-602. E-603, and E-604 are in the advance stage of testing. However, efforts to increase the level of resistance should continue.

In the studies on plant characters associated with stem borer resistance, it was found that thickness of stem as well as the HCN content of leaves and growing points in 40-day-old plants were positively correlated with the susceptibility to the borer.

Work on other borer species needs to be intensified. Initially we should establish the economic status of different species by determining the incidence and losses caused in different areas.

Earhead Pests

The earhead pests infesting sorghum can be categorized in three distinct groups, i.e., insects infesting at the flowering, soft dough and maturing grain stages. The midge *Contarinia sorghicola,* is the most serious pest infesting at the flowering stage. Management components available for this pest have been mentioned in the first paper. It is felt that the information regarding alternate host plants is not fully available. Extensive surveys were undertaken in Maharashtra State after the midge epidemic in 1970/71; however, these surveys failed to give sufficient data to establish whether there was any activity of the midge in the off-season on wild sorghums. Possibly the most important source of midge carry over and infestation is the crop residue of the previous season in which the diapausing larvae are carried over.

An economic injury level of one midge per earhead has been suggested for undertaking the control operations. Some more information may have to be given on the time at which the observations are to be recorded. It has been found that the incidence of midge varies considerably, not only on different days but also at different times on the same day. Peak activity is observed 2 to 3 hours after sunrise. The midge activity on cloudy days is very low. Also very heavy populations may be oserved on a day of peak emergence, while the observation recorded on the previous day may have shown practically no activity (Rao 1975).

Chemical control of midge is reported by various workers to be only partially effective. Midge adults can be observed on the earheads within a few hours after insecticide application. Emergence of midge adults from the treated earheads has been recorded in the laboratory thus indicating that a large number of maggots were not affected by insecticides during their developmental period. However, there is some consolation from the observation that there is also sufficient emergence of parasites from treated heads.

For the effective control of earhead midge, the cultural-cum-varietal approach of sowing uniformly flowering varieties within a short span of time has been found to be satisfactory (Rao and Jotwani 1974).

The most serious pest attacking the soft dough stage is the earhead bug, *Calocoris angustatus.* At present this pest is restricted to certain areas of Andhra Pradesh, Kamataka and Tamil Nadu. Basic information on the biology and behavior of this pest is available. However, much needs to be done on different aspects to combat this insect effectively and to prevent its spread to other sorghum growing areas.

A complex consisting of a number of lepidopterous larvae infests the earheads at the maturing stage of the grains. There has been a steady increase in the incidence of this complex after the release of high yielding varieties and hybrids. This is attributed to the compactness of the earheads of these cultivars which provide a congenial micro-climate for the caterpillars to multiply. Of the different species recorded, *Heliothis armigera* can prove to be the most serious and needs to be watched carefully.

Multiple Resistance and Biotypes

In crops like sorghum where more than one serious pest causes damage at different stages, it may not be practicable to develop varieties resistant to each pest. There is, therefore, a need to identify sources of resistance to as many major pests as possible. Some progress in this direction has been made in India and a number of varieties have been identified which have moderate levels of resistance to two major pests, i.e., shoot fly and stem borer.

One of the lines, i.e., IS—1151 has shown resistance to shoot fly, stem borer and midge. More attention has to be paid to this aspect. The problem of biotypes cannot be overlooked at this stage. Biotypes have already been identified in green bug and with the pests like shoot fly. stem borer and midge occurring in varied agroclimatic areas, it may not be surprising if we discover that there already exist biotypes of these pests.

Economics of Pest Control

Stress has been laid in the first paper on sampling, modeling and economic thresholds for different pests. The importance of these factors in pest management cannot be disputed. However, it may take a considerable time to develop this methodology especially for the developing countries.

The research workers should determine the economic threshold levels for different pests, so that extension workers may be trained to recognize the appropriate stage at which they should recommend control operations. Some work has already been conducted in India on the economic injury level for shoot fly (Rai et al. 1978).

In the FAO publication on integrated control for sorghum pests, a clear distinction has been made for the implementation of programs for 'high input' and 'low input' sorghums which actually amounts to the growing of sorghum in developed and developing countries. For immediate implementation in the countries of Asia and Africa, what we need is to convince the farmers about the advantages of pest control in high yielding varieties. This can be done by operational research projects on farmers' fields where all the feasible methods can be integrated and their effectiveness demonstrated in their own fields. Such operational research projects will require a very efficient program of training of extension workers and methods of assessment of different operations. Information already available on the control of different pests, though not complete, is sufficient to initiate these projects. Simultaneously the work can go on sampling, modeling and determining economic thresholds. More emphasis may have to be laid on cultural methods of control to be carried out as campaigns in groups of villages or blocks.

International Cooperation

The account on insect pests presented in the two papers show a similarity of the problems faced in different sorghum growing areas. The solutions for these problems have, therefore, to be similar with slight variations depending on the local conditions. There is thus a need for close international cooperation in solving the problems of sorghum growers. With this cooperation, the solution of these problems may be more expeditiously obtained and implemented, and also the mistakes committed by the earlier workers can be avoided.

References

DAVIES, J. C, and REDDY, K V. S. 1980. Shoot fly species and their graminaceous hosts in Andhra Pradesh, India. Presented at the International Study Workshop on the Sorghum Shoot fly, 5-8 May, ICIPE, Nairobi, Kenya.

FAO (Food and Agriculture Organization). 1979. Elements of integrated control of sorghum pests. Rome, Italy: FAO.

GRANADOS, Y. R. 1972. The role of wild hosts on the population dynamics of the sorghum shoot fly in Thailand. Pages 112-118 *in* Control of sorghum shoot fly, eds. M. G. Jotwani and W. R. Young. New Delhi, India: Oxford and IBM Publishing Co.

RAI SAMARJIT, JOTWANI, M. G.. and JHA, D. 1978. Economic injury level of shoot fly, *Atherigona soccata* (Rondani) on sorghum. Indian Journal of Entomology 40:254-260.

RAO, N. G. P., and JOTWANI, M. G. 1974. Sorghum midge—suitable varietal policy and surveillance essential. Indian Farming 24:9-11, 20.

RAO, R. S. V. 1975. Studies on the biology, bionomics and chemical control of the sorghum midge, *Contarinia sorghicola* Coquillett. Ph.D. Thesis, Division of Entomology, Indian Agricultural Research Institute, New Delhi.

SINGH, S. P., and JOTWANI, M. G. 1980a. Mechanism of resistance in sorghum to shoot fly—II. Antibiosis. Indian Journal of Entomology 42 : 353-360.

SINGH, S. P., and JOTWANI, M. G. 1980b. Mechanism of resistance in sorghum to shoot fly III. Biochemical basis of resistance. Indian Journal of Entomology 42:551 -566.

SUKHANI, T. R.. and JOTWANI, M. G. 1980. Comparison of cultural and chemical methods for the control of sorghum shoot fly. Entomon 5:291 -294.

YOUNG, W. R., and TEETES, G. L. 1977. Sorghum entomology. Annual Review of Entomology 22:193 -218.

Session 3 Factors Reducing Soghum Yields Insect Pests

Discussion

Parvatikar

In Bijapur and surrounding areas, *rabi* sorghums sown during September have more shoot fly than those sown during October. This is a limitation in recommending early sowings for the *rabi* season. So, what is the remedy?

Jotwani

It is true that the early sown *rabi* crop generally suffers more damage from shoot fly in the traditional sorghum growing areas. In my opinion, if early sowing is to be encouraged, protection against shoot fly should be provided by carbofuran seed treatment.

Niangado

According to Prof. Jotwani's presentation the problem of shoot fly is very important in India. However, in Africa and mainly in Mali, sorghum is sown in only one season. Generally sowing is done in June in the south and in July in the north. Therefore, the shoot fly is a problem on experiment stations where the breeders sow the late varieties first, and then the early ones later.

J. C. Davies

I agree that in many areas in Africa, it is an important problem on research stations only. But in some areas of Eastern Africa it is important on farmers' fields. Even in Western Africa, e.g., Upper Volta, there are areas where shoot fly is important on farmers' fields. The situation in Senegal is somewhat similar to that in Mali.

Nwanze

I agree with Dr. Davies that shoot fly could be a problem in the higher rainfall region of the south of Upper Volta. We have recorded 91.2% damage. Farmers' fields showed on an average 9.5% deadhearts. I also agree with Mr. Niangado that shoot fly is more of a problem on research stations where staggered planting and mixed maturity duration varieties are planted.

Mital

Does early sowing of sorghum reduce the damage by stem borer as mentioned? In my opinion, late sowing reduces the stem borer and early sowing shoot fly damage.

K. V. Seshu Reddy

In many areas early sowing of sorghum reduces the incidence of stem borer.

Vidyabhushanam

It is quite obvious that the future for sorghum pest control lies in identifying resistant sources and properly utilizing them. This is exactly what is being done in India during the present decade with reference to shoot fly and stem borer. Dr. Teetes mentioned in his presentation that a midge resistant hybrid is going to the cultivators next year. I would like to know the material and the resistance of this line.

Teetes

The parent lines for the hybrids I mentioned are from a random mating population and from TAM2566. Both, nonpreference for oviposition and antibiosis (larval death) are the types of resistance. Of the two types, antibiosis is the more important.

Maiti

Have you identified any morphological trait related to midge resistance? It has been stated that green bug resistance is related to bloom and bloomless sorghum. Similarly, glossy and trichome traits are related to shoot fly resistance. Therefore some morphological and biochemical characters need to be identified.

Teetes

No specific morphological traits have been related to midge resistance. However, all currently identified midge resistant sorghums are short glumed. Also, we have evidence to indicate a faster grain growth for midge resistant than midge susceptible sorghum. I agree that a morphological and biochemical basis for insect resistance needs to be identified.

Mital
Which species of green bug is a serious problem in USA? What is the threshold level you recommend for the control of this pest? Are parasites and predators not able to reduce populations of aphids below threshold levels?

Teetes
The green bug, *Schizaphis graminum* (Rondani) is a serious aphid pest of sorghum in the USA. Green bug economic thresholds are as follows: Emergence to 6 inches—small aphid colonies, plant yellowing before seedling death; 6 inches to boot—aphid colonies, before any leaves are killed; boot to flower—aphid colonies sufficient to kill one leaf; flower to maturity—green bug density sufficient to kill two leaves.

Maiti
You have mentioned in your talk that you are looking for multiple pest resistance. You have also indicated that ICRISAT materials selected for stem borer resistance are showing.good performance in Kenya. Have you by chance noted the glossy trait in any line? Dr. Jotwani has mentioned that IS2312 is resistant to both shoot fly and stem borer and it has the glossy character.

K. V. Seshu Reddy
Some lines with glossy trait have shown resistance to shoot fly and stem borer in Kenya also.

Chandurwar
Will you suggest the techniques for working out economic thresholds for shoot fly and midge, and the feasibility of biological control for these in India?

Teetes
There are many techniques to determine economic thresholds, but specific techniques are required for specific pests which depends on whether the economic threshold is based on pest density or damage. Basically a technique is used that results in a comparison of pest density or damage to yield. This requires the technique to control pest density and it is this aspect that determines the technique. Most often cages are used to maintain constant pest density. Sometimes treated and untreated plots are used and as feasible pest density is recorded. There is tremendous feasibility of biological control of shoot fly and midge, especially classical biological control.

V. Jaya Mohan Rao
The need to carry seed from one season to the next is becoming a more important problem because of storage pests. Further, the chalky endosperm varieties or hybrids are liable to heavy losses in storage. In the 80s considerable attention should be paid to storage pests.

Jotwani
The problem of stored grain pests is important and has not received adequate attention so far. We may perhaps start investigations on some of the aspects after collecting basic data on storage of sorghum grains, storage conditions, and the insect pests involved as well as the economic status of different pests.

Harvey
I wonder if we may have overlooked the importance of what we do with the grain after we get it. Would Dr. Davies be willing to comment on the importance of stored grain insects on sorghum?

J. C. Davies
Several schemes have checked the problem in Africa including IDRC in Senegal and FAO at IITA. It is important for us to ensure that new cultivars have good storage ability. There is no doubt that losses in store are high, but the species covered vary with country, cultivar, and storage method.

Thobbi
What is the scope for using the male sterile technique in the 80s for controlling sorghum pests?

K. V. Seshu Reddy
The present status of our knowledge as well as facilities available are not adequate to start any control program using the male sterile technique.

Nwanze
What are the prospects of the use of insecticides as a component in the insect pest management

program for sorghum in West Africa? We know that insecticides in that region have been used primarily on cash crops.

Teetes

Availability and cost of insecticides will limit the insecticide use in West Africa. However, personally, my concern is the toxicity to humans of most insecticides especially when hand applied by uninformed farmers. Insecticides are rarelv used as an insect pest management component because economic threshold levels are unknown.

Mital

It is true that water for spraying is a problem in water shortage areas. However, dusts and granules are quite useful in these situations.

J. C. Davies

Yes, I agree that dusts and granules are useful, but even these have to be transported. Dusts can only be used in many areas of Africa early in the morning. Granules are generally expensive.

Thobbi

What is the scope for the use of synthetic pyrethroids in sorghum pest control in the 80s?

K. V. Seshu Reddy

Some of these pesticides are being tested in the Indian program.

Salifou Mohaman

Do you know about the Coleoptera which attacks the sorghum grains during their milky stage, especially in the surroundings of Lake Chad?

Nwanze

A pest scarabacid attacks sorghum grains in the milk stage and causes a lot of damage; it is particularly severe in the Lake Chad region.

Teetes, Seshu Reddy, Jotwani and Sharma

In light of the increased severity in recent years of sorghum panicle feeding bugs, caterpillars, shootbugs and armyworms, an increased research effort must be directed towards these pests. Research is needed on pest biology and host plant relationships that result in an understanding of the factors that intensify pest severity. An assessment of losses caused by these pests is urgently needed. Also, determination of pest sampling procedures and economic thresholds are needed. Biotic (natural enemies) and abiotic influences on pest incidence and density should be studied.

Gilstrap

I wish to comment on the discussion on crop protection tactics to be researched and implemented on sorghum production in the 1980s. As evidenced by the contents of the published program and by discussions during the symposium, tremendous emphasis has been placed on breeding sorghums resistant to various preharvest losses. This tactic is ideally suited to improving sorghum production as it can be accomplished in the context of other important agronomic needs, is generally stable and dependable once developed, requires no specialized equipment or sophisticated understanding to use at the farm level, and is relatively inexpensive to use. However, it is also clear from this symposium that breeding sorghums resistant to insects has distinct limitations, both in terms of species of insects for which resistance is a satisfactory unilateral solution and in terms of sorghum lines in which resistance sources have been identified for each given pest.

I submit that protection from sorghum losses in developing countries is absolutely incomplete without knowledgeable use of natural enemies of crop pests, i.e., biological control. To date. significant research efforts have not been initiated to control pests in developing countries by importation, conservation, or augmentation of pests' efficacious natural enemies (parasites, predators, and pathogens). Biological control placed in proper perspective is not a panacea for pest control in developing countries any more than is host plant resistance. However, biological control has a long history of successes and is ideally suited for use in developing countries for the same reasons as named above for host plant resistance. Furthermore, successful biological control of arthropod pests is totally compatible with host plant resistance and in fact, can create an environment permitting effective use of lesser levels of resistant traits.

As one of only a handful of educators and scientists trained in depth in the principles and concepts necessary to research and implement biological controls, I am compelled to make these observations and the following plea. Biological control in sorghum has real and tremendously important potential for significantly reducing praharvest losses in sorghum. We are verifying this in Texas, though slowly because of the paucity of researchers trained for such studies even in the USA. In my view, it is absolutely essential to immediately place significant emphasis on in-depth biological control training for students from developing countries in the 1980s. Only then can significant progress be made in developing truly integrated pest management tactics for developing countries. Such students can begin almost immediately making contributions to that progress if such training programs insist that students' degree research be conducted in their home country. Thus, only course work would be obtained in the developed country and an adviser from the developed country would supervise the research in the student's home. Without an approach to biological control in developing countries as described, progress towards genuine integrated pest management and efficient crop protection from prehatvest tosses in sorghum is going to continue to be incomplete and partially successful. In short, host plant resistance must be integrated with biological controls especially in developing countries where resources are so limited and the needs for dependable food production so awesome.

Sidibe

Is it possible to call on different disciplines to reduce the cost of grasshopper control and to adapt the means of control at the farmer's level?

J. C. Davies

The control of grasshoppers at the peasant farm level is difficult. In the case of locusts, there must be efficient migrational surveillance and control. The problems are regional and locusts are no respecters of political boundaries. I believe the Insect Pest Management scheme should enable us to gain a great deal of information on grasshoppers and damage levels on peasant farms. It may then be possible to devise useful control measures. One of the problems with grasshoppers is their seasonality—they may be damaging for a few years and then unimportant for the next few. More detailed biological information is required to develop control strategies.

Sharma

One of the major constraints in breeding for pest resistance has been the nature of cooperation in interdisciplinary teams. It is heartening to note that interdisciplinary teams are working at many centers to achieve the intended objective. However, the lack of appreciation among the cooperators of each other's role has impeded much of the progress which would have been made in this area. It may be noted that a tremendous amount of effort is required in resistance breeding programs by entomologists and pathologists. It would be very helpful if the roles of different disciplines are defined, and guidelines for sharing the credit are put forth. I remember a strong plea made in this regard by Dr. S. D. Beck in the seventies. However, nothing has changed since then, though, much of the cooperation depends on personal understanding, willingness and flexibility on the part of the cooperators in the larger interest of the program.

Diseases

Chairman: D. N. Srivastava
Co-Chairman: E. E. Teyssandier

Rapporteurs: R. Bandopadhyay
S. Pande

Disease Problems in Sorghum

R. A. Frederiksen*

We have reached the point in sorghum pathology where the major diseases are recognized; consequently, the problems that we need to address are those which will yield the best possible information for controlling the more destructive sorghum diseases. Three major treatises on sorghum diseases (Tarr 1962; Saccas 1954; Williams et al. 1980) provide us with an excellent background to the nature of the diseases, the pathogens that cause them, and an insight into ongoing problems. A conference on sorghum diseases for the Americas was held April 1981 in Mexico City. We also recognize that essentially all sorghum improvement programs must include breeding for resistance, disease screening, and evaluation of pathogens as they exist within their particular environment (Frederiksen and Rosenow 1980). These programs should first identify the problems that *are* likely to occur, determine which of these diseases are most likely to cause the greatest losses, or are likely to increase in intensity under the crop management system that will develop as a result of deploying new or improved varieties and cultivation practices.

Recently with the help of S. B. King and N. V. Sundaram (Frederiksen 1979). we attempted to classify most of the world sorghum diseases on the basis of prevalence and severity in temperate and tropical regions (Table 1). The combination of prevalence and severity as well as distribution relates in part to importance and loss. Diseases resulting in greater losses or higher potential losses are arbitrarily classified as major. Losses represent both reduction in quantity as well as quality of product whether it be the grain, forage, or other product of the plant. For some of us, the business of ranking diseases on the basis of economic loss, prevalence, occurrence, appearance, or any other trait is at best an awkward assignment. Year in and year out in Texas, USA. head smut probably causes as much loss as does any other disease. Yet in a given year, charcoal rot may be our most economically important disease. On the other hand, during the past decade, maize dwarf mosaic has become our most prevalent disease. Before the introduction of resistant varieties for downy mildew control, sorghum downy mildew was the most conspicuous disease in areas where it is endemic. Certainly anthracnose has brought about dramatic changes in cultivation of particular host genotypes more than any other disease except maize dwarf mosaic. Grain mold combined with deterioration of grain in the field both on the Great Plains and in the Gulf Coast regions of Texas has been extremely important in some years. We have witnessed so-called "minor diseases" cause major problems because of environmental interactions. This occurred with *Pythium* root rot and small seed on the Texas High Plains and with some of the foliar diseases, particularly grey leaf spot and zonate leaf spot, along the Texas Gulf Coast. The point is that within a given environment one may see a disease move to the top of the list of importance in one year, whereas it may have been near the lower end of the scale in a previous year.

Nevertheless, certain diseases are more troublesome and have a greater geographical range of importance more consistently than others. For the purposes of this paper I have "somewhat arbitrarily" divided the text into major and minor diseases. Diseases are considered to be major because of distribution, economic loss, loss potential, public concern, or their effect on crop improvement programs. The minor disease problems discussed are those which may have damaging effects in endemic or regional areas but could also have major implications in the future particularly as major problems are solved.

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81. Patancheru, A.P.. India. Patancheru. A.P. India: ICRISAT.

Table 1. Tha relative pravalance* and Importance' of sorghum diseases of the world.

Disease	Tem-perate (outside 34° lat.)	Sub-tropical (within 34° lat.)	Tropical highland 1000 (+) m (within 23.15° lat.)	Tropical winter 1000 (-) m	Lowland summer 1000 (-) m
I Foliar diseases					
Leaf blight (*Helminthosporium turcicum)*	++2	+ + 1	++2	+ + +3	+ + 1
Target leaf spot *{H. sorghicola)*	-0	+ 1		+ 1	+ 1
Anthracnose (*Colletotrichum gramincola)*	+ 1	+ +2			+ +2
Grey leaf spot *(Cercospora sorghi)*	+ 1	+ ++2	+ +2	+ + +3	+ ++2
Zonate leaf spot (Gloeocercospora *sorghi)*	-0	+ ++2		+ 1	+ ++2
Sooty stripe *{Ramulispora sorghi)*	++2	++2		-0	+ +3
Rough spot *{Ascochyta sorghina)*	-0	+ + +2		-0	+ + +2
Leaf spot (*Ramulispora sorghicola)*	-0	+ 1		-0	+ + 1
Leaf spot (*Phoma insidiosa)*	+ 1	+ 1		-0	+ + 1
Bacterial leaf stripe *(Pseudomonas andropogoni)*	++2	+ + +2	+ + 1	+1	+ 1
Bacterial leaf streak (*Xanthomonas holcicola)*	+ 1	+ 1	+2	+0	+0
Bacterial leaf spot *{Pseudomonas syringae)*	+ 1	+ 1	+ +2	+0	+0
II Smuts and rusts					
Head smut (*Sphacelotheca reiliana)*	+ +2	+ + +3	++2	+1	++2
Loose smut (*Sphacelotheca cruenta)*	+ 1	+2	+ 1	+0	
Covered smut *{Sphacelotheca sorghi)*	+ 1	+ 1	++3	++3	++3
Long smut (To/yposporium *ehrenbergii)*	-0	-0			+ 1
Rust *{Puccinia purpurea)*	+ + 1	++2	+ +2	+ + +3	+ 1
III Downy mildews					
Sorghum (*Peronosclerospora sorghi)*	+ +2	+ + +3	+ 1	+ +2	+ + +3
Crazy top *(Sclerophthora macrospora)*	+ +2	+ +2	+ 1		
IV Virus and mycoplasm					
Maize dwarf mosaic	+ + +3	+ + +3			-0
Sugarcane mosaic (s)	+ 1	+ +2		+ 1	+2
Yellow sorghum stunt	+ 1	+ 1			-0
Brome grass mosaic	+ 1	+ 1			-0
Cucumber mosaic	+ 1	+ 1			-0
V Stalk rots and root rots					
Acremonium wilt *{Acremonium strictum)*	+ 1	1			+ 1
Fusarium stalk rot	+ +2	+ ++3			++2
Charcoal rot	+ +2	+ + +3			+ +2
Anthracnose	++2	+ + +3	+ 1	+ 1	+ +2
Rhizoctonia stalk rot	+ 1	+ 1			+ 1
Milo disease	+ 1	+ 1			-0
Pokkah-boeng	+ 1	+ +2	+ 1	+ +3	+ 1
Pink root	+ 1	+ 1			-0
Pythium root rot	++2	+ ++3		+ 1	?
VI Head and seed diseases					
Grain mold	+ +2	+ ++3	+ +2	+ +3	++2
Head blight	++2	+ 1	+2		+2
Weak neck	+ 1	+ 1			-0
Sugary disease *[Sphacelia sorghi)*	-0	-0			++2

Table 1. *Continued.*

Disease	Temperate (outside 34° lat.)	Subtropical (within 34° lat.)	Tropical highland 1000 (+) m (within 23.15'lat.)	Tropical winter 1000 (-) m	Lowland summer 1000 (-) m
VII Seedling blight					
(Species of *Pythium, Fusarium. Rhizoctonia* and *Helminthosporium)*	+2	+ +2	+ 1	+1	+ + 1
VIII Nematodes					
Pratylenchus spp	+ 1	+ +2			?
Meloidogyne spp	+ 1	+ 1			?
IX Parasitic plants					
Witchweed *(Striga asiatica)*	+ 1	+ 1	+2	+ +3	
(S. hermonthica)			+ +3		+ +3

a Prevalence: -Not reported present; +Occasionally present; + +Commonly present; + ++Generally found on most plants in most fields

b Importance: 0 Causing no loss; 1 Minor importance; 2 Moderate importance; 3 Representing a major deterrent, at times to crop production.

Major Diseases

The five major problems in order of importance are: grain mold, charcoal rot, downy mildew, anthracnose, and sorghum virus diseases, particularly those caused by the sugarcane mosaic group.

Grain Mold

The grain mold disease group ranks number one, primarily because we are concerned with the quality of grain sorghum as a food crop. This disease has received major attention during the past decade, particularly as we attempt to improve food sorghums and introduce less photosensitive sorghums in the tropical savannas (Williams and Rao 1980). Castor's (1981) comprehensive study on the histopathology of grain mold has provided us with additional evidence that infection takes place by relatively few species of fungi during anthesis. Also a number of different tissues appear to be involved in resistance to colonization. Since infection takes place at such an early stage the presence or absence of a testa probably has little effect on initial colonization. Castor's work substantiated the fact that a mesocarp provides an ideal environment for early colonization and a jumping-off point for fungi to continue the deterioration of the grain after infection has taken place.

Spikelet tissues, including the sterile lemma, lemma, palea, lodicules, anthers, and filaments are sites of infection at anthesis with *Curvularia lunata* and *Fusarium moniliforme.* The ovary, which develops into the kernel, is not colonized until it expands between five and ten days after anthesis. This would suggest that resistance to grain mold and fungi would involve spikelet as well as kernel tissue. Castor also defines the difference between grain weathering and grain molding. Grain molds are prematurity diseases resulting from infection of spikelets or developing kernels as early as anthesis by parasitic field fungi. Grain weathering is a postmaturity deterioration resulting from interactions among environmental and biological factors. The most common fungi associated with grain weathering are *Fusarium semitectum* and *Alternaria* spp. Other species of *Fusarium* and a number of species of *Alternaria* and other species of *Cladosporium* frequently are involved in weathering. There are of course a number of opportunities for grain mold and grain weathering fungi to overlap.

Grain mold fungi may cause the formation of a false or premature black layer which forms 10-16 days before maturity, and results in the development of small seed. Significant losses caused by weathering occur when periods of prolonged moisture exist following physiological maturity of the grain. It is unlikely that we will find sorghum seed free from fungi. These organisms can be deposited within the spikelet from anthesis until grain maturity. The question is whether or not the presence of these fungi causes substantial deterioration of the grain or interfere in the development of the grain. Obviously, some fungi are more detrimental than others. Grain mold is also important because it will continue to be a problem regardless of the type of sorghum culture. In traditional sorghum culture such as in the Nuba mountain region of Sudan, early flowering or late rains may occur which promote grain molds in the photoperiod sensitive types. It is more probable that there will be an increased cultivation of photoperiod insensitive sorghums which have a greater vulnerability to the grain molds.

Stalk Rots

The second major disease group of sorghum is charcoal rot; however, for the sake of discussion, *Fusarium* stalk rot, seedling blight complexes and any number of microfauna as well as microflora which affect root growth and development are included in this category. Charcoal rot ranks high on our list of sorghum diseases because it and the related problems are all influenced by the environmental stresses that are prevalent in areas where sorghum is the preferred cereal. It is a mixed blessing that sorghum has the capacity to withstand a number of environmental stresses because resistance to these stresses, including drought and high temperature, is closely associated with resistance to stalk rot (Rosenow 1980; Dodd 1980). In spite of the optimism expressed by some of our plant breeding colleagues, I am convinced that resistance to the stresses and resistance to colonization by stress-related pathogens, particularly *Macrophomina phaseolina* and *Fusarium* spp, will have to be at some sacrifice to potential yield. Consequently, there will always be attempts to produce higher yielding, less reliable cultivars in those areas where stress has lower probability of occurring regularly as opposed to those areas where there is a much higher probability that stress will occur. Management decisions can and will greatly influence the severity of disease potential as influenced by environment. Root and stalk rots in sorghum are controlled in part through the process of avoidance, and through selection of somewhat more resistant plants (Frederiksen 1979). Continually avoiding stress is characteristic of traditional farming in many parts of the world as well as in developed countries where plant populations of hybrids are reduced to allow the plants to compete more successfully for water. Low yielding sorghums represent an inefficient method of avoiding the disease. It cannot be considered as a reasonable alternative.

Downy Mildew

Another major disease which must be considered in most of the sorghum growing regions of the world is sorghum downy mildew *(Peronosclerospora sorghi).* Sorghum downy mildew is economically damaging. In addition, it is a politically explosive disease (El National 1975). Furthermore, it has a host range beyond the sorghum species, particularly that of maize, and in environments and areas of the world where both crops are grown, *Sorghum* spp constitute the primary inoculum source for infection in maize (Frederiksen and Renfro 1977). Even though the pathogen already has a wide distribution, there is always the probability that it will spread to new areas. Virtually every major sorghum improvement program includes plans for developing suitable levels of host resistance. Fortunately, sorghum downy mildew is a disease that lends itself to integrated approaches. Host resistance (Frederiksen 1980) coupled with cultural (Tuleen et al. 1980) and chemical (Anahosur and Patil 1980) control have already been devised and can be readily utilized in most sorghum growing regions.

Anthracnose

Anthracnose may well be more important than most people recognize. It certainly is the most damaging disease of sorghum in the tropical Americas. It occurs in the more humid, tropical sorghum growing regions of Africa and in many other sorghum growing regions in Asia. As we increase plant densities and if we ignore controlling anthracnose in some of the more widely deployed cultivars, we may encourage serious economic losses. Anthracnose damage may range from grain deterioration (Corrales and Frederiksen 1980) to peduncle breakage to stalk rot, and/or foliar damage. The other reason why it should be considered as a major disease is the rapid rate at which the pathogen can destroy sorghum plants as they approach maturity. Nearly complete losses have been recorded from fields only two weeks following a relatively low incidence of the initial disease.

Sorghum Viruses

Finally, the fifth of our major diseases contains the sorghum viruses. We believe that the sugarcane mosaic group is the most important of these. While most of the sorghum literature has been on maize dwarf mosaic strains A and B, present evidence indicates that these strains are closely related to strains of sugarcane mosaic virus and appear to be widespread throughout the world (Toler 1980). Recently we have learned of serious damages by sugarcane mosaic virus in South America (Frezzi and Teyssandier 1980; Riccelli 1980). These and other virus or virus-like diseases are present in Africa as well as in Asia (unpublished observations, R. A. Frederiksen). Diagnosis, understanding, and misunderstanding of the virus diseases combined with a lack of resistant adaptable germplasm, are among the reasons why they must be considered as important problems of sorghum.

Minor Diseases

Minor diseases are those that are limited in distribution either because of environment, distribution of the pathogen, culture of the crop, or host genotype. Many of the foliar diseases may be considered as minor. Nevertheless, a number of these so-called minor diseases may reach profoundly significant proportions in certain regions of the world. In the Bajio of Mexico, leaf blight *{Exerohilum turcicum),* rust *(Puccinia purpurea),* and grey leaf spot *(Cercospora sorghi)* appear to have contributed substantially to reducing yields during the past two or three years (Betancourt 1980). Foliar anthracnose and grey leaf spot are very important throughout Central America and Brazil as well as other Latin American regions. In the Philippines, tar spot *{Phyllachora sorghi).* rust, and grey leaf spot all appear to cause economic losses in sorghum (Dalmacio 1980). Similarly workers in India have reported several occurrences of grey leaf spot and the wide distribution of leaf blight (Ravindranath 1980). Throughout East and West Africa oval leaf spot, sooty stripe, and occasionally anthracnose are reported as prevalent (Beck 1980; Doggett 1980; Hulluka et al. 1980; Sidibe 1980; Tyagi 1980). In the higher regions of East Africa leaf blight and rust appear in damaging proportions (Hulluka et al. 1980). Bacterial stripe is present throughout the sorghum growing regions of the world. Stripe appears to be very prevalent in Argentina (Frezzi and Teyssandier 1980). A major factor contributing to losses caused by bacterial stripe appears to be the deployment of unusually susceptible cultivars. Bacterial streak on the other hand is known in the cooler sorghum growing areas, and although losses associated with the disease are unknown, its prevalence can reach traumatic levels. Many foliar diseases develop rapidly on maturing sorghum. Some diseases on the other hand prefer only the young tissues, which is a most interesting problem for future research (Tuleen et al. 1980).

Other grain diseases include ergot and the grain smuts. At this point, ergot threatens seed production, particularly with the male-sterile approach to hybrid seed production. Grain smuts have virtually been eliminated from areas where seed dressing fungicides are deployed, but in many traditional sorghum growing regions, moderately high levels of kernel smut prevail. Head smut, a major constraint to sorghum production in Texas, can be classified as only a minor problem worldwide (Frederiksen and Rosenow 1980). Head smut appears to be increasing in some areas of the world and could become a major threat with changing sorghum production. Head smut, for example, has increased dramatically in the People's Republic of China (personal communication, L. R. House). Other minor diseases with potential to affect crop production include such exotic diseases as: Acremonium wilt (Frederiksen et al. in press) (Fig. 1), yellow sorghum stunt (Zummo 1975) (a leafhopper-transmitted mycoplasmal-like organism); and other virus diseases (Toler 1980).

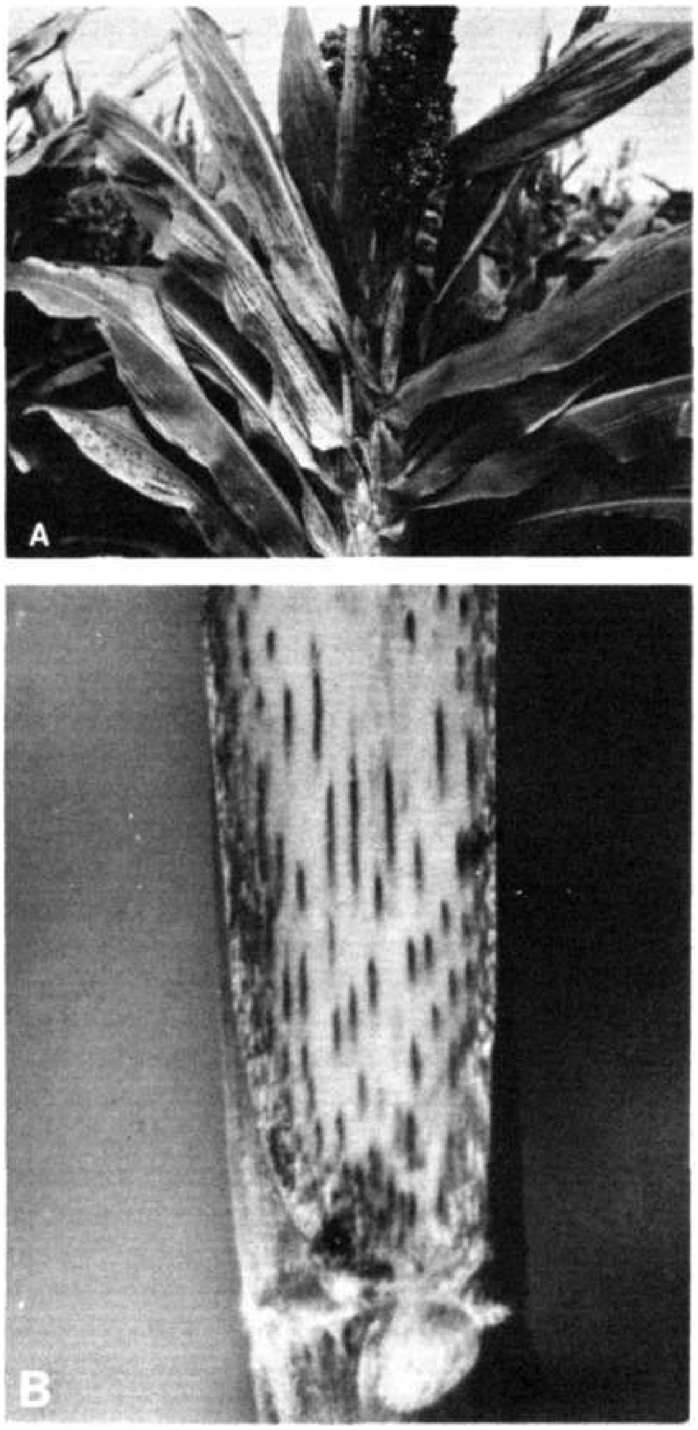

Figure 7. Symptoms of Acremonium wilt: necrosis of leaves with darkened veins (A), and vascular discoloration (B).

Major Disease Research Questions

For the major five diseases, one of the challenging problems will be to resolve and define the potential level of resistance necessary. Using grain mold as an example, extremely high levels of resistance or immunity to mold is highly unlikely. Consequently, the best resistance available will only provide partial control. The opportunity to combine avoidance to grain mold with resistance also constitutes one of the more challenging opportunities in crop improvement for many of the sorghum growing regions of the world. Castor's work suggests that screening for resistance to grain mold should be done at stages prior to filling (Castor 1981). It also suggests that the development of resistance might be more efficient in those environments in which infection is likely to occur at anthesis. Evidence exists that suggests there may be some form of biological control through induced immunity to early grain mold infection. Only a few reports of mycotoxins in grain sorghum exist. An interesting question might be why?

Another major disease group under investigation includes the downy mildews, particularly sorghum downy mildew (SDM) in sorghum. This disease along with several other downy mildews was evaluated at an international conference on graminaceous downy mildew diseases (Durbin et al. 1980). Clearly, the consensus of participants was that much information is already available on the control of SDM, but there were a number of problem areas which needed specific solutions for effective control of these diseases. Some of these included the simple need for clarification of the taxonomy of the pathogens causing downy mildew. Progress has been made on the identification of sources of primary inoculum, determination of physical and environmental factors controlling spore germination and production and determination of the influence of inoculum type, quantity and placement on disease reaction. Continuing research should be done to further the knowledge of specific genetic basis for downy mildew resistance, improve methods in selecting for resistance in breeding programs, determine factors that contribute to the stabilization and development of durable resistance, determine the mechanism of susceptibility, tolerance, and resistance, develop hazard indexes for specific geographical areas, and formulate integrated control programs.

It will be a challenge to pathologists, breeders, and agronomists to identify the interactions between disease stress and lodging resistance in sorghum. A major problem will be to determine the extent to which height genes contribute to lodging and if reasonable compromises in height can be made, particularly when fiber represents a major value of the crop (Tinker 1980). Essentially all stalk rot screening techniques employ the stalk inoculation procedures, yet many stalk rot pathogens invade through the roots. How important is it to determine the reaction of roots to these pathogens? When does infection take place? What are the factors affecting root colonization? Root colonization by parasitic fungi would reduce both the moisture efficiency, heat tolerance, and to a certain extent mineral utilization efficiency of plants.

A tremendous opportunity exists in utilizing beneficial root microflora and mycorrhizae in general. The relationships of these fungi to sorghum have not been investigated and may constitute a major source of nutrient use efficiency and might protect the plant from colonization by root-infecting fungi.

The importance of anthracnose as a disease has not received the recognition it needs (Corrales and Frederiksen 1980). Frequently, an occasional plant with downy mildew will attract more attention than hundreds of hectares of plants killed by *Colletotrichum graminicola.* This is no longer acceptable. Factors contributing to the spread of *C. graminicola* in a sorghum population are probably similar to those of other pathogens, only the rate of disease development is unbelievably fast. Plants that show only a few lesions can within a 2-4 week period be completely killed by the disease. This can happen to entire fields of a susceptible variey if the environment is right. Considerably more emphasis must be placed on the factors influencing and reducing the rate of epidemic development in a population of sorghum plants.

Finally, the occurrence of the virus diseases, particularly the mosaic group, has been widespread and damaging in sorghum germplasm. These diseases have appeared in areas in which sorghum viruses had not been considered to be major problems prior to the deployment of selected sorghum genotypes. This represents one example of what will be encountered as new varieties of sorghum are deployed. In the case of viruses, we will be concerned not only with the host and host effects and the virus, but also the vector, its reservoir, and its relation to alternate hosts.

When one looks at the disease problems collectively, and examines the current organized efforts to combat these problems, one finds that there is a very limited number of trained plant pathologists working on sorghum diseases, particularly on regional problems. Grain smut can be controlled by seed dressings, but who gets the seed dressings to the sorghum producers in the traditional sorghum growing regions? Who teaches the safe use of these seed dressings? Many of the foliar disease problems become more important on ratooned sorghum or on sorghum grown during the rainy season (personal observation and communications with R. R. Bergquist). Crop rotations may reduce some of these problems. The fact that replanting would be superior to ratooning in terms of disease control, but inferior in terms of management, has become a pressing issue with some of the more important foliar diseases.

Concluding Comments

King (1972) concluding for "Sorghum in Seventies", listed seven needs for sorghum pathology. These are: (1) more training, (2) more disease nurseries, (3) the development of disease plots, (4) multiple disease resistance, (5) resistance to *Striga,* (6) a disease reaction data bank, and (7) an illustrated sorghum disease handbook.

Since King's conclusions, we have witnessed a minor revolution in sorghum pathology. Major conferences on sorghum diseases have been held; in part to meet his educational requirements. Sorghum disease nurseries have become widely used, often the primary testing site for much sorghum germplasm as has been the selection of multiple disease resistant sorghum. Several centers have made progress in both the selection of *Striga* resistant sorghums as well as screening techniques. Finally, an illustrated handbook on sorghum diseases was published in Spanish, French, and English.

More Training

Today, as a decade earlier, training in sorghum pathology is still needed at all levels, in most regions of the world. Sorghum pathologists need to recommend and develop integrated controls for reducing disease losses and are needed to work with other sorghum scientists to avoid potential losses.

New Controls

Potential utilization of beneficial microorganisms as well as deployment of environmentally soft protectants will require much more research and careful study. Progress during the next decade should markedly reduce our dependency on and help to conserve good host resistance genes.

Data Base

We have only begun the complicated data banking of sorghum reactions to disease. Data banks are only as valuable as the data entering them. Much more thought must be given to the type of data summarized and what it means and when it should be summarized.

Nature of Resistance

Exciting new ideas regarding disease resistance, gene relations, and escape suggest that higher levels of host resistance through genetic manipulation are highly probable and need to be expanded.

References

ANAHOSUR, K. H., and PATIL, S. H. 1980. Chemical control of sorghum downy mildew in India. Plant Disease 64.1004-1006.

BECK, B. D. A. 1980. Sorghum diseases in Malawi. Pages 40-41 *in* Proceedings, International Workshop on Sorghum Diseases, ICRISAT, 11-15 December 1978, Hyderabad, India: ICRISAT.

BERGOUIST, R. R. 1973. *Colletotrichum graminicola* in *Sorghum tricolor* in Hawaii. Plant Disease Reporter 57:272-275.

BETANCOURT, A., 1980. Sorghum diseases in Mexico. Pages 22-28 *in* Proceedings, International Workshop on Sorghum Diseases. ICRISAT, 11-15 December 1978, Hyderabad, India: ICRISAT.

CASTOR, L. 1981. Grain mold histopathology damage assessment and resistance screening within *Sorghum bicolor* (L) Moench lines. Ph.D. Dissertation, Texas A&M University. College Station. Texas, USA.

CORRALES, M. A., and FREDERIKSEN, R. A. 1980. Sorghum anthracnose. Pages 289-294 *in* Proceedings. International Workshop on Sorghum Diseases. ICRISAT. 11-15 December 1978, Hyderabad, India: ICRISAT.

DALMACIO, S. C. 1980. Sorghum diseases in the Philippines. Pages 70-71 *in* Proceedings, International Workshop on Sorghum Diseases. ICRISAT. 11-15 December 1978. Hyderabad. India: ICRISAT.

DODD, J. L. 1980. The photosynthetic stress-translocation balance concept of sorghum stalk rots. Pages 300-305 *in* Proceedings. International Workshop on Sorghum Diseases. ICRISAT. 11-15 December 1978, Hyderabad, India: ICRISAT.

DOGGETT, H. 1980. Sorghum diseases in East Africa. Pages 33-35 *in* Proceedings, International Workshop on Sorghum Diseases, ICRISAT. 11-15 December 1978. Hyderabad, India: ICRISAT.

DURBIN. R. D.. FREDERIKSEN. R. A., KELMAN. A., and RENFRO, B. L. (eds.) 1980. Proceedings, International Conference on the Graminaceous Downy Mildew Diseases, The Rockefeller Foundation, 28 November -3 December 1979. Bellagio, Italy. Available from The Rockefeller Foundation. Publication Office, 1133 Avenue of the Americas, New York, NY 10036, USA.

El National, Caracas, Venezuela, 2 Aug 1975. La plaga "punta losa" invade los cultivas de maiz.

FERNANDES, F. T., and SCHAFFERT, R. E. 1980. Sorghum in Brazil. Pages 15-17 *in* Proceedings, International Workshop on Sorghum Diseases, ICRISAT, 11-15 December 1978, Hyderabad, India: ICRISAT.

FREDERIKSEN, R. A. 1977. Head smut of corn and sorghum. Pages 89-105 *in* Proceedings, 32nd Annual Corn and Sorghum Research Conference, American Seed Trade Association, 6-8 December 1977, Chicago, Illinois. Available from the American Seed Trade Association. 11030 15th St., N. W. Suite 964, Washington, D. C. 20005, USA.

FREDERIKSEN, R. A. 1979. Diseases of sorghum. Pages 99-109 *in* Proceedings, Elements of Integrated Control of Sorghum Pests. Rome, Italy: FAO.

FREDERIKSEN, R. A. 1980. Sorghum downy mildew in the United States: Overview and outlook. Plant Disease 64:903-908.

FREDERIKSEN. R. A., and RENFRO, B. L. 1977. Global status of maize downy mildew. Annual Review of Phytopathology 15:249-275.

FREDERIKSEN, R. A., and ROSENOW, D. T. 1980. Breeding for disease resistance in sorghum. Pages 137-167 *in* Biology and breeding for resistance, ed. M. K. Harris. Texas Agriculture Experiment Station. MP1451

FREDERIKSEN, R. A., ROSENOW, D. T„ and NATURAL, M. (In press). Acremonium wilt of sorghum. *In* Proceedings, Twelfth Biennial Grain Sorghurh Research and Utilization Conference. SICNA, 25-27 February 1981, Lubbock, Texas.

FREZZI, M., and TEYSSANDIER, E. E. 1980. Summary and historical review of sorghum diseases in Argentina. Pages 11-14 *in* Proceedings, International Workshop on Sorghum Diseases, ICRISAT, 11-15 December 1978, Hyderabad. India: ICRISAT.

HULLUKA, M., and GEBREKIDAN. B. 1980. Diseases of sorghum in Ethiopia. Pages 36-39 *in* Proceedings. International Workshop on Sorghum Diseases. ICRISAT. 11-15 December 1978. Hyderabad. India: ICRISAT.

KING, S. B. 1972. Sorghum diseases and their control. Pages 411-434 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co. 638 pp.

RAVINORANATH, V. 1980. Sorghum diseases in India. Pages 57-66 *in* Proceedings, International Workshop on Sorghum Diseases, ICRISAT, 11-15 December 1978, Hyderabad, India: ICRISAT.

RICCELLI, M. 1980. Current strategies and progress in breeding disease resistant sorghums in Venezuela. Pages 434-453 *in* Proceedings, International Workshop on Sorghum Diseases, ICRISAT, 11-15 December 1978, Hyderabad, India: ICRISAT.

ROSENOW, D. T. 1980. Stalk rot resistance breeding in Texas. Pages 304-314 *in* Proceedings, International Workshop on Sorghum Diseases, ICRISAT, 11-15 December 1978, Hyderabad, India: ICRISAT.

SACCAS, A. M. 1954. Less champignons parasites des sorghos *(Sorghum vulgare)* et des. Penicillaires (*Pennisetum typhoideum)* En Afrique Equatorale Francaise. Agronomie Tropicale 9:136-686.

SIDIBE, O. 1980. Principal sorghum disease in Niger. Pages 42-44 *in* Proceedings, International Workshop on Sorghum Diseases, ICRISAT, 11-15 December 1978. Hyderabad, India: ICRISAT.

TARR, S. A. J. 1962. Diseases of sorghum, sudan grass, and broom corn. Kew, Surrey. United Kingdom: Commonwealth Mycological Institute.

TINKER, I. 1980. Changing energy usage for household and subsistence activities. Important for the Future 5:2-66.

TOLER, R. W. 1980. Viruses and viral diseases of sorghum. Pages 395-408 *in* Proceedings, International Workshop on Sorghum Diseases, ICRISAT. 11-15 December 1978. Hyderabad. India: ICRISAT.

TULEEN, D. M„ FREDERIKSEN, R. A., and VUDHIVANICH, P. 1980. Cultural practices and the incidence of sorghum downy mildew in grain sorghum. Phytopathology 70: 905-908.

TYAGI, P. D. 1980. Sorghum diseases in Nigeria. Pages 42-52 *in* Proceedings, International Workshop on Sorghum Diseases, ICRISAT. 11-15 December 1978. Hyderabad. India: ICRISAT.

WILLIAMS. R. J„ and RAO, K. N. 1981. A review of sorghum grain molds. Tropical Pest Management 27: 200-211.

WILLIAMS, R. J„ FREDERIKSEN, R. A., MUGHOGHO. L. K.. and BENGTSON, G. D. (eds.) 1980. Proceedings, International Workshop on Sorghum Diseases, ICRISAT, 11-15 December 1978, Hyderabad, India: ICRISAT.

ZUMMO. N.. BRADFUTE, O., ROBINSON. D., and FREEMAN, K. C. 1975. Yellow sorghum stunt a disease symptom of sweet sorghum associated with a mycoplasma-like body. Plant Disease Reporter 59:714-716.

Strategies for Sorghum Disease Control

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Most sorghum diseases are amenable to some degree of control through the application of one or more appropriate control measures. These measures fall under the general disease control methods of host resistance, chemical control, cultural control and integrated control. The decision as to which method to apply in any disease situation would depend upon whether the method met the criteria of agronomic effectiveness, environmental effectiveness, economic feasibility, social acceptability, and implementability (Bailey and Waddel 1980). These criteria are necessary in order to tailor control measures to the worldwide requirements of diverse environments, agricultural systems and socioeconomic conditions under which sorghum is grown.

In the 70s, research activity in sorghum disease control was small. A survey of the *Review of Applied Mycology* and the *Review of Plant Pathology* from 1970 to 1980 revealed that in the 1970s, only 67 papers out of a total of 487 papers on sorghum diseases were on disease control. Of these 67 papers, the majority were on host resistance (31 papers) followed by chemical control (29 papers) and only 7 papers were on cultural control. Most of the papers on disease control were from India and the USA and there was none from Africa. The lack of papers from Africa where sorghum is an important crop is a reflection of the skilled manpower bottleneck that is at the root of the present low level of sorghum improvement research in that continent. It also shows that nothing has changed since the call by King (1972) at the Sorghum in Seventies Symposium for indigenous trained pathologists to work on sorghum diseases.

This paper reviews progress in sorghum disease control in the 1970s and presents control strategies for the 1980s. A discussion of the control of individual diseases will not be undertaken as this was adequately covered at the 1978 International Workshop on Sorghum Diseases (Williams et al. 1980).

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Host Resistance

Cultivation of disease resistant varieties is the most valuable and practical solution to disease problems. Host resistance is cheap (to the farmer), simple and effective, and also meets the requirements of broad applicability over a wide range of environmental and socioeconomic conditions. The four essential requirements for development of stable, disease-resistant varieties are:

1. Availability of a large, variable germplasm which can be intensively screened for resistance sources. Diverse germplasm increases the chances of selecting material with resistance to many pathogens and their variants.
2. Development of sound and effective resistance screening techniques.
3. Multilocational testing for stability of resistance under different environments and races of pathogens.
4. Methods for combining resistance(s) with other desirable plant traits.

Rosenow (these Proceedings) provides a more comprehensive review of breeding for disease resistance. This discussion will therefore be limited to the first three requirements.

Germplasm

A very large, variable sorghum germplasm has been assembled and is being maintained at ICRISAT Center (Mengesha and Rao, these Proceedings). Additions are made to it every year. This germplasm is available on request to any scientist wishing to screen or evaluate it for particular traits including disease resistance. Un-

International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru. A.P., India. Patancheru. A.P. India: ICRISAT.

fortunately adaptation problems preclude the evaluation of most of the germplasm at any one location. At ICRISAT Center, for example, more than half the collection does not flower or set seed in the rainy season and cannot therefore be screened for resistance to grain molds, smuts and ergot.

Resistance Screening Techniques

The key to the identification of sources of stable resistance is the development of reliable, efficient and epidemiologically sound screening techniques which allow discrimination between resistant and susceptible genotypes (Williams 1976). The material to be screened should be exposed to optimum levels of pathogen inoculum under conditions conducive for infection and disease development in order to avoid disease escape. Also important is the exposure of the material to graded levels of disease pressure to allow for the expression by the plants of different degrees of resistance which may be important in the stability of resistance.

The biological basis for the development of effective screening techniques is a clear understanding of the basic biology of the pathogens and the epidemiology of the diseases they cause.

In the 1970s substantial progress was made in the development of effective field screening techniques for grain molds, sorghum downy mildew and some leaf diseases (Frederiksen and Rosenow 1979; Williams et al. 1980). The use of these techniques has led to the identification of sources of resistance for use in breeding programs. There are, however, still a number of diseases for which no effective resistance screening techniques are available. These include some economically important diseases such as charcoal rot *(Macrophomina phaseolina* [Tassi] Goid), sooty stripe *(Ramulispora sorghi* [Ellis and Everhart] Olive and Lefebvre), and grey leaf spot *(Cercospora sorghi* Ellis and Everhart).

The continual refinement of existing screening techniques and the development of new ones is a major challenge for the 1980s if host resistance is to continue to play a major part in the control of sorghum diseases.

Multilocational Testing

The final phase in the identification of stable resistance is the exposure of the material, identified as resistant at one location, to many populations of the pathogen under a wide range of environmental conditions. The necessary requirements for a multilocational testing program are twofold: the availability of locations where disease occurs regularly under consistently high pressure, and the presence of interested and capable scientists who can effectively cooperate with the screening.

In the 1970s a significant development in multilocational testing was the establishment of international sorghum disease nurseries by ICRISAT and Texas A&M University in the USA. These nurseries serve three purposes: (a) they identify genotypes with stable resistance for use as parents in breeding programs, (b) they detect the occurrence of races of the pathogens, and also signal changes in pathogen virulence over time, (c) they promote international communication and cooperation on sorghum disease research.

There are currently six international sorghum disease nurseries. Texas A&M University coordinates the International Disease and Insect Nursery (IDIN) and the Anthracnose Virulence Nursery (AVN). while ICRISAT coordinates four nurseries: the International Sorghum Grain Mold Nursery (ISGMN), the International Sorghum Downy Mildew Nursery (ISDMN), the International Sorghum Leaf Disease Nursery (ISLDN) and the *Peronosclerospora sorghi* Host Differential Nursery (PSHDN). The cooperation of national program scientists in growing these nurseries is crucial for the success of this program.

The results of the international disease nurseries have so far been very encouraging. Texas disease-resistant material is used in many breeding programs. In the ICRISAT ISGMN, the line E-35-1, a zera zera from Ethiopia, has been found resistant to several diseases in the semi-arid tropics and in demonstration trials in West Africa where it is being used as a direct introduction. Also from the ISGMN the line IS-9521 from South Africa was selected in Ethiopia and released as a variety in a high rainfall zone of Ethiopia. In the ISDMN the Australian variety QL-3 bred for resistance to sugarcane mosaic virus, has shown absolute resistance to downy mildew *(Peronosclerospora sorghi)* at several locations in India, Africa and Latin America over 5 years of testing. This variety has stable resistance to sorghum downy mildew and is now used in breeding programs where the disease is important.

In the operation of the international nurseries, national program scientists are encouraged to submit their local resistant material for inclusion in the nurseries. One advantage of this is that diseases not occurring in one location or country are screened against in another location/country so that such diseases can be prevented from becoming important even if introduced. To this end, national sorghum programs should develop close links with cooperators elsewhere in the international nurseries so that their material can be screened for "exotic" diseases.

Potential Genetic Vulnerability

Genetic vulnerability to new diseases or new races of pathogens due to extensive use of certain resistance genes is difficult to predict. However, measures designed to increase genetic variability in the varieties grown help reduce the risk of epidemics. The multiline strategy (Browning and Frey 1981) is advocated as one method of preventing epidemics. This strategy of growing a mixture of genotypes is not new to traditional sorghum farmers. In Africa and in India genetically pure stands of sorghum are rare; plantings are in patches or small fields, and a mosaic of local varieties (landraces) are grown. Diseases are always present but such crop production conditions do not readily favor epidemics.

In efforts to transform traditional agriculture the tendency is to introduce and recommend the cultivation of a limited number of varieties (often a single, "best" variety). The risk of epidemics under such conditions is real, and serious epidemics would be particularly damaging to poor farmers and poor societies.

The 1970s were the years of major concern of genetic vulnerability in crops. It was triggered by the maize leaf blight *(Helminthosporium maydis* race T) epidemic in the USA (Tatum 1971). This helped stimulate research for the genetic diversification of crop varieties. In sorghum most of this work was done in the USA where the converted sorghums have provided useful and diverse resistance sources to essentially all economically important diseases in that country (Frederiksen and Rosenow 1979).

The potential problem of genetic vulnerability in sorghum is likely to receive greater attention in the 1980s as the area covered by improved sorghum cultivars expands and as the crop is introduced into new areas. Three areas which are cause for immediate concern are outlined below:

1. Varietal Diversity on the Farm

As already stated, varietal uniformity over large production areas is an invitation to disease epidemics. Even where different varieties are grown these varieties may have been developed using identical parents.

The old adage not to put one's eggs in one basket is particularly apt when choosing varieties. Farmers should be encouraged to grow a selection of genetically diverse cultivars with different sources of resistance to the prevalent diseases in the area. Such varietal diversity within and between farms should substantially reduce the risk of epidemics (Priestley 1981). The adoption of such a strategy would depend on the availability of a number of equally high yield potential varieties and a seed production program capable of rapidly spreading the varieties. This strategy may perhaps not bear fruit in the 1980s but a start should be made in this direction.

2. Cytoplasmic Male Sterility

Wide-scale sorghum hybrid seed production is not feasible without cytoplasmic male sterility, and there is only one satisfactory type of cytoplasm (milo) that is used worldwide. Although cytoplasmic susceptibility to disease appears to be rare (Hooker 1974), the USA experience with the maize leaf blight epidemic of 1970 (Tatum 1971) is a warning of the danger of reliance on a single source of cytoplasmic male sterility in sorghum. Current research in the USA, in the All India Coordinated Sorghum Improvement Project and at ICRISAT to diversify cytoplasmic male sterility should be encouraged and supported.

3. International Distribution and Exchange of Material

In his presidential address to the British Mycolcgical Society, Macer (1975), while extolling the benefits of international exchange of breeding material, also warned of the danger of spreading material of limited genetic diversity in the following words:

> "National breeding programs rely increasingly on international aggregations of source material for parents. Breeders and their pathological

colleagues tend to draw heavily on this material and to select similar, if not identical sources of resistance. Indeed, the practice of submitting resistant parents and selections to international nurseries tends to encourage breeders to use these and to concentrate efforts within even limited ranges of resistance. This restricts further the genetic base and makes many breeding programs, often encompassing a wide geographical area, vulnerable to a single change of virulence of the pathogen. The free exchage of resistant material has advantages in encouraging international cooperation and allowing the widespread testing of the "resistant material" but these advantages may be more than offset if too great a use is made of a restricted range of material."

The solution to the problem raised by Macer lies in the continual search, testing, exchange and utilization of genetically diverse sources of resistance in breeding programs. The germplasm collection at ICRISAT is so large and diverse that it is quite conceivable that genetically diverse sources of resistance to one or more diseases can be located.

The history of breeding for disease resistant sorghums, especially in the tropics, is a very short one, and in the developing countries only an insignificant proportion of the sorghum area is covered by improved varieties. It is therefore too early to discover all the pitfalls that may have been built into the new varieties, but the extreme susceptibility of the hybrid CSH-6 to charcoal rot *(Macrophomina phaseolina* [Tassi] Goid) in India provides a timely signal of the problem. Constant vigilance is therefore necessary to monitor weaknesses in these varieties as their adoption and areas of cultivation expand.

Chemical Control

Two aspects of chemical control will be discussed: protective chemical application to an established crop, and chemical treatment of seed before sowing.

Chemical Protection of an Established Crop

Chemical application to control diseases in an established crop is not a common practice in sorghum production. In the 1970s results of research, particularly in India, showed that some important diseases could be effectively controlled by applications of a broad range of fungicides (Gangadharan et al. 1976; Singh and Pavgi 1977; Pawar and Patil 1978). However, at the farm level, chemical disease control in an established crop is uneconomic because sorghum yields a low cash return per hectare. Even in the highly productive systems of the USA or Argentina, the low profit margin in sorghum production is a barrier to the use of chemicals against diseases in a standing crop. This situation is likely to prevail throughout the 1980s as costs of chemicals continue to rise faster than the market price of sorghum.

Chemical Seed Treatment

The economic argument—despite the well-known phoblems of phytotoxic side effects, human and environmental hazards, iatrogenic diseases (Griffiths 1981) and development of resistance to chemicals—does not apply to the use of the relatively inexpensive seed treatment chemicals to destroy or control seed-borne pathogens and soil-borne pathogens adjacent to the seed at sowing. Seed treatments, applied as dusts or slurries, are inexpensive because, unlike chemicals applied to a standing crop, they are applied only once and in very small quantities per hectare, no expensive equipment is required and labor and water costs are minimal. Their uniform distribution below the soil surface, and the time interval from sowing to harvest also suggest that chemical seed treatment is not as hazardous to human food and the environment as other methods of chemical disease control.

Another advantage of seed treatment is that where seed for planting is commercially produced, chemical treatment can be done at the source at very little extra cost.

During the most critical growth period from germination to the establishment of the young seedling, the young succulent tissues of sorghum are susceptible to a variety of unspecialized, soil-inhabiting fungi. These are chiefly species of *Fusarium* and *Pythium* which cause seed rots, clamping off and seedling blights, and are an important factor in poor crop establishment (Tarr 1962). Control of these diseases by host resistance has proved difficult because the pathogens are relatively nonspecific in their host requirements. Chemical seed treatments have proved to be most effective means of controlling these diseases.

An essential requirement of seed for planting is freedom from seed-borne pathogens which often adversely affect germination, crop establishment and further plant growth. Infected seed is also an important means of pathogen dissemination over long distances, and the introduction of diseases into new areas. Chemical seed treatment has essentially eliminated covered grain smut, caused by *Sphacelotheca sorghi* (Link) Clinton and loose smut caused by S. *cruenta* (Kuhn) Potter in the USA (Edmunds 1975). In Africa sorghum grain losses due to these smuts could be similarly prevented through the use of chemically treated seed. The problem appears to be the unavailability of the chemicals, or of chemically-treated seed, the lack of education of the farmer and the lack of extension advisors on diseases and their control.

In the 1970s a variety of chemicals including Vitavax, Thiram, Benlate, Dithane M-45, Dithane Z-78 and Ceresan were reported as effective seed treatments against seed rots, seedling blights and seed-borne diseases of sorghum (Hansing 1970; Mishra and Siradhana 1978; Agrawal and Khare 1978; and Bidari et al. 1978). Perhaps the most significant event was the development of the CIBA-GEIGY systemic fungicide metalaxyl [N-(2, 6-dimethyl phenyl)-N-(methoxyacetyl)-alanine methyl ester, CGA 48988, Ciba-Geigy Corporation] which, as a seed dressing, significantly reduced the incidence of sorghum downy mildew caused by *Peronosclerospora sorghi* (Weston and Uppal) Shaw (Venugopal and Safeeulla 1978) at rates as low as 0.1 g a.i./kg of seed (Frederiksen and Odvody 1979). This new development means that the resistance levels of some sorghum varieties and hybrids can be enhanced by chemical seed treatment. The effective control of oosporic and conidial inoculum by metalaxyl seed treatment (Frederiksen and Odvoidy 1979) would minimize the introduction and spread of the disease through seed. The use of metalaxyl needs careful monitoring for possible phytotoxic effects and the capacity of the sorghum downy mildew pathogen to develop strains resistant to it as has already occurred in the downy mildew of cucurbits caused by *Pseudoperonospora cubensis* (Berk. & Curt.) Rostow (Reuven et al. 1980).

The experience of the 70s of the soaring cost of energy-based chemicals precludes any possibility of the use of chemicals for disease control in an established crop. Research in this area would also be a waste of resources, both human and financial. There is, however, tremendous scope for chemical seed treatment to control seed-borne diseases. This would facilitate seed movement and exchange, so important for sorghum improvement, by greatly reducing the risk of introducing pathogens. It is the fear of introducing diseases through seed that restricted the exchange and distribution of sorghum germplasm and breeding materials in certain countries in the 1970s.

In the developing countries, the development of seed companies which would routinely treat all seed at source would promote seed treatment as an effective measure of disease control. Chemical companies should be encouraged to continue to develop cheaper systemic compounds that act specifically against seed-borne pathogens.

Cultural Control

Cultural control may be defined as the tactical use of regular farm operations or crop husbandry practices to delay or reduce disease incidence and spread. It includes all practices which modify the environment to favor crop growth and minimize or avoid conditions which favor disease development.

Two problems need consideration in the use of cultural practices for disease control. First, most cultural practices effective in disease control tend to be location-specific, i.e., they are effective in particular soils, locations and climates where they have been developed. Consequently they are of limited application over diverse environments. Second, the development of cultural control methods requires adequate knowledge of the basic biology and epidemiology of the disease. For most sorghum diseases, this information is not available and would require a considerable research effort to obtain it. The question for the 1980s is whether this area should receive priority attention.

Some cultural practices which have been implicated in sorghum disease control are discussed below.

Tillage

Generally tillage promotes biological control of diseases through reduction in inoculum density and replacement of pathogens by saprophytes in crop residues (Baker and Cook 1974). Tillage also accelerates soil drying which helps reduce populations of certain soil-borne fungal pathogens and nematodes.

Deep burial of infected crop residue is known to have beneficial effects by reducing the seasonal carry-over of inoculum. Tuleen et al. (1980) reported that deep plowing to bury oospores reduced the incidence of sorghum downy mildew and increased yield in a susceptible sorghum cultivar when compared with conventional plowing. Conservation tillage or no-tillage systems where crop residues on the soil surface are subjected to minimum or no tillage may affect plant diseases by providing a habitat for pathogens and thereby serving as foci of inoculum (Summer et al. 1981). Disease incidence can be expected to be high for trash-borne diseases, e.g., anthracnose, leaf blight, sorghum downy mildew and bacterial diseases.

In the tropics most small farmers practice minimum tillage since they do not have the implements and power for deep plowing. Under such conditions the risk of seasonal carry-over of inoculum on plant debris is high. However, in some regions, such as in India, the removal of the stalk for fodder at grain harvest minimizes this danger.

An indirect beneficial influence of crop residues was the reduction in the incidence of stalk rot of sorghum in a reduced tillage system (ecofallow) in Nebraska (Doupnick and Boosalis 1975). This was because ecofallow increased soil moisture storage and thereby made plants less predisposed to infection.

Time of Sowing

Adjustments to time of sowing often make it possible for crops to escape from disease by ensuring that the crop is not in the most disease-susceptible stage when pathogen inoculum is abundant and the weather favorable for infection and disease spread. This strategy has, however, received little attention in sorghum disease control. The advantage of early planting to avoid significant grain losses caused by sorghum downy mildew at Dharwar, India was reported by Balasubramanian (1974). On the other hand Tuleen et al. (1980) reported that delayed planting reduced the incidence of the same disease in Texas. These two contrasting reports emphasize the location specificity of cultural control measures.

In areas of variable and unpredictable rainfall, such as the semi-arid tropics where most of the sorghum is grown, the physiological and ecological advantages are nearly always with the early planted and established crop. In such areas delayed or late sowing is not desirable since yields of late sown crops are low even if free from a particular disease.

Avoidance of disease through adjustments in time of sowing should simultaneously avoid the period of activity of insect pests. It would be futile to protect a crop from diseases when pests would damage it.

Mineral Nutrition

Mineral nutrition is an important factor which determines in large measure a plant's resistance or susceptibility to disease. Different types, levels, and balance of nutrients, or their unavailability influence the reaction of a plant to pathogen challenge depending upon particular host-pathogen combinations. Even different forms of the same nutrient may affect host susceptibility or pathogen virulence (Huber 1980).

Reports from India indicated that high levels of nitrogen increased the susceptibility of sorghum to ergot disease *(Sphacelia sorghi* McRae) (Chinnadurai 1971), leaf disease (Naik et al. 1976) and stalk rot (Anahosur et al. 1977). Susceptibility of sorghum to downy mildew was unaffected by increases of nitrogen, but was increased by increases in phosphorus (Balasubramanian 1973).

Nutrition appears to be an important factor in the predisposition of sorghum to stalk rots and lodging. Murphy (1975) reported that excessive nitrogen and deficiencies in potassium, when combined with moisture stress, favored stalk rots and lodging. Recently at ICRISAT Center, Seetharama (personal communication) observed that in the CSH-6 hybrid, charcoal rot was more severe when grown under high (120 kg N/ha) than under low (40 kg N/ha) fertility conditions. Although other factors are involved, it is clear that nutrient imbalances play a role in the susceptibility of sorghum to charcoal rot.

Cropping Systems

Sorghum is produced under a variety of cropping systems (Willey, These Proceedings). Intercropping is the most widespread system in the traditional sorghum areas of India and Africa, and also in Central America. There is no published information on disease problems in the intercrop situation, and most research on sorghum disease control continues to be done on sole crops. Disease control methods devised under sole crops may not be satisfactory for intercrops.

In intercropping, the modification of the crop micro-environment (humidity, light, free moisture, temperature, air movement, etc.) and differences in nutrient uptake by the intercrops are likely to influence plant infection, diseases development and spread. Research on disease problems and control in intercrops deserves attention in the 1980s.

Crop rotation is a classical cultural practice that helps to control soil-borne diseases caused by fungi, nematodes and other organisms. Diseases usually become a problem where the rotational cycle is reduced through intensive cultivation and monocropping. In sorghum, there is a dearth of information on crop rotation as a means of disease control. As with other cultural practices, knowledge of the basic biology and epidemiology of the pathogens is a prerequisite for nonempirical application of crop rotation in disease control. In the intercrop systems of the tropics a sound rotational practice could be difficult to implement because of the diversity of crop components.

Some sorghum cropping systems are not sound for disease control. One such system is ratoon cropping which has the advantages of providing more than one harvest from a single sowing, and ensuring the maximum use of a growing season that may be too short for two sown crops in succession (Plucknett et al. 1970). The disadvantage is that systemic diseases such as sorghum downy mildew, smuts, bacterial and viral diseases tend to increase in severity on ratoon crops. Unless resistant varieties are used, ratoon cropping cannot be recommended.

Integrated Control

We have discussed how different strategies of host resistance, chemical treatment and crop husbandry practices can be successfully used in sorghum disease control. In practice, a single control strategy often does not provide a permanent solution to a disease problem. For example, host resistance may "break down" due to the development of new races of the pathogen, or the pathogen may develop new races resistant to a fungicide. Cultural practices too are subject to the variability of the weather, and sometimes are heavily dependent on the cooperation of neighboring farmers. In view of this, the application of several control methods becomes necessary. In other words, the diversification of disease control methods can help maintain disease levels below economic injury.

Sorghum downy mildew is a disease which lends itself easily to control through the use of several methods in Texas, USA. Resistant varieties are available, several cultural practices have reduced the incidence of the disease, and seed dressing with metalaxyl also has controlled the incidence of the disease (Frederiksen 1979). The paucity of research on various methods for the control of specific diseases does not make it possible to come up with recommendations for other diseases elsewhere.

In future, multiple measures will be required for successful disease control. Again, the need is for more research.

Problems and Challenges in the Eighties

In looking ahead to the 1980s it is not unrealistic to foresee a decade of increasing importance of disease problems as improved varieties and crop management systems developed in the 1970s are adopted by farmers on an extensive scale. Previously insignificant or unknown diseases, or new races of known pathogens are likely to come to prominence and cause economic crop losses. The breeding successes of the last decade will pale into insignificance unless innovative approaches to disease control are undertaken. The problems and challenges of the eighties need to be attacked from several angles:

1. Resistance Screening Techniques

As host resistance is likely to be the favored method of disease control, particularly among the resource-poor farmers of the developing countries, an expanded and intensive effort should be made to the refinement and/or development of methods for creating artificial epidemics at desired intensities for rapid screening of germplasm and breeding lines. In spite of the successes of the 1970 s there are still a number of diseases for which no sound screening techniques are avail-

able. We must learn how to manage the diseases in the field.

2. Genetic Diversity

Genetic diversity must receive increased attention in breeding programs to reduce the risks of epidemics in genetically uniform material. Research in nonnuclear inheritance needs to be expanded and accelerated.

3. International Cooperation

The value and fruits of international cooperation in plant disease research were emphasized 20 years ago by Rodenhizer (1962). In the 70s international disease nurseries contributed to progress in the identification, exchange and utilization of stable disease resistant material. However, there is room for substantial expansion in this activity. There is need for (a) more cooperators in national programs, (b) improvement in the management of the nurseries and the recording of data, and (c) the inclusion in the test entries of material submitted by national programs.

Another area of international cooperation is the development of cooperative research projects. In many countries, limited resources, lack of trained manpower or lack of a screening opportunity due to environmental factors or quarantine regulations prevent the execution of a comprehensive research program. Scientists in such countries should cooperate with scientists in other countries in order to find solutions to mutual problems.

4. Interdisciplinary Team Effort

Disease control is inseparable from the total production system of a crop. Many of the measures of disease control represent a relatively small proportion of the many factors involved in growing a crop. Disease control alone will not increase and stabilize yield; other yield limiting factors need to be considered simultaneously. Accordingly a sound research program on disease control should be a team effort of pathologists, entomologists, breeders, geneticists, physiologists, soil scientists, and socioeconomists. A working relationship with farmers who are ultimately responsible for the implementation of disease control measures is also essential.

5. Training

The skilled manpower bottleneck is a major constraint to the development and adoption of modern agricultural technology in the developing countries. This point was driven home in a more sensational way by Paddock (1967) when he said, "Do not expect an agricultural revolution in the hungry world—there is no one to lead the revolution." At the "Sorghum in Seventies" symposium King (1972) urged that more indigenous plant pathologists be trained to conduct research which was at that time neglected or done by expatriates on a temporary basis. At the beginning of the 1980s the situation is certainly not better and is perhaps worse than in 1971. With the exception of India and the USA, there is a critical shortage of sorghum pathologists. The increase in the number and activities of national sorghum improvement programs has meant that the few trained pathologists are not sufficient. In the 80s, training of national research and technical staff in sorghum pathology should receive top priority.

Conclusion

Over 10 years ago, Paddock (1967) made a plea for "new, more imaginative disease control methods specifically for the needs of the developing world" where the greatest need exists for increased and stable food production. This plea is still valid today. The 1980s will require a critical evaluation of disease problems and innovative strategies for their control.

References

AGRAWAL, S. C, and KHARE, M. N. 1978. Chemical control of seed-borne pathogenic fungi of jowar. Pesticides 12:25-26.

ANAHOSUR, K. G., RAJASHEKHAR, B. G., and GOUDREDDY, B. S. 1977. Effect of nitrogenous fertilizer on the incidence of charcoal rot of sorghum. Sorghum Newsletter 20:23-24.

BAILEY, G. W., and WADDELL, T. E. 1979. Best management practices for agriculture and silviculture: an integrated review. *In* Best management practices for agriculture and silviculture, eds. Loehr et al. Ann Arbor, Michigan, USA: Ann Arbor Science Publishers Inc. 740 PP-

BAKER, K. F., and COOK. R. J. 1974. Biological control of plant pathogens. San Fransisco. California, USA: Freeman. 433 pp.

BALASUBRAMANIAN, K. A. 1973. Influence of nitrogen and phosphorus fertilizers on the expression of downy mildew of sorghum. Plant and Soil 38:477-479.

BALASUBRAMANIAN, K. A. 1974. Role of date of seeding, soil moisture, temperature and pH in the incidence of downy midlew of sorghum. Plant and Soil 41 :233 -241.

BIOARI, V. B., SATYANARAYAN, H. V., and HEGDE, R. K. 1978. Effect of fungicides against the seed rot and seedling blight of hybrid sorghum CSH-5. Mysore Journal of Agricultural Sciences 12:587-593.

BROWNING. J. A., and FREY, K. J. 1981. The multiline concept in theory and practice *In* Strategies for the control of cereal disease, eds. J F. Jenkyn and R. T. Plumb. Oxford, UK: Blackwell Scientific Publications. 219 pp.

CHINNADURAI, G. 1971. The role of fertilizers on the incidence of sugary disease of sorghum. Tropical Agriculture, Trinidad 48 : 51 -53.

DOUPNICK, B. JR.. and BOOSALIS. M. G. 1975. Ecofallow reduces stalk rot of sorghum. Phytopathology 65: 1021-1022.

EDMUNDS, L. K. 1975. Sorghum disease problems and programs in North America. *In* Proceedings, International Sorghum Workshop, 7-11 January, University of Puerto Rico, Mayaguez, Puerto Rico. 592 pp.

FREDERIKSEN, R. A., and ROSENOW, D. T. 1979. Breeding for disease resistance in sorghum. *In* Biology and breeding for resistance to arthropods and pathogens in agricultural plants, ed. M. K. Harris. College Station, Texas, USA: Texas A&M University.

FREDERIKSEN, R. A., and ODVODY, G. 1979. Chemical control of sorghum downy mildew. Sorghum Newsletter. 22:122.

GANGADHARAN, K., SUBRAMANIAN, N.. MOHANRAJ, D., KANDASWAMY, T. K., and SUNDARAM, M. V. 1976. Efficiency of fungicides in the control of foliar diseases of sorghum. Madras Agricultural Journal 63:413-414.

GRIFFITHS, E. 1981. Latrogenic plant diseases. Annual Review of Phytopathology 19:69-82.

HANSING, E. D. 1970. Control of seed-borne fungi with systemic fungicides. Proceedings of the International Seed Testing Association 35:815-820.

HOOKER, A. L. 1974. Cytoplasmic susceptibility in plant disease. Annual Review of Phytopathology 12:167 -179.

HUBER, D. M. 1980. The role of mineral nutrition in defence. *In* Plant disease, an advanced treatise Vol. V, How plants defend themselves, eds. J. G. Horsfall and E. B. Cowling. New York. USA: Academic Press. 534 PP-

KING, S. B. 1972. Sorghum diseases and their control. *In* Sorghum in seventies, eds. N. G. P. Rao and L. R. House, New Delhi, India: Oxford and IBH Publishing Co. 638 pp.

MACER, R. C. F. 1975. Plant pathology in a changing world. Presidential address. Transactions of the British Mycological Society 65:351-374.

MISHRA, A., and SIRADHANA, B. S. 1978. Chemical control of anthracnose of sorghum. Indian Phytopathology 31:225-227.

MURPHY, L. S. 1975. Fertilizer efficiency for corn and sorghum. Pages 49-72 *in* Proceedings, Thirtieth Annual Corn and Sorghum Research Conference.

NAIK, S. M., SINGH, S. D., and SINGH. B. P. 1976. Effect of nitrogen fertilization on the incidence of the leaf spot diseases of sorghum. Indian Journal of Mycology and Plant Pathology 61:145-147.

PADDOCK, W. C. 1967. Phytopathology in a hungry world. Annual Review of Phytopathology 5:375-389.

PAWAR, N. B.. and PATIL, B. P. 1978. Fungicidal control of *Helminthosporium* leaf spot of hybrid jowar. Journal of Maharashtra Agricultural Universities 3:178-179.

PLUCKNETT, D. L, EVENSON, J. P., and SANFORD, W. G. 1970. Ratoon cropping. Advances in Agronomy 22: 285-330.

PRIESTLEY, R. H. 1981. Choice and deployment of resistant cultivars for cereal disease control. *In* Strategies for the control of cereal disease, eds. J. F. Jenkyn and R. T. Plumb. Oxford, UK: Blackwell Scientific Publications. 219 pp.

RAO, N. G. P., VIDYABHUSHANAM, R. V., RANA. B. S., JAYAMOHAN RAO. V., and VASUDEVA RAO. M. J. 1980. Breeding sorghums for disease resistance in India. Pages 430-433 *in* Proceedings, International Workshop on Sorghum Diseases. ICRISAT, 11-15 Dec 1978, Hyderabad, India. Patancheru, A.P., India: ICRISAT.

REUVENI, M., EYAI, H., and COHEN, Y. 1980. Development of resistance to metalaxyl in *Pseudoperonospora cubensis.* Plant Disease 64:1108-1109.

ROOENHISER, H. A. 1962. Prospective fruits of international cooperation in tropical plant pathology. Phytopathology 52:950-953.

SINGH, D. S., and PAVGI, M. S. 1977. Field evaluation of some fungicides and antibiotics for the control of rough and zonate leaf spot diseases of jowar. Indian Journal of Plant Protection 5:21-28.

SUMMER, D. R., DOUPNIK, B. J. R., and BOOSALIS, M. G. 1981. Effects of reduced tillage and multiple cropping on plant diseases. Annual Review of Phytopathology 19:167-187.

TARR, S. J. 1962. Diseases of sorghum, sudan grass and broom corn. Kew, Surrey, England: The Commonwealth Mycological Institute. 380 pp.

TATUM, L. A. 1971. The southern corn leaf blight epidemic. Science 171:1113-1116.

TULEEN, D. M. FREDERIKSEN, R. A., and VUDHIVANICH, P. 1980. Cultural practices and the incidence of sorghum downy mildew in grain sorghum. Phytopathology 70 : 905-908.

VENUGOPAL, M. N., and SAFEEULLA, K. M. 1978. Chemical control of downy mildews of pearl millet, sorghum and maize. Indian Journal of Agricultural Science 48:537—539.

WILLIAMS, R. J. 1976. The objectives and proposed activities in cereal pathology. ICRISAT, Hyderabad, India. 27 pp.

WILLIAMS, R. J., FREDERIKSEN, R. A., MUGHOGHO, L. K., and BENGTSON, G. D. (eds.) 1980. Proceedings of the International Workshop on Sorghum Diseases, ICRISAT, 11-15 Dec 1978, Hyderabad, India. Patancheru, A.P., India: ICRISAT. 469 pp.

Session 3 Factors Reducing Sorqhum Yields Diseases

J. Craig* Discussant

Dr. Frederiksen has presented a comprehensive survey of sorghum disease problems, their relative importance, and the current state of sorghum disease research. His remarks on the difficulty experienced in deciding the relative importance of these disease problems illustrate a major weakness in our disease programs. We are not able to translate our observations on the occurrence and severity of a disease into numerical statements of yield reduction.

As Dr. Frederiksen noted, the interest in a disease is often determined by the visibility of the symptoms rather than the magnitude of yield reduction. As a result, research funds and personnel are not used to best advantage.

There is an urgent need for research on disease loss assessment in sorghum. Some research efforts have been conducted, but obviously this has not been a popular choice of endeavor among sorghum pathologists (Bockholt and Toler 1968; Tuleen et al. 1980). Various models and methodology for assessing crop disease losses have been proposed (Burton and Wells 1981; James 1974; Madden et al. 1981), but experimental data are needed to test the applicability of these models to sorghum diseases.

Standard approaches for determining yield loss caused by disease are the use of chemical pesticides to secure healthy plants for yield comparisons, and the use of isogenic lines for yield comparisons between genotypes which differ only in reaction to disease. Both methods have defects. Chemical pesticides may affect plant yield in the absence of disease, and the production of isogenic lines is costly in terms of time and effort.

Recently, Burton and Wells (1981) proposed a method of assessing disease losses in millet that should be applicable to sorghum. In this method, the F_2 generation of a cross of susceptible and resistant genotypes is exposed to the disease under study. Under disease attack, the F_2 population exhibits a range of disease reactions which can be used to determine the effects of disease on yield. This seems to be a solution to this problem.

The variations in virulence found in some sorghum pathogens are serious problems. The threat posed by new races of head smut is well known (Frederiksen et al. 1969). Recently similar variabilities for pathogenicity have been noted in anthracnose and sorghum downy mildew (Corrales 1980; Craig and Frederiksen 1980). Information on the potential variability of virulence in sorghum pathogens will be of value.

Dr. Mughogho in his paper on disease control strategies has presented a detailed survey of the current situation on disease control in sorghum and identified areas which should be given attention in the future. As Dr. Mughogho stated, host resistance is the only practical means of control of many sorghum diseases.

The long-term success or failure of a disease control program based on host resistance is determined by the ability of the pathogen to produce new, virulent biotypes. Sudden and complete loss of resistance to new biotypes of the pathogen is characteristic of monogenic or oligogenic types of resistance. These types of resistance are favored in sorghum breeding programs, because they are easily recognized and easily utilized by breeders. However, greater preference must be given to polygenic types of

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resistance if we are to improve the stability of disease resistance in sorghum.

Programs for the identification and utilization of resistant sorghum genotypes have been very successful. However, these programs have done little to increase our knowledge of the genetic factors involved.

If we are to advance beyond the current empirical approach to the use of disease resistance, we must have more information on the number of, and relationships among, factors determining the inheritance of disease resistance.

Dr. Mughogho has pointed out that the use of metalaxyl, an extremely effective control agent for the downy mildews, on cucurbits has resulted in the development of a strain of *Pseudoperonospora cubensis* resistant to this fungicide. It is probable that the indiscriminate use of metalaxyl to control sorghum downy mildew will result in the development of resistant strains of *Peronosclerospora sorghi.* Metalaxyl should be used only on sorghums resistant to downy mildew. This would serve to control virulent new biotypes of the pathogen, with little risk of developing a metalaxyl resistant strain, because the development of a pathogen biotype combining resistance to metalaxyl and virulence to the resistant genotype would require two simultaneous changes in the pathogen.

The possibilities of biological control of sorghum diseases should be given serious consideration. Microbial antagonists and parasites of many of the causal agents of sorghum diseases abound. If the present equilibrium in these relationships could be tilted against the sorghum pathogens, a valuable weapon would be added to our arsenal for control of sorghum diseases.

References

BOCKHOLT. A. J„ and TOLER, R. W. 1968. Effect of maize dwarf mosaic on grain sorghum. Texas Agricultural Experiment Station Progress Report PR-2509.

BURTON, G. W.. and WELLS, H. D. 1981. Use of near-isogenic host populations to estimate the effect of three foliage diseases on pearl millet forage yield. Phytopathology 71:331-333.

CORRALES, M. A. 1980. Variation in pathogenicity of *Colletotrichum graminicola* (Cesati) Wilson, and in symptom expression of anthracnose of *Sorghum bicolor* (L) Moench. Ph.D. thesis, Texas A&M University, College Station, Texas. 122 pp.

CRAIG, J., and FREDERIKSEN, R. A. 1980. Pathotypes of *Peronosclerospora sorghi.* Plant Disease 64 : 778-779.

FREDERIKSEN, R. A., ROSENOW, D. T., REYES, L, and EDMUNDS, L. K. 1969. A new race of *Sphacelotheca reiliana* in south Texas. Plant Disease Reporter 53 :171 -172.

JAMES, W. C. 1974. Assessment of plant diseases and losses. Annual Review of Phytopathology 12 : 27-48.

MADDEN, L. V., PENNYPACKER, S. P., ANTLE, C. E., and KING SOLVER C. H 1981. A loss model for crops. Phytopathology 71 : 685-689.

TULEEN, D. M., FREDERIKSEN, R. A., and VUDHIVANICH, P. 1980. Cultural practices and the incidence of sorghum downy mildew in grain sorghum. Phytopathology 70: 905-908.

Session 3 Factors Reducing Sorghum Yields Diseases

Discussion

Srivastava

Dr. Safeeulla, would you like to make any comments?

Safeeulla

In India more than 80% of the sorghum area cultivated is sown to traditional varieties. In these varieties, sorghum downy mildew is still the number one disease. However, grain mold is the most important disease in newly introduced cultivars. Most downy mildew resistant cultivars are becoming more susceptible. Cultivars which were once resistant like IS-148, CSH-5 etc., now show up to 30% disease incidence. It is therefore suggested that a monitoring service to forecast the performance of a cultivar be started. At Mysore in India, it was possible to give such information after testing a few hybrids and cultivars constantly ten to twelve times in a year where the disease incidence in the downy mildew sick plot is very high throughout the season. My suggestion, therefore, is to locate such sites and obtain information which would be helpful for breeders and pathologists.

I agree with Dr. Craig that the control of sorghum downy mildew using both resistant lines and chemical seed treatment should be used. Ridomil as a seed treatment is very effective in controlling sorghum downy mildew. However, the trend is towards the development of resistance to this chemical. Now Ciba-Geigy has recommended new formulations containing other effective fungicides in addition to Ridomil (active ingredient).

Garud

Efficient screening techniques are important for screening sorghum against diseases. Equally important, perhaps, is the grading system used which must be correlated with yield losses.

K. N. Rao

Looking back at sorghum pathology in the seventies, excellent progress has been made in grain molds, downy mildew, anthracnose and head smut, in terms of developing reliable screening techniques, screening of large numbers of germplasm and breeding material, and identification of a reasonably good level of resistance in sorghum. While breeders are busy in developing elite and resistant lines for these diseases, the sorghum pathologists should devote all out efforts during the eighties on charcoal rot, grey leaf spot and sooty stripe as we know very little of these now. These are potentially very important diseases limiting sorghum production all over the world.

Scheuring

I would like to further dampen the optimism concerning the use of metalaxyl in the semi-arid tropics. Over the past 3 years, we have seen the phytotoxic effect of metalaxyl in the presence of seedling drought. We have seen up to a 70% stand loss in fields planted with metalaxyl treated seed. In the laboratory we have observed decreasing formation of root hairs with increasing dosage. The recommended Ciba-Geigy dosage of 7.5 g product per kg seed results in over 75% seedlings having inhibited root growth.

Williams

I would like to say a few words in support of the much maligned oligogenic or vertical resistance. Oligogenic resistance per se is not bad, the way it is used is bad. If a single resistance gene is isolated and used it is not likely to provide durable resistance to a variable pathogen. However, there are strategies for the use of oligogenic resistance that are much more likely to provide stable resistance, e.g., multilines, pyramiding *or* sequential use. To do this, we need clear information on the genetics of resistance. So I suggest that an important activity of the next few years is the joint study, by breeders and pathologists, of the varieties identified as resistant, in order to identify and isolate resistant genes so that they can be used in a planned strategy.

Morris

When it comes to the question of the use of insecticides or fungicides in farmers' fields there is a need for economic studies of the value of yield loss, losses from the sale of moldy grain so that we can provide an economic basis for research priorities, and also for what farmers could afford to pay for treatment (until host resistance is developed).

Parameswarappa

Ridomil is an excellent fungicide but unfortunately is not available in India. Therefore, identification of, and research on, this chemical has just remained a matter of academic interest. In the eighties more efforts are necessary to identify more-effective, less-expensive and easily-available chemicals to control diseases. This also applies to insecticides like Carbofuran which is recommended by entomologists for control of shoot fly. However, its cost is so high that a common farmer cannot apply this chemical.

Prasad

1. A parent of QL-3 was originally developed at Coimbatore by Krishnaswamy and his group.
2. QL-3 shows some symptom of downy mildew. It is not 100% resistant but gives up to 6 to 8% infection.
3. QL-3 cannot be used directly as one of the parents as its combining ability is poor.

Safeeulla

QL-3 is a highly resistant cultivar—the best we have so far. Some centers have reported susceptible reaction in QL-3 against downy mildew. This may be due to segregation from the use of unselfed seed. Some of the sister lines are showing susceptibility.

K. N. Rao

QL-3 was developed in Australia as an MDMV resistant source material and it was included in Texas A&M University's International Disease and Insect Nursery to ICRISAT in 1974. I made single plant selections out of the total population which were resistant to sorghum downy mildew. Progenies from these selections proved to be immune to sorghum downy mildew in multilocational testing.

Gowda

Two sources of downy mildew resistance (QL-3 and UchV-1) were studied for comparison of combining ability for disease resistance as well as yield and its .components; QL-3 is a better combiner for disease resistance whereas UchV-1 is a good combiner for yield and its components. Though QL-3 showed a higher frequency of resistant segregants as compared with UchV-1, all these segregants were poor for agronomic traits as well as grain color. As such, it is better to use UchV-1 instead of QL-3 in future breeding programs.

Kambal

Dr. Mughogho made a strong plea for training more African pathologists. My worry is how to keep those already trained. The loss of trained manpower in Africa is more alarming. With his consent, I would like to expand the recommendation to cover more training and encouragement of those trained to stay there. The efforts of IDRC in supporting national programs by providing facilities for research are commendable.

Galiba

As mold resistance is dynamic, often the varieties which are said to be resistant are found moldy because they have not been harvested in time. They are ripe and are subjected to the last rains. If they are sown later they do not terminate their cycle, and if sown earlier they become moldy. This has been the case with E35-1 which is known to be mold resistant.

Mughogho

The solution is to develop mold resistant cultivars. The ICRISAT Sorghum Pathology Program has identified good sources of resistance to grain molds among the red and brown seeded sorghums which breeders can utilize in developing mold resistant lines.

Sangitrao

Presently, the sorghum material supplied by International Centers for testing by collaborators in several countries is due to free seed exchange. Is it not possible that due to this, pathogens of minor diseases are travelling and multiplying in local conditions and may become important in the near future?

Mughogho

So far I am not aware of any disease that has been spread through international disease nurseries in which extreme care is taken to produce disease-free seeds. In addition, the seed of the nurseries pass through strict quarantine procedures before they are despatched to other countries.

Striga and Birds

Chairman: D. N. Srivastava
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Striga and Other Weeds in Sorghum

K. V. Ramaiah and C. Parker*

This paper considers the problem of the parasitic *Striga* spp (witchweeds) with particular reference to sorghum. Relatively little work has been carried out on this parasite and several gaps exist in our knowledge of this problem. In this paper an attempt is made to critically examine the available information and to focus on the possible future course of *Striga* research. It also considers more briefly the status of control measures for other nonparasitic weeds.

Striga—Species, Distribution, and Host Range

Striga asiatica (L) Kuntze (= *S. lutea.* Lour., *S. hirsute* Benth.)

This is the most widespread of the important species, centered on the Indian subcontinent, where it most often has a white flower, but extending into China and South East Asia where it more commonly has a yellow flower and where depauperate forms also occur with pink, mauve, or purple flowers. The white-flowered form extends westwards as far as South West Arabia (L. Kasasian, personal communication) while in Africa (mainly East and South) it is generally red. The species has a relatively wide range of wild grass hosts. The main distinguishing features from other major species include the slender, usually branched habit, up to 30 cm high, and the large number of ribs on the calyx at least 10 and sometimes more. Observation on strains from USA, Africa, India and Indonesia suggests that they are all autogamous (self-pollinated) hence tend to preserve the distinct morphological forms (Musselman et al. 1981).

Striga hermonthica (Del.) Benth (= *S. senegalensis* Benth.)

This is the major species of Africa stretching across a northern tropical belt from Senegal to Sudan extending eastwards into South West Arabia and south into Tanzania, Malawi, and Zimbabwe but it is generally less important than *S. asiatica* south of the equator, for reasons not fully understood.

Although quite variable morphologically, especially in the shape of the pink corolla there are no distinct morphological strains as occurring in *S. asiatica.* perhaps because of the need for outcrossing in this species (Musselman et al. 1981).

This species is usually more robust than *S. asiatica.* often up to 50 cm and occasionally 1 m high. The calyx has five ribs.

The host range is almost as wide as that of *S. asiatica* and there is evidence of some host specificity of physiological strains within the species, (Parker and Reid 1979).

Striga densiflora Benth.

This species is almost restricted to the Indian subcontinent attacking sorghum but it does also occur in South East Arabia. It has a white flower, but is rather more robust, less -branched and with a more dense inflorescence than *S. asiatica.* Calyx ribs are five only.

A few less important species are S. *angustifolia* (Don) (= S. *euphrasioides* Benth), S. *aspera* (Willd.) Benth. and *S. forbesii* Benth.

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Striga—Biology

Germination

With the exception of S. *angustifolia* which can possibly establish without the aid of a host, the *Striga* spp of agricultural importance are all obligate parasites in that the seeds are only 0.2 to 0.4 mm long and can only produce a radicle up to 5 or 10 mm before seed reserves are exhausted. They must, therefore, become attached to a host root within a few days of germination. To ensure that a host root is available, they normally germinate only in response to certain substances exuded by host roots. One natural stimulant, strigol, has been identified (Cook et al. 1972) but the work of Visser and Botha (1974) suggests that there is a wide range of stimulant compounds exuded by different crop species and it is not yet certain to what extent the species and strains of *Striga* vary in their response to all these compounds. Sorghum probably exudes strigol itself but this has not been positively confirmed.

Other requirements for germination include: (a) after-ripening—many collections of seed are not readily germinated by whatever means for several months after harvest, yet at least one strain of *S. hermonthica* from Abu Naama, Sudan has given high germination" within 3 months of collection; (b) imbibition for at least a week before exposure to stimulant—this is often referred to as "pretreatment", "conditioning" or "preconditioning". Reid and Parker (1979) found in the laboratory that with a range of strains of *S. asiatica* and S. *hermonthica* the optimum period of imbibition varied from 1 to 5 weeks and that S. *asiatica* responds better to conditioning at 33°C than at 23°C, while the converse is true for *S. hermonthica.* The biochemical processes occurring during conditioning are not yet fully understood, but an important discovery has been that conditioning in the presence of germination stimulant reduces the subsequent germination (Hsiao et al. 1979, Pavlista et al. 1979). Vallance (1950) showed that prolonged imbibition results in a steady decline in germination ("wet dormancy") of S. *hermonthica.* Reid and Parker (1979) confirmed this phenomenon with several strains of *S. hermonthica.* The importance of this phenomenon in the pattern of development of *Striga* infestations in the field needs a great deal more study; (c) a suitable germination temperature, which is relatively high for both species. Detailed work has not been done on many strains but Reid and Parker (1979) show a sharp fall in germination percentage below 30°C for both *S. hermonthica* and *S. asiatica.*

Attachment to the Host Plant

Once triggered by the stimulant, germination occurs very rapidly, within 24 hours; and the radicle extends. In the absence of a host root, however, no further development normally occurs. A very recent report by Reddy and Rao (1980) indicates some plumular and "colleter" development in vitro in *S. asiatica.* but it is now confirmed that the seeds were of *S. angustifolia* and not S. *asiatica.* On contact with a host root the tip of the radicle swells and produces root hairs. Nickrent et al. (1979) have shown that this response can be initiated in *S. asiatica* by an extract of gum tragacanth (a substance isolated from *Astragalus* spp). They report that S. *asiatica* in USA normally fails to form haustoria on the roots of a nonhost such as *Phaseolus vulgaris,* but if provided with such a haustorial factor there is normal haustorial development, attachment and parasitization. Lynn et al. (1981) have now isolated an active substance "xenognosin" from gum tragacanth. The extent to which iiphaustorial factors are involved in host specificity is an area deserving much further study, though it does not so far appear to be involved in the resistance mechanisms of sorghum varieties.

The penetration of the host root by the haustorium appears to occur by an enzymic process although once the penetration has occurred, the cortex is conspicuously split by expansion of the haustorial "peg". Anatomical studies show direct linkage of the xylem systems of host and parasite but no direct linking of phloem to phloem. When first attached, the *Striga* is totally parasitic and requires sugars from the host but whether it obtains all these from the xylem or through some bridging tissue from the phloem is not certain. Apart from sugars the parasite also depends on cytokinins from the host for normal development of the plumule (Yoshikawa et al. 1978), but once that has been triggered, the work of Okonkwo (1966) suggests that it is only water, sugars and inorganic minerals that are required. The parasite once attached, very soon produces adventitious roots which ramify extensively. The ability of these roots to absorb water or minerals direct from the soil is doubtful as root hairs are only formed at the points of contact with host roots.

prior to the development of secondary haustoria (closely resembling the primary attachment).

Effect on the Host

The effect of the parasite on the host is out of all proportion to the amount of carbohydrate that is removed. Unpublished Weed Research Organization (WRO) work has shown that when the total dry weight of *S. hermonthica* "seedlings" on a sorghum root system is less than 1 % of the total dry weight of the host, the host dry weight may be reduced by as much as 25%. This reduction in host weight is almost all in the shoot, the root development of the host often being significantly increased, at least initially, before reduced shoot growth eventually results in gross reduction of the whole plant system.

It is common for the host to be significantly reduced in height and vigor even before any *Striga* has emerged from the soil. These effects, particularly on stem elongation, are common to both S. *asiatica* and S. *hermonthica,* but other symptoms are quite different. *S. asiatica* causes a pronounced wilting of its hosts, even under wet soil conditions, while *S. hermonthica* rarely causes wilting but instead produces chlorotic blotches on the foliage.

Drennan and El-Hiweiris (1979) looked to determine whether the stunting of sorghum shoot systems by S. *hermonthica* might be the result of a change in growth regulator balance in the infected plants. They confirmed a dramatic reduction in the cytokinins and gibberillins in xylem sap exuding from cut host stems and a significant increase in the inhibitors ABA and farnesol. It appeared that most of the damaging effects would be due to this imbalance in the host's own growth substances and need not involve any transfer of toxin from parasite to host, other than perhaps a substance triggering the host's drought response system. It was notable that subjection of the sorghum to drought stress elicited almost identical changes in the growth regulators. No corresponding work has been done with S. *asiatica.*

These effects can result in severe reduction in sorghum yield, even causing total crop loss where the infestation is heavy and occurs early. Conversely light infestation may cause only minor loss. Although some damage is done before *Striga* emergence, Ogbom (1972a) has shown that removal of emerged *Striga* can be beneficial and lead to increased yields. It is also observed that sorghum varieties vary in their tolerance of *Striga,* apparently equal infestation causing much less damage to some varieties than to others. Variety 1499 is regarded as such a "tolerant" variety in Nigeria (Ogbom, personal communication) and CE90 in Upper Volta.

Factors Influencing Severity of Attack

The distribution and severity of *Striga* infestation in the field is influenced by a number of climatic, soil and cultural factors, notably:

Soil Moisture

Striga appears to thrive on intermittent dry conditions and is conversely suppressed by continuous soil moisture as occurs during the peak rainy season in Northern Nigeria (Ogbom 1972b). This is perhaps a result of "wet dormancy" but may be because of lower soil temperatures, dilution and /or leaching of root exudates, increased fungal attack or possibly because of reduced photosynthesis and hence reduced vigor of root growth. As expected, irrigation generally reduces or prevents *Striga* infestation but in Sudan some strains of S. *hermonthica* do continue to cause some problem in spite of irrigation.

Soil Fertility

Low fertility also encourages *Striga,* particularly low nitrogen status. Conversely high N helps to suppress the weed. Again it is not known which of a complex of possible mechanisms is mainly responsible for this effect. The possibilities include: a reduction in stimulant exudation (shown by Teferegan 1973); a change of host physiology resulting in reduced susceptibility to attachment; the reduced vigor of the *Striga* radicle (A. H. Pieterse, personal communication); a reduced root/shoot ratio accompanied by reduced flow of photosynthates to the root; or increased leafiness of the crop resulting in qreater shade and lower soil temperature.

Crop Rotation

Inevitably a succession of susceptible sorghum crops under soil and climatic conditions favorable to *Striga* results in a buildup of infestation. Any rotation with resistant crops (provided there is removal of wild hosts of *Striga)* will interrupt this buildup and crops exuding stimulant may act as "trap crops" to accelerate the natural depletion of seed in the soil (see below).

Striga—Available Control Measures

Physical Control

Hand-pulling at too early a stage may result only in breakage of the shoot below the soil and rapid regrowth. It may also reduce the competition between *Striga* plants on the host root system and result in greatly increased emergence (Ogborn 1972a). Dense infestations are not practical to hand-pull but sparse infestations (particularly newly discovered ones or residual populations after use of other control measures such as herbicide or resistant cultivars) should be hand-pulled shortly before flowering to protect yield and to prevent buildup of seed. Such hand-pulling should continue through to harvest and beyond so long as flowering is occurring. *Striga* can continue to survive, mature and set seed for several weeks after the death of the host shoot. Once the crop is harvested, pulling the crop stubble will help to prevent continued growth of the parasite.

Cultural Control

Short-term "cultural" measures which may result in immediate reduction of *Striga* infestation include:

Irrigation

Almost certain to be effective but rarely available.

Nitrogen

Even when available it may not be certain that nitrogen will give an economic response. Much will depend on rainfall and soil characteristics including the status of other nutrients. The exact timing and form of N are not believed to be critical, the essential being simply that the crop absorbs it and responds. The quantity required is difficult to define. Almost any N should result in some benefit but the increased vigor of the host may eventually result in increased *Striga* emergence. Only with dense planting and shading of the soil. or very high levels of N will emergence be prevented altogether.

Time of Planting

There is rarely much choice in the time of planting but in some areas infestation can be avoided or reduced by: (a) planting early to establish the crop before temperatures are high enough for *Striga* (e.g., in Southern Africa); (b) planting late when rains become more continuous, so avoiding the intermittent drying cycles which favor *Striga* (Ethiopia, personal observation).

Long-term cultural measures tending to reduce seed production and a buildup of *Striga* populations include:

Crop Rotation

Any rotation into a nonhost crop (kept free of wild grass hosts) will tend to reduce the *Striga* problem, but there are a number of crops known as "trap-crops" which are more positively beneficial in stimulating *Striga* seeds to germinate without themselves being parasitized. Crops claimed to be effective include: linseed, cotton, sunflower, cowpeas, groundnut, castor bean, millet, dolichos bean, velvet bean.field peas, but it is not certain that both *S. asiatica* and *S. hermonthica* will respond in the same way and results reported by Parker and Reid (1979) suggest that different strains of *S. hermonthica* may differ in their response to some of these trap-crops.

Unfortunately once a severe infestation has developed it may take many years, even with trap-crops, to reduce the population to non-damaging levels. In USA, Robinson and Dowler (1966) found millet *(Pennisetum americanum)* the most effective for S. *asiatica* but only after 2 years were yields of a susceptible crop significantly improved. With soybeans, sorghum and field peas, 3 or 4 years were needed and Doggett (1965) found that it took 5 years for infestations to be effectively reduced in Uganda, using sorghum itself and preventing new seed by hand-pulling.

While not readily effective in controlling established infestation, rotation may well be useful in preventing the buildup in the first instance and to improve the soil fertility status (Upper Volta, personal observation). The relative unimportance of *Striga* in Senegal could perhaps be attributed to the regular alternation of sorghum with groundnut, while Ogborn (personal communication) has indicated the benefit of growing sorghum only every fifth year as a sole crop, rather than as a one-fifth component of a crop mixture every year.

Sorghum itself can be grown before the main crop as a "catch crop", which is then destroyed after a few weeks together with any developing *Striga* but this technique is applicable only where the rainy season is long enough (or irrigation is available)

Biological Control

Greathead and Milner (1971) suggested that there were organisms worth considering for "classical" biological control—East African *Smicronyx* and *Ophiomiya* species which might be tried in India and conversely *Eulocastra argentisparsa* could be tried in Africa. Several attempts have been made to establish *E. argentisparsa* in Ethiopia (T. Crowe, FAO, personal communication) but the results are not known.

More recently we have observed severe damage to *S. hermonthica* in West Africa, from a complex of insects, predominantly the gall-forming *Smicronyx* spp. It is doubtful whether these insects can be exploited within the region, but as they are causing significant reduction in seed production at present, any reduction in their abundance by insecticide use could be detrimental. Most recently the butterfly *Precis orithya* Swinhoe has received attention both in South East Asia (Boonnitee 1977; Mangoendihardjo and Soerjani 1978) and in USA (L. J. Musselman, personal communication). The larvae have a voracious appetite for *Striga* foliage but their specificity to *Striga* species has yet to be confirmed.

Chemical Control

Fumigants

Methyl bromide is used on a local basis in the USA at about 200 kg/ha but owing to its very high cost, it is appropriate only to the intensive eradication program in that country, or to the establishment of clean plots for experimental purposes.

Herbicides

A very large number of herbicides have been tested in the USA and a number are used in various ways in the *Striga* eradication program (Langston et al. 1979). The most important is 2,4-D sprayed twice as a postemergence directed treatment in maize to kill emerged plants and prevent seed production. Oxyfluorfan as an early postemergence directed spray has been shown to be effective in preventing *Striga* emergence but it does not necessarily prevent attachment to the roots below the herbicide layer and the crop may still suffer *Striga* damage. Paraquat and glyphosate may be used as late directed treatments to kill late emerging plants. A number of other herbicides are used to kill *Digitaria sanguinalis* and other weed hosts in rotational crops.

Elsewhere 2,4-D has proved moderately effective in Sudan and in India (Yaduraju and Hosmani 1979). Under ideal conditions an early post-emergence treatment may help to prevent *Striga* germination and attachment. Generally it is only effective in killing emerged parasites which have already had some damaging influence and so does not completely eliminate the effect of the parasite. It can. however, greatly alleviate the damage, and should probably be exploited much more widely than it is at present.

Ogborn, working with mixed crops where 2,4-D is not safe, has found spot applications of ametryne, bromoxynil and linuron to be effective substitutes to 2.4-D (Ogborn 1972a).

Attempts to find more perfectly selective chemicals, either soil applied or translocated through the host, have not so far been successful.

Germination Stimulants

There have long been hopes of achieving complete control of *Striga* by triggering its suicidal germination. The greatest success in this so far has been achieved with ethylene in USA. A single application of 1 -2 kg/ha has resulted in over 80% reduction in viable seed in the soil (Eplee 1975). This treatment is now being used regularly on many thousand hectares each year to accelerate the eradication process and it can perhaps be regarded as the single most successful of all direct control measures. There have been no reports of direct comparison with catch-cropping, but it appears probable that ethylene treatment provides a more complete effect perhaps because the gas can penetrate the full soil profile and if timed correctly will reach and influence a very large proportion of seeds—only those in the soil surface tending to escape. It can either be used in a rotational break crop, or around the time of sowing the susceptible crop, so removing the need for rotation. Although Chancellor et al. (1971) have reported the effectiveness of ethephon on S. *hermonthica* there are as yet no reports of the use of ethylene on this species in the field. Unless it proves to be significantly less active on this species, ethylene must be regarded as a very important control option. Although relatively sophisticated equipment is needed, the chemical cost is relatively low and treatment could be provided as a government service. Alternatively farmers could possibly treat their own land by hiring a "back pack" injector (Eplee and Langston 1976).

Strigol, the natural stimulant which has now been synthesized on a small scale, is likely to be much too expensive to apply in the field. Johnson et al. (1976), however, reported on the synthesis of simpler analogues (especially GR7 and GR24) which have a greater chance of being economic. Work published so far, while showing significant stimulaion of *Striga* germination in the field and occasional benefits in terms of reduced infestation and/or increased yield, have not compared well with ethylene. There has been no commercial development yet and with the increasing costs of toxicological and environmental testing, their future is uncertain. If they are to be used to best effect, the timing of application may be critical, depending on their residual life in the soil and the danger, noted above of *Striga* germination being reduced where the stimulant has been present during the conditioning period.

Crop Seed Treatment

"Hardening" of sorghum seeds in solutions of phenolic acids resulted in reduced stimulant exudation by the seedlings, and thus could confer increased resistance (Bharatalakshmi and Jayachandra 1980). The technique involves repeated imbibition and drying of the seeds. Unfortunately there is no further report on this work and attempts to repeat it (WRO. unpublished) have not been successful.

Host Resistance

Though some control methods as described above are available they have not become popular at the subsistence farmers' level either because they are not practicable or are very expensive. Resistant crop cultivars on the other hand require no costly inputs. As *Striga* incidence is influenced by soil type, fertility and rainfall-host resistance is not just the result of interaction between the host and *Striga,* but also of their independent interactions with the climatic factors. This is further complicated by the presence of physiological strains within *Striga.* A knowledge of physiological strains has a very important bearing in developing broad-spectrum stable resistant cultivars.

Physiological Strains of *Striga*

Tremendous variability exists within *Striga* as indicated by the variation in germination and pretreatment requirements and interactions wih nonhost factors. Our observations over the last several years confirm that both *Striga asiatica* and S. *hermonthica* have strains which are specific to different crops (intercrop specific strains) and strains within different crops (intracrop specific strains).

The intercrop specificity is mainly observed between sorghum and millet crops. Broadly speaking, a *Striga* strain (irrespective of whether it is *S. hermonthica* or *asiatica)* which attacks sorghum, does not attack pearl millets and vice versa. Pearl millet strains of *Striga asiatica* in Rajasthan (northwestern India) do not attack sorghums whereas the sorghum strains of *S. asiatica* in South India do not generally attack millets. Similar observations *are* made on *Striga hermonthica* in Africa (Wilson Jones 1955; Zummo 1975; ICRISAT, unpublished). In the northern drier Sahelian zone of West Africa where pearl millets are predominantly grown, millet strains of *S. hermonthica* have been selected out which do not attack sorghum whereas in the northern Sudanian zone the reverse is true. Exceptions to this general observation are found depending upon the soil types and the intensity of a particular crop being grown in succession in a particular area.

ICRISAT unpublished results do indicate the presence of strains which can attack both sorghum and pearl milet in the transition zone of West Africa (around 13°N latitude) where the cultivation of sorghum and millet overlaps. We have also observed the presence of two different strains, one specific to sorghum, and another specific to millet in the same ecological zone of high rainfall Sudanian zone between latitudes 11° and 12°N. The distribution of strains of *Striga hermonthica* in West Africa along the North-South transect is very interesting though valid explanations are still awaited. A detailed examination of strains of *Striga* in relation to host crops and nonhost factors would be very valuable.

There is also evidence for intracrop specific strains in both the *Striga* species. *Striga asiatica* attacking sorghum in southern India has two different strains as indicated by the reaction of IS-5603 (ICRISAT. unpublished). It was highly resistant to a strain in Akola (Maharashtra State) but became susceptible to a Patancheru strain (ICRISAT Center). Similar observations were made by Bharatalakshmi and Jayachandra (1979) who reported significant differences between two samples of *Striga asiatica* collected from two different sorghum fields in Karnataka State in southern India.

In Upper Volta. intracrop specific strains were also observed within S. *hermonthica* but in view of the significant interactions between *Striga,* host and soil factors it is difficult to attribute all the variation in the behavior of a particular cultivar to variation within the *Striga* species alone. Detailed investigations need to be carried out to separate *Striga* strain effects from other factors to establish precisely the differences in physiological strains.

Resistance Mechanisms

As discussed in the section on Biology (above) there are several stages in the life cycle of *Striga* where the host can successfully interfere.

There are certain chemical factors (stimulants) that are required for *Striga* seed to germinate. Therefore, host cultivars which do not produce or produce very low quantity of the stimulant substance in their root exudate can avoid *Striga* attack. Sorghums which have resistance based on a low stimulant mechanism have been reported by several workers (Kumar 1940; Rao 1948; Williams 1959; ICRISAT 1977/78. p. 41).

After the germination of the *Striga* seed, the next major hurdle is its successful penetration of the host root tissue. The factors which interfere in this process are termed antihaustorial. These factors are highly sclerenchymatised endodermal cells, pericycle , silica crystals in endodermal cells and may be not yet identified chemicals present in the root-tissue (ICRISAT 1978, p. 40). Host cultivars with this form of resistance were identified by .Saunders (1933) working in South Africa, Doggett (1965) in East Africa and ICRISAT (1978. p. 40) in India.

Even though certain host cultivars allow successful establishment of *Striga* they do not further permit its normal growth and development. Attempts to identify this resistance mechanism in sorghum cultivars are not yet successful. ICRISAT preliminary results in collaboration with COPR (Centre for Overseas Pest Research) indicated the possible involvement of phenolic acids in the roots of certain *Striga* resistant sorghum cultivars. The role of host defence chemicals in several other diseases has been well established (Day 1974; Cowan 1978; Cartwright et al. 1977).

Field Screening Techniques

Field screening on naturally *Striga* infested fields gives less consistent results because of nonuniform distribution of *Striga* seeds in an experimental area. Deliberate artificial infestation of the experimental plots should lead to uniform *Striga* infestation. Creation of a sick plot is thus an important requisite for reliable and consistent results. Artificial infestation of the fields could be done several ways: broadcasting the seeds in the beginning of the season and incorporating them by plowing or sowing the *Striga* seed with a seed drill (tractor driven or hand pushed) in rows to be planted for the test material. Both these methods have given good results in India and in Upper Volta.

There are no studies to indicate the optimum plot size, number of replications, number of locations and number of seasons for reliable evaluation. Our experience shows that smaller plot size, fewer number of replications in each location and several such locations are desirable to guard against the likely failure of *Striga* emergence in some locations.

The criteria for evaluating the test material for *Striga* resistance are: number of emerged *Striga* plants, and yield and/or agronomic expression in a sick plot. The basis for selecting against *Striga* thus could be no or a low number of emerged *Striga* plants plus a higher yield.

Laboratory Screening Techniques

Simple laboratory techniques are very valuable in view of the difficulties encountered in field screening. A technique has been developed by Parker and Reid (1977) to identify low stimulant crop cultivars. The technique involves three steps: (a) pretreatment of *Striga* seeds at about

25°C for 10-14 days; (b) growing of host crop seedlings for one or two weeks in sterilized sand pots; and (c) germinating the pretreated *Striga* seeds with host root exudate in an incubator at 30-35°C for 24 hours. This is relatively simple, about 100 cultivars can be screened per week. At ICRISAT Center almost all the sorghum world collection has been screened and 640 low stimulant lines have been identified. Though they have been found to be low stimulant against a local strain of *Striga asiatica* (Patancheru, ICRISAT Center) they are being field tested in different African countries against *S. hermonthica.* A few lines have been identified as resistant in Ethiopia, Sudan, Upper Volta, and Ghana. Unfortunately most of them are very late maturing and photosensitive and have no immediate use. A breeding program thus has been initiated to correct certain undesirable traits.

Considerable progress has been made at ICRISAT Center to develop a laboratory technique for antihaustorial factors (ICRISAT 1978, p. 40). One cultivar, N-13, was identified as possessing this mechanism. The technique involves growing sorghum seedlings on moistened filter paper rolls, monitoring the primary root growth every day, inoculating the ready-to-germinate *Striga* seeds on root regions of different ages and establishment on the host root by a root clearing technique using aniline blue stain. With this technique it was shown that N-13 has developed resistance as its roots aged. A lot more refinement of this technique is required with temperature and humidity controls.

Resistant Sorghum Cultivars and Yield

As with resistance to other diseases, *Striga* resistance is mainly associated with very poor agronomic performance. This association between resistance and low yield and poor grain quality makes it difficult to improve them further. N-13 is the best resistance source available as of today followed by SPV 103 and SRN 4841. A red seeded cultivar, SRN 4841 of African origin has exceeded the yield level of local susceptible check. Another cultivar CE 90, although highly susceptible, yielded as much as a less susceptible cultivar like SRN 4841. This variety perhaps has tolerance which when combined with resistance is very valuable. Tolerance on its own is less desirable and less likely to solve the *Striga* problem in the long run since it permits *Striga* to multiply. A breeding program, therefore, is in progress to combine these two mechanisms, so that by virtue of resistance, *Striga* numbers are brought down and by tolerance, the damage to the host by relatively few *Striga* plants supported by the host is minimized.

Inheritance of Resistance

In sorghum, inheritance of *Striga* resistance has not been fully understood. Saunders (1933) working in South Africa reported that field resistance to S. *asiatica* in two out of three crosses studied was recessive and in a third was partially dominant. Chandrasekharan and Parthasarathy (1953) reported in India the dominant nature of *S. asiatica* resistance, but Narasimha Murthy and Sivarama krishnaiah (1963) reported it to be recessive. It appears that the nature of gene action varies with the parents involved in crossing. Three out of the five parents studied by us have shown susceptibility as being dominant over resistance, whereas in one parent (IS 5603) the resistance was dominant and in another (IS 6942), it was partially dominant. The indication of the dominant nature of resistance in IS 5603 is very encouraging as it may be possible to get some resistant male parents (restorers) which can transmit resistance to hybrids. This is very valuable particularly in India and elsewhere where *Striga* is posing a serious threat to commercial hybrid production. In S. *hermonthica* also, the resistance was reported to be recessive and controlled by at least two genes (Obilana 1980). A similar picture emerged even when individual components of resistance were studied. The low stimulant form of resistance appears to be controlled by a recessive gene (ICRISAT 1978, p. 42). Future breeding efforts should include careful characterization of different resistance sources and determination of gene action.

Breeding Approach

The breeding strategy largely depends upon the nature of gene action of the trait concerned. The indications so far are that *Striga* resistance is controlled by a relatively fewer number of genes. Therefore a classical backcrossing program using "adapted" parents as recurrent parents should be worthwhile. Several of the resistant cultivars identified so far are in a very poor agronomic background and when crossed with adapted parents combine very poorly. Thus, the classical breeding program is tedious and time consuming. This is made more difficult with the problems encountered in field testing of the segregating generations. Simple laboratory techniques, if available, would be very valuable to identify the resistant plants/progenies in the early segregating generation of a cross.

Development of random-mating populations using male-sterile genes has also been recommended for sorghum improvement. This system eliminates the tedious and time-consuming hand emasculations. For *Striga* resistance, this scheme involves incorporating resistant genes and high-yielding genes into a random-mating population and allowing them to random mate for about three generations and then following an appropriate recurrent selection scheme. Recurrent selection with full-sib system with testing of full-sibs under *Striga* sick plot conditions may be worth attempting.

Weeds other than *Striga*

Major Weed Species

There are few weeds, other than *Striga.* that are particularly closely associated with sorghum and the range of species varies widely in different sorghum growing regions. The annuals include many broad-leaved and grass species but it is the grasses which almost certainly cause the greatest losses, being less easily removed by weeding practices whether traditional or chemical. A wide range of annual grasses occur in the semi-arid tropics, including *Eleusine, Dactyloctenum. Echinochloa, Setaria, Brachiaria, Digitaria* spp, etc. Where chemical methods are in use some others may achieve greater importance, especially *Rottboellia exaltata, Pennisetum* spp, (e.g., *P. pedicellatum. P. polystachion)* and *Sorghum bicolor* itself in the form of "shattercane", already an increasingly serious problem in USA and Australia. These are not adequately sensitive to the standard herbicide atrazine and require additional special treatments.

Perennials include grasses such as *Cynodon dactylon* and *Sorghum halepense,* sedges such as *Cyperus rotundus* and broad-leaved species such as *Convolvulus arvensis. Solarium eleagnifolium* and *Launaea comuta.* Although the last three are only of local importance, all these perennials present serious difficulties of control. Furthermore *S. halepense* can be of importance as an alternate host of sorghum midge, e.g., in USA (Pitre and Gourley 1980).

Mechanical and Cultural Control

The normal traditional methods include combinations of preplanting plowing, harrowing, hoeing, hand-weeding and interrow cultivation. Interrow cultivation is a technique perhaps less fully exploited than others as the crop is still so often not planted in rows.

For the rhizomatous perennial weeds (sedges and grasses) additional deep, dry-season cultivations are likely to be the most effective and economic wherever farmers have access to sufficient power. Without tractors, however, there is much greater difficulty.

Chemical Control

Standard herbicide treatments in the more developed sorghum growing areas are atrazine + propachlor. Atrazine is moderately tolerated by sorghum, but not as well as by maize and recommendations generally preclude its use on sandy or very light soils. Propazine is available in some areas as a substitute on some of these soils but is still not regarded as completely safe. Mixtures of terbutryne and terbuthylazine have been recommended for lighter soil situations and also where there are fears of residual carryover of atrazine or propazine. Linuron is also recommended to some extent for similar reasons in both USA and Nigeria.

Propachlor is relatively expensive and has to be used at moderately high doses (to provide the grass control which is often incomplete with atrazine alone). Alachlor and metolachlor are more active on weeds but although sometimes reported safe on sorghum (e.g., by Deuse and Hernandez 1978 in Senegal), they are liable to cause at least some damage under most conditions. Now, however, Ciba Geigy, through their associated seed companies are able to offer seed of certain varieties, treated with the herbicide safener cyometrinil (Ellis et al. 1980). This safener applied as a seed dressing at 0.15% by weight makes the crop more or less fully resistant to normal field doses of alachlor and metolachlor. Monsanto now have a comparable compound MON 4606 under development for the same purpose (Roeth 1980). These safeners, however.

have not yet been shown to help in control of shattercane owing to the limited susceptibility of the weed to alachlor, etc. Broad-leaved weeds not controlled by preemergence treatments may be treated with postemergence applications of 2,4-D or dicamba or various mixtures based on these compounds. Recommendations are usually for 0.25-1, and 0.12-0.25 kg/ha respectively as overall sprays 10-25 days after emergence or as later directed, interrow treatments.

A great many newer herbicides are under test especially in USA, and bifenox looks promising as a preemergence treatment.

Biological Control

Biological control is not available for any of the major weeds of sorghum with the possible exception of *S. elaegnifollum* for which the host-specific nematode *Nothanguina phyllobia* is looking very promising in the USA (Esser and Orr 1979).

A more detailed discussion of weed control in sorghum is given by FAO (1979).

Outlook for the 1980s

1. Development of reliable screening techniques for identifying *Striga* resistant cultivars both at laboratory and field level.
2. Development of broad-spectrum stable resistant cultivars with higher yields and good food quality. This should include indentification of different resistance sources (gene-identification); strengthening of resistance (gene-pyramiding), and utilization in the breeding program (gene-deployment).
3. Determination of the relationship between *Striga* resistance and drought resistance to explore the possibilities of developing sorghums resistant to these two major yield reducing factors.
4. Understanding of the reasons for "wet dormancy" and other factors influencing the seasonal emergence pattern of *Striga.*
5. Determination of suitable trap crops to be used in crop rotations.
6. Development of "integrated *Striga* management practices" with resistant cultivars as principal components. Other control measures to be explored in this package are: trap crops which reduce the *Striga* seed reservoir in the soil; clean cultivation which includes pulling out of *Striga* before it flowers; removal of crop stubbles after harvest to prevent *Striga* seed production; use of nitrogen fertilizers and 2,4-D spraying (early postemergence) wherever available.
7. More basic research into understanding of the host resistance mechanisms; host-parasite specificity, etc.

References

BHARATALAKSHMI and JAYACHANDRA. 1979. Physiological variations in *Striga asiatica.* Pages 132-143 in Proceedings of the Second Symposium on Parasitic Weeds. Raleigh, North Carolina, USA.

BHARATALAKSHMI and JAYACHANDRA. 1980. Pre-sowing hardening of the host with phenolic acids reduces induction of seed germination in root parasite *Striga asiatica.* Tropical Pest Management 26:308-312.

BOONNITEE, W. 1977. Biocontrol studies of *Striga asiatica* (L.) O. Kuntze in Java. BIOTROP, Indonesia. Mimeo Report. 15 pp.

BUDDENHAGEN, I. W„ and BIDAUX, J. M. 1978. *Striga* root parasite—a problem of dryland rice in the African savanna environment. International Rice Research Newsletter 3:22.

CARTWRIGHT, D., LANGEAKE, P., PRYCE, R. J., and LCWORTHY, D. P. 1977. Chemical activation of host defence mechanism as a basis for crop production. Nature 267:511-513.

CHANCELLOR, R. J., PARKER, C, and TEFEREDEGN, T. 1971. Stimulation of dormant weed seed germination by 2-chlorethyl-phosphonic acid. Pesticide Science 2 :35 -37.

CHANDRASEKHARAN, S. N., and PARTHASARATHY, S. V. 1953. Cytogenetics and plant breeding. Madras, India: P. Varadachary and Co.

COOK, C. E.. WHICHARD, .L P., WALL, M. E., EGLEY. G. H„ COGGAN, P., LUTHAN. P. A., and MCPHAID, A. T. 1972. Germination stimulants *2.* The structure of strigol—a potent seed germination stimulant for witchweed (*Striga lutea* Lour.). Journal of the American Chemical Society 94:6198-6199.

COWAN, M. C. 1978. Lignification in wheat roots parasited by *Gaeumannomyces graminis* and *Phialphora radicicola.* Annals of Applied Biology 89:101.

DAY, P. R. 1974. Genetics of host parasite interactions. San Francisco, USA: W. H. Freeman.

DEUSE, J. P. L, and HERNANDEZ, S. 1978. Chemical weed control trial in sorghum in Senegal. Pages 194-200 *in* Proceedings, 3rd Symposium sur le Desherbage des Cultures Tropicales, Dakar, Senegal.

DOGGETT, H. 1965. *Striga hermonthica* on sorghum in East Africa. Journal of Agricultural Science 65:183 -194.

DRENNAN, D. S. H„ and EL-HIWERIS, S. 0. 1979. Changes in growth regulating substance in *Sorghum vulgare* infected by *Striga hermonthica.* Pages 144-155 *in* Proceedings, 2nd International Symposium on Parasitic Weeds, Raleigh, North Carolina, USA.

ELLIS, J. F., PEEK, J. W., BOCHLE, I., and MULLER, G. 1980. Effectiveness of a new safener for protecting sorghum *{Sorghum bicolor)* from metachlor injury. Weed Science 28:1 -5.

EPLEE, R. E. 1975. Effectiveness of ethylene in control of witchweed. Pages 300-305 *in* Proceedings, 28th Annual Meeting Southern Weed Science Society, Memphis, USA.

EPLEE, R. E., and LANGSTON, M. A. 1976. Developments in the control of *Striga* in the USA. PANS 22 : 61 -64.

ESSER, R. P., and ORR, C. C. 1979. *Northanguina phyllobia,* a nematode pest of a noxious weed *Solanum elaeagnifolium.* Nematology Circular, Florida Department of Agricultural and Consumer Services, No. 51. 2 PP

FAO (Food and Agriculture Organization). 1979. Elements of integrated control of sorghum pests. Plant Production and Protection Paper No. 19. 159 pp.

GREATHEAD, D. J., and MILNER, J. E. D. 1971. A survey of *Striga* spp *(Scrophuiariaceae)* and their insect natural enemies in East Africa with a discussion on the possibilities of biological control. Tropical Agriculture (Trinidad) 48:111-124.

HSIAO, A. I., WORSHAM, A. D., and MORELAND, D. E. 1979. Factors affecting conditioning and germination of witchweed (*Striga asiatica* (L.) Kuntzel seeds under laboratory conditions. Pages 193-201 *in* Proceedings, 2nd International Symposium on Parasitic Weeds. Raleigh, North Carolina, USA.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1978. Annual Report 1977/78. Patancheru. A.P., India: ICRISAT.

JOHNSON, A. W., ROSEBERY, G.. and PARKER. C. 1976. A novel approach to *Striga* and *Orobanche* control using synthetic germination stimulants. Weed Research 16: 223-227.

KUMAR, L. S. S. 1940. *Striga* research in Bombay. Indian Farming 1:609-610.

LANGSTON, M. A.. ENGLISH, T. J., and EPLEE, R. E. 1979. Witchweed *{Striga asiatica)* eradication in the United States of America—herbicides. Pages 273-277 *in* Proceedings, 2nd International Symposium on Parasitic Weeds, Raleigh, North Carolina, USA.

LYNN, D. G., STEFFENS, J. C. SHABANOWITZ, J., and RIOPEL, J. L. (In press). Isolation and characterization of the first host recognition substance for parasitic angiosperms. American Journal of Chemistry.

MANGOENDIHARDJO, S., and SOERJANI, M. 1978. Weed management through biological control in Indonesia. Pages 323-337 *in* Proceedings of the Plant Protection Conference, Malaysia.

MUSSELMAN, L. J., PARKER, C.,and DIXON, N. (In press). Notes on autogamy and flower structure in agronomically important species of *Striga (Scrophulariaceae)* and *Orobanche (Orobanchaceae).* Beitrage zur Biologie der Pflanzen.

NARASIMHA MURTHY, B. L, and SIVARAMAKRISHNAIAH, M. 1963. Modern trends of agricultural research with reference to *Striga* resistant sorghum types for maximum food production. Andhra Agricultural Journal 10:6-11.

NICKRENT, D. L, MUSSELMAN, L. J.. RIOPEL, J. L. and EPLEE, R. E. 1979. Haustorial initiation and nonhost penetration in witchweed *(Striga asiatica).* Annals of Botany 43:233-236.

OBILANA, T. A. 1980. (In press). Inheritance of resistance to *Striga (Striga hermonthica* Benth) in sorghum. Theoretical and Applied Genetics.

OGBORN, J. E. A. 1972a. The control of *Striga hermonthica* in peasant farming. Pages 1068-1077 *in* Proceedings, 11th British Weed Control Conference. London. UK: British Crop Protection Council.

OGBORN. J. E. A. 1972b. Significance of seasonal pattern of emergence of *Striga hermonthica* Benth. Pages 562-571 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co. 638 pp.

OKONKWO, S. N. C. 1966. Studies of *Striga senegalensis.* III. In vitro culture of seedlings. Establishment of cultures. American Journal of Botany 53:679-687.

PARKER, C. and REID, D. C. 1979. Host specificity in *Striga* species—some preliminary observations. Pages 79-90 *in* Proceedings, 2nd International Symposium on Parasitic Weeds, Raleigh, North Carolina, USA.

PARKER, C, HITCHCOCK, A. M., and RAMAIAH. K. V. 1977. The germination of *Striga* species by crop exudates: techniques for selecting resistant cultures. Pages 67-74 *in* Proceedings, 6th Asian Pacific Weed Science Society Conference, Djakarta. Indonesia.

PAVLISTA, A. D., WORSHAM. A. D„ and MORELAND. D. E. 1979. Witchweed seed germination. II. Stimulatory and inhibitory effects of strigol and GR7 and the effects of organic solvents. Pages 228-237 *in* Proceedings, 2nd International Symposium on Parasitic Weeds, Raleigh, North Carolina. USA.

PITRE, H. N., and GOURLEY, L. M. 1980. Johnson grass in relation to damage by the sorghum midge in North Mississippi. Mississippi Agricultural and Forestry Experiment Station Research Reports 5.

RAO, P. K. 1948. Annual Report of the Millet Breeding Station. Coimbatore, India.

REDDY, B. V. N., and RAO, P. N. 1980. Colleters on the cotyledons of in vitro raised seedlings of witchweed —*Striga asiatica* (L) Kuntze. Current Science 49: 595 -597.

REID. D. C, and PARKER, C. 1979. Germination requirements in *Striga* species. Pages 201-210 *in* Proceedings, 2nd International Symposium on Parasitic Weeds, Raleigh, North Carolina, USA.

ROBINSON, E. L, and DOWLER, C. C. 1966. Investigations of catch and trap crops to eradicate witchweed *(Striga asiatica).* Weeds 14:275-276.

ROETH, F. W. 1980. Herbicide injury reduction in grain sorghum with MON 4606 seed treatment. Research Report North Central Weed Control Conference 37: 130-131.

SAUNDERS. A. R. 1933. Studies on phanerogamic parasitism with particular reference to *Striga lutea* Lour. South African Department of Agricultural Science Bulletin No. 128. 56 pp.

TEFEREDEGN, T. 1973. Stimulation of *Striga* (Benth) germination with sorghum root exudate. Master of Technology Thesis. Brunei University, Uxbridge, UK. 36 PP

VALLANCE. K. B. 1950. Studies on the germination of the seeds of *Striga hermonthica.* I. Influence of moisture treatment, stimulant-dilution and ripening on germination. Annals of Botany 14:347-363.

VISSER, J. H., and BOTHA. P. J. 1974. Chromatographic investigations of the *Striga* seed germination stimulant. Zeitschrift fur Pflanzenphysiologie 72:352-358.

WILLIAMS, C. N. 1959. Resistance of sorghum to witchweed. Nature 184.1511.

WILSON JONES, K. 1955. Further experiments on witchweed control. II. The existence of physiological strains of *Striga harmonthica.* Empire Journal of Experimental Agriculture 23:206-213.

YADURAJU, N. T.. and HOSMANI. M. M. 1979. *Striga asiatica* control in sorghum. PANS 25:163-167.

YOSHIKAWA, F., WORSHAM, A. D„ MORELAND, D. E„ and EPLEE, R. E. 1978. Biochemical requirements for seed germination and shoot development of witchweed, (*Striga asiatica).* Weed Science 26:119-122.

ZUMMO, K. 1975. Annual report. Cereal Pathology. Institute for Agricultural Research, Ahmadu Bello University, Zaria, Nigeria. 158 pp.

Bird Pests and Crop Protection Strategies for Cereals of the Semi-Arid African Tropics

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Sorghum *(Sorghum bicolor)* and millet *(Pennisetum typhoides),* the staple foods of Africa (Cummings 1976), particularly for the low-income subsistence farmers in Sahelian countries, generally are grown in marginal areas of high climatic risk and account for as much as 97% of the annual cereal production in some of the drought-prone sub-Saharan countries (Table 1). Yields of subsistence crops have stagnated or declined in many of these Sahelian countries (Lele 1981) at a time when increased production is needed. Vertebrate pests are responsible for serious preharvest and postharvest losses to these cereals (Jackson and Jackson 1977).

Historical Overview: Cereal Production and Bird Damage

Among the variety of vertebrate pests, small passerine birds present the greatest threat to increased cereal production in most of the Sahelian countries. The agricultural floodplains in the semi-arid Sahel are within the range of red-billed quelea *(Quelea quelea),* considered as perhaps the most numerous and most serious avian crop pest in the world (Magor 1974). Quelea congregate in wet-season nesting colonies and dry-season roosts in numbers of several hundred thousand to several million birds. Although it has been postulated that they prefer wild grass seeds (Ward 1965), enormous flocks often descend on maturing cereal grains.

Because of their sheer numbers, quelea are particularly destructive pests to the small grains of sorghum and millet. Other ploceid species, including village weavers *(Ploceus cucullatus),* black-headed weavers (P. *melanocephalus),* chestnut weavers (P. *rubigenosus),* sparrows (Passer spp.), and bishops *(Euplectes* spp.) also can cause considerable local damage wherever they are abundant. The biology, movements, and crop depredations have been more intensively studied for quelea than for any of these other species. However, village weavers and golden sparrows (P. *luteus)* are now being more completely investi-

Table 1. Sorghum and millet production as percent of total cereal crop production and percent of annual cereal consumption that Is Imported In 15 Sahelian countries of Africa.

Country	Cereal production % sorghum and millet (Anon. 1980a)	% of cereal consumption imported (Anon. 1980b)
Niger	97	3
Mauritania	93	69
Upper Volta	90	2
Chad	90	3
Sudan	90	2
Uganda	86	1
Senegal	76	28
Somalia	75	34
Mali	73	6
Nigeria	86	10
Gambia	57	28
CAR.	50	10
Ethiopia	48	1
Cameroon	46	8
Tanzania	19'	13

a. Marketed products only. Subsistence production is higher.

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International Crops Research Institute for the Semi-Arid Tropics 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru, A.P., India. Patancheru. A.P. India: ICRISAT.

gated (DaCamara-Smeets 1978; Morel and Morel 1978).

Bird damage to cereal production began receiving international attention in the mid-1950s and early 1960s when African nations requested assistance from the United Nations. In the early 1970s, a United Nations Food and Agriculture Organization project was established in about one dozen Sahelian countries to conduct research into the biology, ecology, and control of quelea and other pest birds. Other countries received bilateral assistance from organizations such as Office de la Recherche Scientifique et Technique Outre-mer (ORSTOM), U.S. Agency for International Development (USAID), British Centre for Overseas Pest Research (COPR), and German Technical Assistance (GTZ) to evaluate bird pest problems and strengthen existing plant protection departments. Presently, United Nations-funded regional and national projects and government bird control units exist in both East and West Africa; emergency funds also are regularly allocated for control operations in several other countries.

Although the adverse impact of bird pests on cereals is generally recognized, very little objective information on the actual magnitude of losses was available in any of the affected countries until very recently; these systematic assessments have clarified the seriousness of the bird pest to agriculture (Anon. 1981). Bird damage to cereals is now estimated to annually exceed U.S. $1 million in Somalia (Bruggers 1980). U.S. $3 million in Kenya (Kitonyo and Allan 1979). U.S. $2.4 million in Tanzania (Elliott and Beesley 1979), U.S. $3 million in Ethiopia (Jaeger and Erickson 1980), and U.S. $6.3 million in Sudan (Anon. 1981), or a total of at least U.S. $15 million annually in eastern Africa. Cereal losses to birds in Senegal, the only West African country where reliable data are available, are valued at U.S. $4-5 million; sorghum and millet suffer more than 78% of these losses (Bruggers and Ruelle 1981).

Most of the Sahelian countries must import cereals to meet their annual consumption requirements. Some countries such as Gambia, Senegal, Somalia, and Mauritania import as much as 28-69% of the cereals consumed annually (Table 1). With an estimated food deficit for developing countries of the world by 1990, projected to be 120 million tonnes, food production must be increased wherever feasible and appropriate, particularly in low-income agrarian countries (Wortman 1980). There is a great potential for increasing sorghum and millet production (Cummings 1976), and yields can be protected if bird depredations are reduced. The expenses for research and bird control operations will be returned manyfold by the employment of appropriate crop protection techniques.

Crop Protection, Control Operations, and Research of Bird Pests

Traditional Crop Protection

Bird scaring in traditional African agricultures is an important part of a family's farming activity (Doggett 1957). Farmers presently are protecting their crops from birds with the same traditional techniques used since crop cultivation began, including trying to frighten birds by shouting; using noise making devices such as gourds, cans, drums, or cracking whips; throwing mud or stones; and protecting the cereal heads with coverings of grass or cloth. Many farmers, in their frustration, resort to hiring shamen and to using fetishes in attempts to alleviate damage. Some of these frightening methods can provide some protection when bird numbers are low and when farmers are protecting their own small fields (Pepper 1973; Ruelle and Bruggers, in press). However, these methods are effective only on those areas that a family can manage and protect. Still, damage is seldom prevented but instead redistributed more evenly than would naturally occur (Flegg 1980). As agricultural practices are upgraded and fields are enlarged, the scale of farming makes these methods impractical (Park 1974) and they disappear (Doggett 1957). Furthermore, traditional methods are ineffective in most quelea damage situations and can constitute as much as 15-80% of the production cost on large government agricultural production schemes (Bruggers 1980). New, innovative, more effective approaches to crop protection are needed that could free farmers from the task of scaring birds and allow them to devote more time to improving cultural practices. Proper cultural practices have the potential of minimizing or even alleviating bird damage.

National Control Operations

Because of the failure of traditional methods to cope with pest birds, national and regional bird control organizations were formed in the 1950s and 1960s. These organizations now operate in some 16 countries (Ward 1979), employing lethal techniques that annually destroy up to 1 billion birds in a strategy apparently aimed at overall population reduction.

Ndiaye (1979) reported that in the Senegal River Valley the use of flame throwers killed 150 million fledglings in 1953, explosives killed 20-60 million adults between 1953 and 1966, and parathion sprays killed 200 million fledglings and adults in 1964. Mallamaire (1959) stated that in the Senegal River Valley over 500 million quelea were killed by flame throwers and explosives in control operations between 1954 and 1956. In the Republic of South Africa, over 100 million quelea were destroyed by aerial spraying of avicides in 1 year. Yet damage continued (Flegg 1980) and many farmers have been compelled to forego sorghum production (D. Lourens, personal communication to J. De Grazio). During 1980 in Tanzania, the avicide fenthion was applied to 29 breeding colonies totaling 944 ha, with varying degrees of success (Elliott and Beesley 1979). Likewise, an average of 77 colonies and 35 roosts reportedly are annually located in Sudan, and 75% of them treated with avicides (Anon. 1981). These massive annual control campaigns (in conjunction with a variety of causes of desertification) apparently can reduce the quelea population in local areas such as the Senegal River Valley. A strategy of total population reduction is doomed to fail in most situations because of the high reproductive potential of quelea. the vast inaccessible areas in which they are distributed (Ward 1979), and because all the major bird pests in the African savanna are highly mobile migrants (Jones 1975) and opportunistic feeders. More than 50-60% of the total population would need to be located and killed in control operations just to remove the expected annual recruitment; it is likely that most of the adults killed each year are the "doomed excess" (Ward 1979) and may not even be responsible for damage. Likewise, the many inaccessible "reservoirs" existing in the vast range of quelea preclude a strategy of permanent reduction in numbers (Ward 1965; Ward 1979).

The importance of wild seeds versus cultivated cereals in the diet of quelea needs further investigation. Ward (1965) found that quelea in Nigeria ate predominately wild seeds and postulated that they actually prefer them to cultivated seeds. From food habit studies in Somalia, only 15% of 3282 quelea collected between 1975 and 1979 had eaten cereal crops (the rest ate wild seeds or insects); about half of those eating cereals had eaten sorghum. Erickson (in press) found wild and cultivated seeds to be the main diet of quelea in agricultural zones of Ethiopia. Forty-six percent of the adult quelea sampled in the Upper Awash Valley during 1977/1978 had eaten cultivated grain; the concentration and availability of seed was more important than its size and type. Sorghum was, however, an important cereal grain in the diet of over 2000 village weavers and chestnut weavers collected in Somalia (Bruggers 1980). These species may even prefer cultivated grain to wild seed, a belief also shared by Erickson (in press) for village weavers in Ethiopia. For these reasons, and because only a small proportion of birds in a population may actually be causing damage, more sophisticated and specific approaches to control of bird damage are needed.

Many improvements have been made in the actual control practices of national crop protection organizations (Anon. 1980c). Parathion has been replaced with 60% fenthion and spray quantities of this avicide have been reduced from more than 30 l/ha to 10-15 l/ha when applied by fixed-wing aircraft and 1-2 l when applied by helicopter equipped with ULV spraying equipment. Chemicals such as cyanophos, which are potentially safer and less persistent, are being evaluated (Jaeger and Erickson 1981; P. Ruelle, personal communication). Spray operation procedures, improved with an increased understanding of spray formulations and dynamics and the behavior of the target species, have resulted in fewer and more efficient applications to colonies in some countries. However, spray application improvements are still needed. In addition, techniques such as firebombs have been recognized as obsolete (Mallamaire 1959) and have been eliminated in most countries; they are still used in Kenya. Others, such as poisoning waterholes and using explosives, are still used but only, in a few countries. Overall, there has been a slow but perceptible change to the more careful use of methods that are more effective and environmentally safe.

Crop Protection Research—Chemical Repellents

The past decade has also seen the experimental introduction of methods to directly protect cereals from birds. In the laboratory, the insecticide-molluscicide methiocarb [3,5-Dimethyl-4-(methylthio) phenol methylcarbamate] is repellent at the level of 0.015% to red-billed quelea (Shumake et al. 1976) and to some other bird pests (Shefte et al., in press). Its application to ripening cereals has given increasingly positive results as the behavior of the species has become better understood; the application techniques have been refined; and specific, appropriate pest situations for its use were identified. Methiocarb has effectively protected sorghum and millet in Senegal (Bruggers, in press) and Ethiopia (Bruggers et al. 1981b; Erickson et al., in press) (Table 2). It has a half-life of 6-7 days on ripening sorghum in Senegal and residues on the seed and glumes at 20-25 days after application of 24 ppm (3.0-3.5 ppm on the seed itself) indicating that it can be safely applied at normal repellent use levels (Gras et al. 1981). It is registered as a bird repellent in the United States, both as a seed treatment and on several fruit crops (DeHaven et al. 1979; Schafer 1979).

Barriers

The use of physical barriers such as nylon or plastic nets with characteristics to withstand ultraviolet radiation is another method used to protect ripening cereals. Nets were not regularly used in Africa before the mid-1970s, but are now being increasingly employed at research centers and production schemes. When properly installed and maintained they can provide nearly complete protection from birds. Their expense, however, limits their use to high-value crops. !n Kenya (F. Pinto, personal communication), Senegal (J. Denis, personal communication), and Ethiopia (B. Gebrekidan, personal communication) permanent netting enclosures, costing as much as U.S. $1000/ha are being used to protect valuable seeds in variety trials from birds. Nonetheless, the cost compares favorably with that of hiring bird scarers for the entire maturation period of a crop (Bruggers, in press).

Genetic and Phonologic Characteristics

Plant breeders presently are directing much effort into breeding varieties of sorghum that are "bird resistant" or that mature when birds are not present. However, Doggett (1957) stated that "bird resistance" is a relative term and noted the improbability of developing strains of sorghum that would be immune to attack by hungry birds in the absence of alternate food. Even so, certain plant characteristics, such as loose and pendant heads, large glumes, awns, and bitter taste or astringency, have at times been associated with reduced damage. Sorghum varieties with these characteristics might be more appropriately termed "less susceptible."

The most promising deterrent of these characteristics seems to be a high content of astringent tannins. Certain varieties have the tannins present at repellent levels during the milk and early dough stages (usually the most susceptible period to bird attack) before losing their astringency at harvest, and are thus nutritionally acceptable to farmers (Bullard and Elias 1979; Bullard et al. 1981). These varietal characteristics are difficult to evaluate, because when they are screened and grown in proximity, birds avoid the less acceptable ones, giving a false estimate of "resistance" (Beesley and Lee 1979). When they are planted in areas with high bird pressure and little alternate food, they are usually heavily damaged, as in Puerto Rico (Roger R. Bullard, personal communication) and Botswana (Beesley and Lee 1979). Plant breeders are continuing to actively pursue the development of improved varieties. In Kenya the variety "mombassa" is planted over a wide area by farmers and incurs less damage than other varieties (F. Pinto, personal communication).

Because pest birds of Africa are migratory (Jones 1975), a potentially promising approach might be the development of cereal varieties that mature while birds are absent. Although this approach is complicated by inconsistencies in periods and amounts of rainfall and the traditional sowing practices of farmers (Doggett 1957), it is becoming more attractive as agriculture is upgraded by development schemes. From observations in Chad and Cameroon during several years, Elliott (1979) documented that the planting time of irrigated rice could be regulated so that harvest occurred before the birds arrived in the area, and damage could be greatly reduced. In one season damage was less than 1%. He also noted the practical difficulties of timing crops to such a precise schedule, but believed it would be worthwhile as damage increased to 13-26% when the timing of harvest and the arrival of the birds overlapped.

Table 2. Results from selected field and cage trials with methlocarb appllad to ripening haada of sorghum and millet in Africa. All data are available in manuscripts chad in references.

Location	Year	Area (ha)	No. replicates	Avg % damage and/or yield	
METHIOCARB FIELD STUDIES					
Sorghum					
Darou, Senegal,	1975				
—treated		0.22	1	4%	49.4 g/head
—untreated		0.17	1	67%	15.8 g/head
Melkassa, Ethiopia					
—treated	1980	12.00	1	14.2%	
	1979	12.00	1	22.1%	
	1978	1200	1	5.7%	
	1977	12.00	1	<2-3% after application, 23% before application	
—untreated	1976	1200	1	42%	
Millet					
Bambey. Senegal,	1975				
—treated		0.04	1		4.6 g/head
—untreated		0.04	1		2.2 g/head
METHIOCARB CAGE STUDY					
Sorghum					
Jodah, Sudan,	1978				
—treated		8 m^3	3	0.9-2.6%	
—untreated		8 m^3	1	42.6%	
NETTING ENCLOSURE STUDIES					
Sorghum					
Machachos, Kenya,	1979				
—treated		0.02-0.06	3	0-4%	
—untreated		3.00	1	9.8%	
Millet					
Bambey, Senegal,	1976				
—treated		0.10	1	15.5%	
—untreated		0.04	3	93-100%	

Future Advances and Crop Protection Implications

The need to increase cereal production in tropical Africa, where "...food consumption will actually decline below present inadequate levels" (Barney 1980), is particularly acute. Reducing cereal losses caused by birds is one of the most difficult and challenging of all vertebrate pest problems, yet it is one important way of helping to achieve this goal. The past two decades have been characterized by a growing awareness of the extent and cost of bird damage to crops and the formulation of a scientific approach to understanding and solving the problems. During the coming years, research will play an important role in describing the behavior and movements of bird pests relative to crop damage, and in defining particular approaches to effective crop protection efforts based on this knowledge.

Development of an effective control strategy requires survey information on the seasonal distribution of susceptible crops and of the bird pests. During the 1970s, survey work was first accomplished using solely Landrovers, then Landrovers in conjunction with fixed wing aircraft, and later helicopters. This work is extremely time-consuming, logistically difficult, and expensive. Some new and interesting techniques to facilitate gathering this kind of information recently have been investigated. Miniature radio transmitters weighing 1.8 g have been developed (Bruggers et al. 1981a) and successfully used to locate nesting colonies of quelea and follow their movements and those of village weavers in remote parts of Ethiopia (Bruggers et al., in press). The transmitters provide an economically efficient tool for locating and subsequently controlling nesting colonies during their early development. Likewise, aerially applied fluorescent particles used to mass-mark birds in the Ethiopian Rift Valley during 1981 also have control implications (Jaeger et al., in press). A number of marked birds already have been recovered in roosts and breeding colonies in the northern Rift Valley, as far as 750 km from the nesting colonies in which they were sprayed in mid-June. This preliminary finding suggests a fragmented and probably multidirectional dispersal from breeding colonies in southern Ethiopia. These findings demonstrate that quelea breed twice in the Rift Valley and imply that there is little justification for their control in the south (Jaeger, unpublished data). The feasibility of detecting trace element patterns in feathers to identify populations is also being investigated. These techniques can provide information that will allow for early detection of colonies and permit control operations to be directed at those colonies actually causing damage even though they may be temporally and spatially separated from cropping areas.

Such a strategy, but based on morphological criteria of the birds and breeding phenology, was successfully employed in Ethiopia between 1978 and 1980 (Jaeger and Erickson 1980). Bird damage to sorghum was much lower between these years as compared with the previous 2 years when control was not attempted. Without lethal control of breeding colonies during 1976 and 1977, the combined estimated losses of sorghum to birds in certain critical cropping areas were 27 to 30% in 1976 and 13% in 1977 representing U.S. $4.0 and 0.7 million, respectively. Average overall losses for this area are projected at 40 000 metric tons annually (16%), valued at U.S. $6.0 million. This compares with overall losses of 2, 3, and 4% during 1978, 1979, and 1980, respectively (representing between U.S. $0.3 and 0.9 million each year), when selected breeding colonies were destroyed (Table 3). During 1980, avicidal sprays were directed at quelea concentrations of more than 8 million birds occupying more than 90 ha in 7 locations of Ethiopia with 50-90% success (Table 4). The success of these control operations is being systematically evaluated *on* the basis of preharvest damage assessments and increased yields, not solely the percent kill of birds, as is commonly practiced in Africa.

Ways of using the chemical repellent methiocarb more effectively also are being explored. Practices are changing from those of applying the chemical to an entire field to spraying only the edges or spots in the field that are being damaged (Bruggers et al. 1981b). Similarly, laboratory and preliminary field trials have shown that combining a sensory cue (like wattle tannin) with reduced quantities of methiocarb can provide protection that is comparable, but less expensive, than that obtained when methiocarb was used alone (Bullard, Bruggers, and Kilburn, Denver Wildlife Research Center, unpublished data).

Woronecki and Dolbeer (1980) pointed out that the control of bird damage usually is directed at the pest bird with little consideration given to understanding its relationship to the control of other pests in the field. They show that the presence or absence of insects may greatly influence bird damage control programs, particularly when chemical repellents are used. Similarly, the presence of weeds in a field can completely negate any repellent effects of a chemical (Bruggers, unpublished data). Management techniques will be more consistently effective if bird damage control is approached from an integrated, not isolated viewpoint (Woronecki and Dolbeer 1980) and cultural practices are considered. An important outgrowth of the interest in bird- pest prob-

Table 3. Sorghum production estimate ranges for the major growing areas associated with the Awash River Basin In Ethiopia as related to preharvest losses to birds (1976-1980).*

Production estimates for sorghum	Without quelea concentration control		With queiea concentration control		
	1976	1977	1978	1979	1980
(1) Total area (ha x 10^3)	147-220	86-142	119-194	98-167	98-169
(2) Total yield[b] (mt x 10^3)	147-220	86-142	119-194	98-167	98-169
(3) Area assessed (ha x 10^3)	80-100	25-35	82-122	85-135	85-140
(4) (3)/(1) (%)	54-45	29-25	69-63	87-81	87-83
(5) Loss to birds (mt x 10^3)	24.1-26.8	3.3-4.6	1.5-2.2	2.3-3.5	3.8-6.1
(6) (5)/(3) (%)	30-27	13-13	2-2	3-3	4-4
(7) (5)/(1) (%)	16-12	4-3	1-1	2-2	4-4
(8) Actual loss ($ x 10^6) (5) x $150/mt[c]	3.6-4.0	0.5-0.7	0.2-0.3	0.3-0.5	0.6-0.9

a. 1976-1979 data from Jaeger and Erickson (1980).
b. Based on an average yield of 1 metric ton (mt), or 10 quintals/ha.
c. Average market value.

Table 4. Control operations on night roosts and breeding colonies of *Quelea quelea* (September-December 1980) threatening sorghum-growing areas associated with the Awash river basin in Ethiopia.

Target location	Bird concentration	Date	Area (ha)	Est. no. queiea (x 10^3)	No. of spray sortie	Est. kill (%)
Melkassa	nesting	18-19 Sept	15-20	Unknown	2	>90
Abadir	nesting	23-25 Sept	10	2 600	2	>80
Nura hera	nesting	24-25 Sept	11-13	300-350	2	<50
Lake Zwai	nesting	4 and 21 Oct	30-40	≥5 000	2	>80
Melkassa	roosting	13-14 Oct	10	100-200	2	>80
Bisidimo	roosting	4 Oct	2-3	40-50	1	>80
Kemisse	roosting	4-5 Dec	2-3	40-50	2	>90

lems is the growing awareness and concern shown by individuals planning agricultural developments. With increasing regularity, the potential damage by bird pests to these projects is being considered. On some occasions, the crops are changed to those less susceptible to bird damage; on others, plant protection specialists or consultants are hired and money is budgeted for crop protection operations (Anon. 1980d; D. Gowing, personal communication). Although seemingly obvious concerns, these are recent developments.

The transfer of appropriate scientific and technological advances through assistance programs to government control organizations and agricultural institutions will become easier in the future as more trained individuals become incorporated into plant protection departments. At the University of Gezira, Sudan, formal undergraduate training in vertebrate pest problems already has begun, and a M.S. degree program in crop protection is proposed for ratification. The University of Nairobi also is considering including a course on vertebrate pest management in its M.S. program.

Several American universities, including the University of California at Davis and Bowling Green State University, Bowling Green, Ohio, are involved in training international students in vertebrate pest management. Bowling Green State University has provided degree- and nondegree training in crop protection techniques to over 40 international students during the past 20 years.

Many of the students presently in the program are from Tanzania, Somalia, Kenya, Ethiopia, and Sudan. An experimental vertebrate pest management course aimed at the needs of international students is being taught at Colorado State University, Fort Collins, Colorado, and plans are being made to establish a degree program in that specialty. African plant protection personnel have recently completed extended training courses in pesticide application methods, finished pilot training projects, and participated in field techniques workshops on quelea control. Most of the individuals involved in these kinds of training return and continue working in their country.

In conclusion, considerable progress has been made in the last 10 years in understanding the biology and behavior of pest birds particularly quelea and in developing control techniques and strategies of crop protection by a relatively few number of individuals. Many crop protection choices presently exist and more will become available in the future. With more trained individuals evaluating the pest species and its habitat related to agricultural practices, then selecting appropriate methods to alleviate damage, with the emphasis on effectiveness, safety, cost, and minimal environmental contamination, integrated crop protection programs can be expected to be more frequently implemented in the future.

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The improvement of existing methods and development of new procedures for protecting crops have resulted through the cooperation of many interested individuals and organizations. For the work with sorghum and millet, these include Drs. J. Denis and J. Deuse of L'institute Senegalaise Recherches Agronomiques, Dr. G. Gras. University of Dakar, and Drs. Brhane Gebrekidan of the Ethiopia Sorghum Improvement Project and F. Pinto of the Kenya Sorghum and Millet Improvement Project. Colleagues of several United Nations Development Program/Food and Agriculture Organization, ORSTOM, USAID, COPR, and GTZ projects have contributed much to advancing the knowledge of the biology, behavior and control of the pest bird species. J. W. De Grazio, M. W. Fall, and J. 0. Keith of the Denver Wildlife Research Center (Section of International Programs) and W. B. Jackson of Bowling Green State University reviewed the manuscript.

References

ANONYMOUS. 1980a. Cereal crop pests in Africa with particular reference to birds. Part I. Synthesis of replies to a questionnaire prepared by FAO and sent to 33 countries. Rome. Italy: FAO.

ANONYMOUS. 1980b. Agricultural development indicators—a statistical handbook. New York, USA: International Agricultural Development Service.

ANONYMOUS. 1980C. Crop protection manual—African grain-eating birds. United Nations Development Programme/Food and Agriculture Organization Report RAF 73/055. Rome, Italy: FAO.

ANONYMOUS. 1980d. Assessment of environmental effects of proposed developments in the Senegal River Basin—partial report for ornithology. Gannett Fleming Corddry and Carpenter, Inc., Harrisburg, Pennsylvania, USA, in association with ORGATEL Societe Africaine d'Etudes Techniques. Dakar, Senegal.

ANONYMOUS 1981. An assessment of the bird pest problem in Sudan, Ethiopia, Somalia, Kenya, Tanzania. Rome, Italy: FAO.

BARNEY, G. O. 1980. The global 2000 report to the President—Entering the twenty-first century. Volume 1. Washington, D. C. USA: Government Printing Office, 47 pp.

BEESLEY, J. S. S., and LEE, P. G. 1979. The assessment of bird resistance in sorghum cultivars in Botswana. PANS 25:391-393.

BRUGGERS, R. L. (in press). Summary of methiocarb trials against pest birds in Senegal. Proceedings, 8th Bird Control Seminar, Bowling Green, Ohio.

BRUGGERS, R. L. 1980. The situation of grain-eating birds in Somalia. Pages 5-16 *in* Proceedings. 9th Vertebrate Pest Conference, Fresno, California, USA.

BRUGGERS, R. L, ELLIS. J., SEDGWICK, J., and BOURASSA. J. 1981a. A radio transmitter for monitoring the movements of small passerine birds. Pages 69-79 *in* Proceedings. 3rd International Conference on Wildlife Biotelemetry, 27-28 July 1981, Laramie. Wyoming, USA.

BRUGGERS, R. L. MATEE, J., MISKELL, J., ERICKSON, W.. JAEGER, *M.,* JACKSON. W. B., and JUIMALE, Y. 1981b. Reduction of bird damage to field crops in eastern Africa with methiocarb. Tropical Pest Management 27:230-241.

BRUGGERS R. L.,and RUELLE, P. 1981. Economic impact of pest birds on ripening cereals in Senegal. Protection Ecology 3:7-16.

BRUGGERS, R. L., JAEGER. M. M.. and BOURASSA, J. B. (in press). The application of radio telemetry for locating and controlling concentrations of red-billed quelea in Africa.

BRUGGERS, R. L, and RUELLE, P. (in press). Efficacy of nets and fibres for protecting crops from grain-eating birds in Africa. Crop Protection.

BULLARD, R. W., and ELIAS, D. J. 1979. Sorghum polyphenols and bird resistance. Pages 43-72 *in* Polyphenols in cereals and legumes, ed. J. H. Hulse. Proceedings, 36th Annual Symposium of the Institute of Food Technologists, St. Louis, Missouri, USA.

BULLARD, R. W., YORK, J. O., and KILBURN. S. R. 1981. Polyphenolic changes in ripening bird-resistant sorghums. Journal of Agricultural Food Chemicals 29 : 973 -981.

CUMMINGS, R. W., JR. 1976. Food crops in the low-income countries: the state of present and expected agricultural research and technology. Working Papers, The Rockefeller Foundation.

DACAMARA-SMEETS, M. 1978. Contribution a l'Etude Ecologique en vue du controle des oiseaux granivores — Le cas de *Ploceus cucullatus* an Tchad Ph.D Dissertation, Universite Catholique de Louvain, Belgium.

DEHAVEN, R. W., MOTT, D. R., GUARINO, J. L, BESSER, J. F.. KNITTLE, C. E., and SCHAFER, E. W., JR. 1979. Methiocarb for repelling birds from ripening sweet cherries. International Pest Control 21 :12-14.

DOGGETT, H. 1957. Bird resistance in sorghum and the quelea problem. Field Crop Abstracts 10: 153-156.

ELLIOTT, C. C. H 1979. The harvest time method as a means of avoiding quelea damage to irrigated rice in Chad/Cameroon. Journal of Applied Ecology 16:23 -35.

ELLIOTT, C. C. H., and BEESLEY, J. S. S. 1979. Qualitative and quantitative assessment of bird damage in Tanzania. Minutes, 1st Annual Technical Meeting of Food and Agriculture Organization/United Nations Development Programme RAF 77/042, 27-31 August, Nairobi, Kenya.

ERICKSON, W. A. (in press). Diets of the red-billed quelea *{Quelea quelea)* in the Awash river basin of Ethiopia. Proceedings, 8th Bird Control Seminar, Bowling Green, Ohio.

ERICKSON, W. A., JAEGER, M. M., and BRUGGERS, R. L. (in press). The development of methiocarb for protecting sorghum from birds in Ethiopia. Ethiopian Journal of Agricultural Sciences.

FLEGG, J. J. M. 1980. Biological factors affecting control strategy. Pages 7-19 *in* Bird problems in agriculture, eds. E. N. Wright, I. R. Inglis, and C. J. Feare. Monograph No. 23. Reading, Berkshire, UK: Lamport Gilbert Printers Ltd. 210 pp.

GRAS, G., HASSELMAN C, PELLISSIER, C, and BRUGGERS, R. L. 1981. Residue analysis of methiocarb applied to ripening sorghum as a bird repellent in Senegal. Bulletin of Environmental Contamination and Toxicology 26:393-400.

JACKSON, W. B.. and JACKSON, S. S. 1977. Estimates of bird depredations to agricultural crops and stored products. Pages 33-43 *in* Plant Health Newsletter: Colloquium on Crop Protection Against Starlings, Pigeons, and Sparrows. European and Mediterranean Plant Protection Organization (EPPO) Publications, series B, No. 84, Paris, France.

JAEGER, M. M., and ERICKSON, W. A. 1980. Levels of damage to sorghum in the Awash Basin of Ethiopia and the effects of the control of quelea nesting colonies (1976-1979). Pages 21 -28 *in* Proceedings, 9th Vertebrate Pest Conference, Fresno, California, USA.

JAEGER, M. M., and ERICKSON, W. A. 1981. *Quelea quelea* control: spray trials on quelea nesting colonies comparing cyanophos L-50 and fenthion L-60. United Nations Development Programme/Food and Agriculture Organization RE-01-0031. Rome. 4 pp.

JAEGER, M. M., BRUGGERS. R. L., JOHNS, B. E., and ERICKSON, W. A. (in press). Mass marking red-billed quelea *(Quelea quelea)* with fluorescent particles to determine seasonal migration patterns in the Ethiopian Rift Valley.

JONES, P. J. 1975. The significance of bird migration to bird pest control strategy. Pages 883-889 *in* Proceedings, 8th British Insecticide and Fungicide Conference.

KITONYO, R. M., and ALLAN, R. G. 1979. Quantitative and qualitative assessment of bird damage in Kenya. Minutes. 1st Annual Technical Meeting of Food and Agriculture Organization/United Nations Development Programme RAF 77/042, 27-31 August, Nairobi, Kenya.

LELE, U. 1981. Rural Africa: modernization, equity, and long-term development. Science 211 : 547-553.

MAGOR, J. 1974. Quelling the quelea-bird plague of Africa. Spectrum 118:8-11.

MALLAMAIRE, L. 1959. Control of weaver bird in West Africa. Food and Agriculture Organization Plant Protection Bulletin 7:105-112.

MOREL, G. J., and MOREL, M.-Y. 1978. Elements de comparison entre *Quelea quelea* (L) et *Passer luteus* (Lichtenstein) dans les savannes tropicales de l'ouest Africain. Cahiers Office de la Recherche Scientifique et Technique Outre-Mer, Serie Biologioe XIII: 347-358.

NOIAYE, A. 1979. Fight against grain-eating birds. Proceedings, Seminar on Crop Protection, Pesticides, and Food Crops, 12-16 February, Dakar, Senegal.

PARK, P. 0. 1974. Granivorous bird pest in Africa. SPAN 17:126-128.

PEPPER, S. R. 1973. Observations on bird damage and traditional bird-pest control methods on ripening sorghum. Food and Agriculture Organization /United Nations Development Programme, Internal Report No. 304. 6 pp.

RUEELLE, P., and BRUGGERS, R. L. (in press). Traditional approaches for protecting cereal crops from birds in Africa. Proceedings, 10th Vertebrate Pest Conference.

SCHAFER, E. W., JR. 1979. Registered bird damage chemical controls. Pest Control. pp. 36-39.

SHEFTE, N., BRUGGERS, R. L, and SCHAFER, E. W., JR. (in press). Repellency and toxicity of three bird control chemicals to four species of African grain-eating birds. Journal of Wildlife Management.

SHUMAKE, S. A„ GADDIS, S. E., and SCHAFER, E. W„ JR. 1976. Behavioral response of quelea to methiocarb (Mesurol"). Pages 250-254 *in* Proceedings, 7th Bird Control Seminar, Bowling Green, Ohio.

Ward, P. 1965. Feeding ecology of the black-faced dioch *Quelea quelea* in Nigeria. Ibis 107:173-214.

WARD, P. 1979. Rational strategies for the control of queleas and other migrant bird pests in Africa. Philosophical Transactions of the Royal Society of London, Biological Sciences 287, 289-300.

WORONECKI, P. P.. and DOLBEER, R. A. 1980. The influence of insects in bird damage control. Pages 53-59 *in* Proceedings, 9th Vertebrate Pest Conference. Fresno, California, USA.

WORTMAN. S. 1980. World food and nutrition: the scientific and technological base Science 209:157 -163.

Session 3 Factors Reducing Sorghum Yields *Striga* and Birds

H. Doggett* Discussant

Witchweed *(Striga* spp) and birds have the distinction of being the two most serious causes of crop loss on cereals in the rainfed semi-arid tropics: yet, over the past 30 years, *Striga* has received least attention from national and international funding agencies. Also, much more attention to bird control is required. I would add to the authors' comments that *Striga* is a farming problem, needing attention from those with practical farming experience in the tropics. This is true of birds to a lesser extent, but both birds and *Striga* require control measures which are far beyond the resources of the small farmers in the semi-arid tropics. Control is needed on a government scale and a regional scale, and more money is required from donor agencies. As stressed in the paper on birds, integrated crop protection systems are required for both sets of pests, and these must form a part of the total farming systems approach followed.

Birds

Turning first to the paper on birds, it is encouraging to learn that control operations are still continuing, and the methodology is being improved.

The economic cost of birds is rather greater than that quoted. Large areas of several African countries are growing maize where sorghum or millet are the more reliable crops with better, more consistent yields across seasons. Maize does, not need bird scarers. Maize crop failures in some seasons are preferred to bird losses in all seasons. The area under the high tannin grains has also been accepted as inevitable. People have learnt how to use them, and perhaps nothing can be done to frustrate the birds, at least not until very much larger areas of Africa are under the plow. The paper brings out clearly that, like *Striga,* the crop lost which could otherwise have been harvested, represents a substantial production loss which usually has to be replaced by imports of grain.

The possibilities of a permanent reduction in the *Quelea* population are clearly small, so crop protection is the only course. The farming system modifications of planting time and maturity are the least expensive way of reducing bird damage. In Tanzania, a short-term crop planted in February in the northern part of the Lake region makes out all right, provided that there are good enough showers to get it established; birds are little trouble then. Further south, the rainfall is lower and less reliable; more work needs to be done. In Uganda, the weaver birds decimate grain in March-April plantings, but August plantings of 100-120 days varieties have no bird problem, at least in Teso district. Again, more studies are needed in other parts of the country.

Other methods of control cost money, chemical repellants may need subsidies for the small farmers in the poorer areas; methiocarb requires a cash outlay; family bird scaring does not. Studies are needed of farmer—or rather, farmer's wife—reactions to the flavor of the products prepared from grain which has been treated with methiocarb. It is to be hoped that the search for cheap and effective bird repellents will be continued.

The control of birds illustrated in Tables 3 and 4 in the paper by Bruggers and Jaeger is very encouraging. Clearly, much can be done. However, we need some cost figures; and control by attacking colonies of *Quelea* must surely be quite expensive, although evidently good progress has

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International Crops Research Institute for the Sem.-Arid Tropics 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru, A.P., India Patancheru. A.P. India: ICRISAT.

been made in making the control operations more efficient and more cost effective.

There is one comment on Table 1. The figure of 86% for Uganda as the percentage of sorghum and millet in total cereal production is misleading in this context, since the millet is *Eleusine* (finger) millet, which is not vulnerable to birds until it has ripened. It is customary to go through the fields at intervals at harvest time, cutting the heads, as they ripen.

An important and welcome emphasis in the presentation on birds is the emphasis on training staff. Has any serious training of any kind yet been undertaken for *Striga?* Can any progress be expected until trained local staff are available?

Striga

The *Striga* paper reminds us of the variability in *Striga* populations: in all sexually reproducing organisms, much variability in morphological and physiological characters must occur. The difference in breeding systems results in *S. asiatica* being a mixture of lines, while *S. hermonthica* populations consist of heterogeneous individuals. In both cases, one has the typical interaction of host and parasite illustrated by wheat rusts: a resistant host plant automatically exercises a selection pressure on the population of the parasite which favors forms able to break down the resistance.

Crop Loss

The information on the disturbed balance of the growth hormones of the host plant is interesting, and is likely to account both for the drought symptoms, and for the disproportionate damage inflicted by the young *Striga* plant on the young host plant. However, with a crop growing in the field and reaching the grain-filling stage, the additional burden of feeding large numbers of *Striga* plants must be responsible for much crop loss. My figures showed that *each Striga* plant was associated, on average, with a gain loss of 2 to 3 g per hectare, which even at 40 000 sorghum plants/ha must represent less than the average weight of a *Striga* plant when correction has been made for the difference between the moisture content of the grain and the *Striga* plant. It.is the *Striga* numbers which are so devastating. The damaging effects of *Striga* are well established, even if difficult to quantity.

Our main concern is with *Striga* control. Proper control can only come from improved farming systems, which integrate a series of measures each of which contributes something towards the reduction of *Striga* numbers.

Resistance

The biggest component is host plant resistance, but this should be a component of a system and not the sole defence against *Striga.* The resistance required is one which results in relatively few *Striga* plants emerging and flowering, while at the same time maintaining an acceptable yield level, i.e., the host must tolerate the *Striga* plants which do establish.

The indications of an interaction between nitrogen and resistance are most interesting. It looks as though some forms of resistance are not expressed unless a minimum basic level of N is present in the soil.

Progress in breeding for *Striga* resistance has been slow: the resistance of Framida was known at least 25 years ago; other mechanisms were reported 22 years ago.

Testing

The development of the technique for assessing stimulant production marked a big step forward in the methodology of breeding for resistance. Field testing for *Striga* resistance is difficult. Obilana in Nigeria uses hill planting for early testing; ICRISAT is trying interspersing frequent control plots. I would like to see more population breeding used, allowing the *Striga* itself to select the resistant sorghums. Sorghum populations could be subdivided and grown on the relatively small patches of heavily infested *Striga* land which are characteristic of the bad *Striga* areas in Africa as well as in Asia.

Strains

Attention has been drawn to *Striga* strains. There can be no doubt about the existence of intercrop resistant strains. There are probably also intracrop resistant strains but I would like to reenforce the cautions expressed in the paper. Long-term testing is required to establish the existence of these. The variability of *Striga* populations i6 such that there can be marked seasonal differences in *Striga* numbers due to interaction with environmental differences.

The agronomic measures required to supplement resistance in the host are effective on well managed fertile land. Building up the soil fertility, including using sufficient nitrogen, herbicides, weeding out *Striga,* crop rotation with false hosts, in combination with resistant cultivars, would control *Striga* at a low level. The answer to the question "would this be economic?" must surely be " it has got to be made economic", by adjusting prices and subsidies. We cannot afford to have large areas of land abandoned because of *Striga,* or low grain yields over extensive areas for the same reason.

Once *Striga* has got a grip on the land, as it has in many parts of Africa, the measures outlined are totally inadequate. It would take years to achieve any progress. Heavy subsidies for cleaning up *Striga* infested land are inevitable, and must be faced.

Some of the enormous reservoir of *Striga* seed in the soil must be reduced. There are three possible methods:

1. Trap cropping with susceptible hosts, and plowing under before the *Striga* has flowered. This would need to be repeated several times, and in many parts of Africa it would be difficult or impossible. Were it to be done successfully, the problem of keeping the *Striga* from building up again would be considerable. This is possible on large farms, but not for the small farmer. The most effective trap crop for sorghum *Striga* is often pearl millet.

2. Ramaiah and Parker draw attention to ethylene injection, which will germinate 90% of the *Striga* seed in one application. It requires tractor-mounted injection equipment, supplemented by a backpack applicator for awkward corners. The area of the Carolinas infested with *Striga* in 1957 was around 20 000 ha. Today, it is around 150 000 ha. Ethylene injection began in 1973, when 300 ha were treated. Today, only some 4000 to 4500 ha are treated annually, because of limitation of funds. If that is the situation in the USA, one has serious doubts on how much could be achieved in the third world. The backpack applicator is not suitable for large areas: each thrust treats a cylindrical volume of some $7m^3$. It will take a long time to do 5 ha. Even if large-scale ethylene treatment were somehow done, how would the *Striga* be prevented from building up once more? Again, this is a possible approach for large farms, but not for the small farmer.

3. The third possibility is the synthetic analogues of strigol. One of the first things I did in 1972 after joining IDRC was to look for a scientist to develop strigol analogues. Professor Alan Johnson of Sussex University agreed to operate a project, and the Board of IDRC agreed to support it. Some of these compounds show good promise. GR7 combined with paraquat or oxyfluorfen was as effective as ethylene in tests in the USA, and also useful alone. There appeared to be a synergistic effect. However their value has not yet been demonstrated in the third world.

Compounds of this type hold out the best hope of a practicable method of reducing the burden of *Striga* seed in the soil. Subsidies, perhaps heavy subsidies, would be needed on the GR7, the fertilizers and the herbicides. However, I am sure that a crop rotation, with fertilizer, GR7 or other analogue of strigol used with a herbicide, together with good management of the crop (especially weeding) would get on top of the *Striga.* There would be a steady buildup in fertility accompanied by a steady decline in the number of *Striga* seeds in the soil. The land would become much more productive, and the farmer, having himself cleaned up his own land, would keep it that way.

In my view, financial help in the most cost-effective way which can be devised for the control of both *Striga* and birds should be a major concern of donor agencies. This approach would be of much greater value than some of the large-scale production schemes; much grain could be saved, as these papers have demonstrated. I would strongly urge the need for more donor agency support. There is only one solitary scientist, a plant breeder, working full-time on *Striga* in the whole of developing Africa. Yet it is the most serious problem, other than perhaps birds. At least one team of scientists is essential, and further support is needed for the bird control work.

I have commented only on a few topics in the *Striga* section of this comprehensive paper, but the proceedings of the recent *Striga* Workshop at Ouagadougou go thoroughly into many of the problems discussed by the authors.

Finally, let me add that I found both papers comprehensive and very informative: they form an excellent basis for our discussions.

Session 3 Factors Reducing Sorghum Yields *Striga* and Birds

Discussion

Stoop

The *Striga* problem in West Africa is generally associated with soils of very poor fertility. Therefore a more permanent solution to this problem is to be expected from improved soil fertility management (including use of manure, besides chemical fertilizers alone) rather than from direct chemical control measures.

Parker

I consider that the basic solution to the *Striga* problem is good farming which must include better soil fertility and structure. However, there are areas where this is going to be a very long-term solution unless a direct assault on the *Striga* seed reservoir in the soil can be made. I like the GR 24 + herbicide approach because it can be used by the farmer as a part of the process of building up the farm.

Parvatikar

In India there is a contention that if coriander is grown mixed with sorghum, then the *Striga* incidence is less; comments please.

Ramaiah

I heard about this beneficial effect, but I failed to verify this under laboratory conditions by mixing the root exudates of sorghum and coriander in different concentrations. This did not suppress the *Striga* seed germination. This is a very good concept and there is need to study various crop combinations for beneficial effects in suppressing *Striga.*

Thobbi

What is the future of the insect *Smycronix* as a biological agent in the control of *Striga?*

Ramaiah

Several insects have been reported feeding on *Striga* plants including *Smycronix.* When it attacks the capsule it is very effective in preventing seed set. However, the population of this parasite is too low to be considered effective and because there are still large numbers of capsules which produce seeds, the *Striga* problem remains alive. The efficiency of biological control needs review.

Balasubramanian

I would like to ask Dr. Ramaiah what method he would use to classify sorghum cultivars as low stimulant types and high stimulant types. How could you quantify this?

Ramaiah

We did this by a standard screening technique which involves pretreatment of *Striga* seeds under optimum moisture conditions in an incubator maintained at 25°C. Sorghum seedlings are grown for one or two weeks in small pots from which the root exudate is extracted. This exudate is put on the ready-to-germinate *Striga* seeds. The number of germinated *Striga* seeds is expressed as a percentage of susceptible check. Those lines with 10% *Striga* germination are low stimulant types and the rest are high stimulant.

M. J. Vasudeva Rao

1. In view of the fact that we do not have any absolute resistance to *Striga.* the resistant varieties do not appear to be the answer to *Striga* control. However, it must be recognized that it is an integral part of an agronomic package to control *Striga* and a lot more effort is required to develop an integrated approach.
2. Recently, we have noticed that *Striga* is not a single type as we earlier thought, but that it is a polymorphic complex, i.e., many morphological types exist in any one field. This has much wider implications. Therefore, I strongly feel that more work must be initiated on understanding the biology of *Striga.*
3. There is no need to be pessimistic about the

progress in breeding for *Striga* resistance. Several advanced generation derivatives, both from Upper Volta and Hyderabad are doing well.

Alahaydoyan

The use of strigol-like compounds to force germination in *Orobanche* spp, which are important parasites on *Solanaceae* in Lebanon, failed very drastically at the evaluation stage. Although the general idea is good and in the test tube, under controlled conditions they might work, the conditions in the soil where they will be used are so complex that one needs to study the use of these chemicals very carefully and refrain from the propaganda they are given before anything concrete, based on reproducible data, is proven.

King

I very much agree with Dr. Doggett's statement that host plant resistance is the most logical approach for attacking the *Striga* problem and that its solution will require a sizable team effort. Because the *Striga* plant is in reality a plant pathogen, I believe that such an effort should include considerable input from the perspective of pathology.

Nicou

I think that not much emphasis has been given to to agronomic techniques concerning the control of *Striga.* In Senegal, where *Striga* is found mainly on pearl millet, it has been demonstrated that when the soil fertility improved, *Striga* disappeared. Besides, it is known that *Striga* is not a problem on research stations. Dr. Ogbom has shown that shade has a negative effect on *Striga.* When sorghum or millet grow well and fast, *Striga* finds it difficult to grow. Farming systems, particularly the preparation of soil, play an important role in this case. And finally, it has been proved that the uprooting of *Striga* before flowering makes it disappear completely within 2 or 3 years. It is perhaps a painful task but this shows that the simplest techniques are often excellent and that fertility improvement remains the best long-term means of control of *Striga.*

Jotwani

Mention was made about the biological control of *Striga.* A weevil and a caterpillar pest have been recorded on *Striga* and were quoted as examples. We have to approach this aspect cautiously as these pests, under certain conditions, may become pests of other cultivated crops and may cause more harm than the expected benefit.

M. J. Jones

I would be grateful if Dr. Parker could make some comment on the specificity of different strains of *Striga* for particular cereal crops; i.e., millet, sorghum, maize and the persistence of this specificity'under field conditions. This has considerable relevance to use of rotation to minimize *Striga* damage.

Parker

In most areas, sorghum is not attacked by the millet strains of *Striga* and also millet is not attacked by sorghum strains. Maize sometimes shows resistance to the above strains but this resistance generally fails with continued cropping.

Parvatikar

If 2,4-D is to be used as a control measure for *Striga,* then how often will it have to be sprayed? The *Striga* emergence continues for quite a long time; and one spray may not be effective. Will it be economical to give 2-3 sprays?

Parker

For greatest effect 2,4-D needs to be present near the germinating *Striga* seed. The timing and need for multiple applications will depend on the seasonal pattern of germination. More than one application may well be needed, but could still be economic under some circumstances.

Parvatikar

How is *Striga* established in pot experiments?

Parker

Striga seed (about 1000 per pot) are mixed with the top 6-8 cm of soil in 12-15 cm diameter pots. Crop seeds are sown into the soil and watered normally. At suitable temperatures, emergence of *Striga* can be reliably expected within 4-6 weeks.

Bunting

In the eastern clay plains of the Sudan, *Striga* does not attack the wild sorghum which is the dominant grass species. Cultivated sorghum which is often attacked by *Striga,* is the main crop of the region. Many fields of cultivated sorghum are surrounded by hybrid swarms through which they are in genetic contact with the wild forms. Perhaps exploration in this region would lead us to valuable new sources of resistance to *Striga.*

Parker
Most wild sorghum of the S. *arundinaceum* type in west Africa is attacked by *Striga* but it would certainly be well worth looking at other types in Sudan for their possible resistance.

King
I question whether tolerance to *Striga* is really an appropriate objective in a breeding program for its control. Although yield loss can be reduced by this means, tolerant genotypes support growth of an abundance of *Striga* plants which further infest soil with seed for years to come. Would it not be better to focus genetic control measures on resistant genotypes which not only improve yield but at the same time support the growth of only a limited number of *Striga* plants?

Parker
I agree that tolerance should not be a primary breeding objective, but there are almost certainly very large differences in the inherent tolerance of sorghum varieties to *Striga* attack. Many local types may be relatively little affected. If attention were paid to determining the tolerance of the better semiresistant varieties, it could lead to the selection of the more tolerant of those varieties for use in further breeding work. We do not expect to achieve total resistance, some tolerance will help to ensure the least damage from the low levels of attack that will still tend to occur, at least under suboptimal conditions.

Obilana
It makes me feel better to hear one of the longest workers on sorghum and its production problems in Africa. Dr. Doggett has exactly put the amount of crop loss in sorghum in its right perspective. It is very true that we have problems in Africa concerning *Striga.* The solution to the problem needs to be institutionalized by the countries in Africa with a lot of financial support and staffing, and the problem is confounded and complicated by the presence of only a very few researchers in *Striga* studies and control. In addition, a further problem arises from the fact that the few resistant cultivars and elite varieties identified and developed (as in Nigeria) are not very acceptable for food quality requirements. It is therefore very necessary to increase the number of researchers in *Striga* control and resistance studies if any effective results are expected soon.

Riccelli
Has the toxicity of pesticides used to control birds in relation to grain consumption been studied?

Bruggers
Yes, there are residue data on methiocarb both as a topical application to ripening sorghum and as a seed dressing. As a topical application of 2 kg/ha, the half-life is 6-7 days and the residues are 3.5 ppm on the seed itself and 24 ppm on the seed+glume, 3 weeks after application. As a seed dressing of 0.2% by seed weight, the residues are from 1-2 ppm after 20 days. At normal repellent use levels, it is a safe chemical.

D. B. Jones
1. It sounds as if methiocarb is a deterrent rather than an avicide and it appears that the tests have been fairly localized. This makes me wonder whether the effect is yet another preferential one. With general 100% use, will it still work?
2. Comment to Dr. Doggett/Bruggers: We do not know the cost-benefit ratio of bird control.

Bruggers
Methiocarb is a deterrent, i.e., a repellent and not an avicide, and most tests have been in localized situations although the sizes of the fields have ranged from < 100 m^2 to 1100 ha. It would not be economically feasible to use it as a generalized control strategy over large areas. It is one technique that is applicable in certain situations either alone or in combination with other methods and should be accepted on that basis.

Jotwani
1. Has methiocarb been found to be effective against *Quelea* and other bird species?
2. Is methiocarb registered for use on sorghum in any country and is there any tolerance limit fixed for sorghum grains and fodder?

Bruggers

1. Yes, It has been effective on pest birds in Uruguay and on other pest birds in Africa besides *Quelea.*
2. No, it is not registered for use on sorghum as a bird repellent in any country to my knowledge. There just is not the demand as yet, although there are discussions at present to this effect in the United States. It is registered for use on several fruits and as a seed dressing in the USA.

Chaudhary

In Mexico we have tremendous sorghum grain damage due to birds. However, we have observed in the northern part of the Mexico that there are some birds that feed on the sorghum seedlings causing considerable loss. Dr. Bruggers, I wonder if you have come across birds damaging sorghum seedlings in Africa.

Bruggers

Yes, birds do occasionally take newly sown sorghum seed in Africa, but not on a large scale. Most damage or losses to newly sown seed and seedlings are from wading birds and ducks to rice seed. This has been minimized on several occasions using a methiocarb seed dressing.

Riccelli

In the Caribbean area, there is a migrant sparrow from the U.S. that causes severe damage in sorghum every year. We have observed that tannin in the grain is effective as long as other nonbrown sorghums or other grains (rice, for example) are present. Afterwards, birds eat brown sorghum as well. What has been the experience in Africa?

Doggett

Exactly the same. Bird resistance is relative; when the brown sorghums are the only food available they get wiped out.

Rana

The migratory pattern of *Quelea* in East Africa is well defined and fixed. In Western Kenya, the *Quelea* birds appear in August. However, the sowing season starts in March and long-duration (150-180 days) sorghums grown are some times attacked. We in the FAO Kenya Sorghum and Millet Development Project followed the strategy to select 100-day maturing varieties which can be harvested 50 days before the arrival of birds. We feel that a change in genotypes and cropping pattern can help to minimize the loss to cereal crops.

Session 4

Genetic Resources

Chairman: J. M. J. de Wet
Co-Chairman: F. R. Miller

Rapporteurs: K. E. Prasada Rao
S. Appa Rao

Current Situation and Future of Sorghum Germplasm

M. H. Mengesha and K. E. Prasada Rao*

Collection and conservation of sorghum germplasm was accelerated about two decades ago because of the danger caused to the landraces by the release of new varieties and hybrids. For example, "Zera-zera" and "Hegari" landraces of sorghum once present in the Gezira province of Sudan are now completely out of cultivation (Prasada Rao and Mengesha 1980). Although landraces are still found in Africa and Asia in large areas, it is no longer safe to expect that the same situation will exist after another 10 years. Our recent experience shows that several primitive landraces once abundant in parts of Africa and Asia are now extinct. Therefore, we are now in a critical, transitional stage when there is an urgent need to collect and conserve the traditional landraces and their wild relatives at an accelerated pace.

The first major effort in the assembly of a world collection of sorghum was made in the sixties by the Rockefeller Foundation in the Indian Agricultural Research Program (House 1980; Murty, et al. 1967; Rockefeller Foundation 1970). A total of 16 138 accessions were assembled from different countries and were assigned IS. (at that time "Indian Sorghums") numbers. An assessment of this collection indicated that only half the total number of the accessions is an authentic-indigenous collection representing field collections with sufficient information about its origin (Harlan 1972).

Of these 16 138 I.S. numbers only 8961 could be transferred to ICRISAT by the All India Coordinated Sorghum Improvement Project (AICSIP), Rajendranagar, India, in 1974 because the remainder had lost their viability due to a lack of proper storage facilities before they could be transferred to ICRISAT. Special efforts were made by ICRISAT to fill the gaps, by obtaining duplicate sets from Purdue University; the National Seed Storage Laboratory, Fort Collins, USA, and from Mayaguez, Puerto Rico; this yielded 3000 of the missing accessions thus leaving a permanent gap of about 4000 accessions in the world collection presently conserved in the ICRISAT gene bank (Mengesha et al. 1979). The efforts will continue as long as there are gaps. However, it is unlikely that many more will be retrieved.

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Assembly of Germplasm

The addition of sorghum gemplasm to the world collection that had been assembled by the Rockefeller Foundation, became the responsibility of ICRISAT and is being carried out in accordance with the recommendations made by the Advisory Committee on Sorghum and Millets Germplasm sponsored by the International Board for Plant Genetic Resources (IBPGR)/FAO (IBPGR 1976b).

The year-by-year collection and assembly is shown in Figure 1. So far there have been 9486 new accessions from 68 countries through collection expeditions and correspondence. All germplasm that is imported to ICRISAT must first be received, inspected and released by the Quarantine Authority of the Government of India. The Central Plant Protection Training Institute (CPPTI), Ministry of Agriculture, located at Rajendranagar, is charged with the responsibility of quarantine clearance for the importation of ICRISAT's major crops.

At present, ICRISAT is the major repository for the world sorghum germplasm with a total collection of 21 264. The accessions listed according to

International Crops Research Institute for the Semi-Arid Tropics 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81. Patancheru, A.P., India Patancheru, A.P. India: ICRISAT.

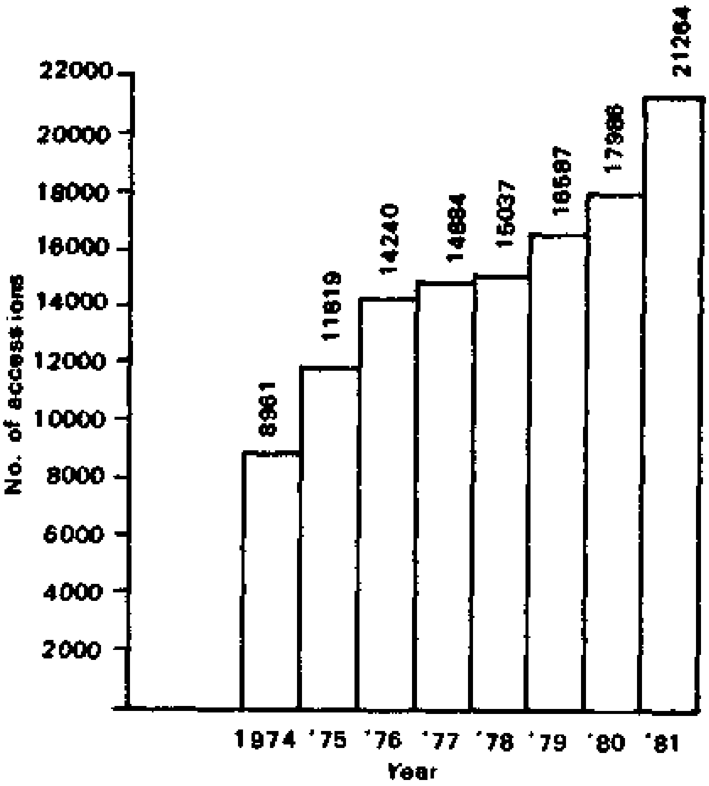

Figure 1. Sorghum germplasm collection and assembly at ICRISAT from 1974 to 1981.

their country of origin can be seen in Table 1. Among the major donors, the most important ones are the Ethiopian Sorghum Improvement Project, Ethiopia, Gezira Agricultural Research Station, Sudan, and the All India Coordinated Sorghum Improvement Project and agricultural universites of India. It is also interesting to note that about 80% of the total sorghum collection has come from the developing semi-arid tropics.

Past Collection Missions

As of today, the countries relatively well-represented are Ethiopia, India, Sudan, and Cameroun, for these have contributed more than half of the present world collection. The Advisory Committee on Sorghum and Millets Germplasm sponsored by IBPGR/FAO, and ICRISAT identified conspicuous gaps in .the collection and made recommendations for collections indicating the priority areas (IBPGR 1978 and 1979). The progress made in recent years in covering the specific geographical gaps is summarized in Table 2.

Priority Areas of Future Collection

Priority areas of collection are determined by the extent of genetic erosion that different areas of diversity face and not necessarily by the abundance of germplasm that exists (IBPGR 1976a). In view of the urgency of the task, those areas that are known to have landraces, and those that are threatened by accelerated breeding programs and for other reasons are given high priority for collection. Such priority areas of collection are identified in consultation with sorghum scientists around the world. The best forum for such activity has so far been the IBPGR/FAO Advisory Committee on Sorghum and Millets Germplasm. In our opinion, IBPGR's effort in this area is commendable. Furthermore several individuals, institutes, organizations and foundations have made substantial contributions in identifying priority areas for sorghum germplasm collection throughout the world (IBPGR 1976b; Harlan 1972; 1976; Gebrekidan 1979).

Figure 2 shows the important areas of collection worldwide and the priority areas for the present and future collection are shown in Table 3. New areas could be added to the list as we get fresh information from sorghum workers. Recently, for example, there have been strong recommendations that we should explore the sorghum germplasm in some parts of Central and South America which have previously received little attention.

Collection Strategies

Two distinct methods are followed in our collection strategies. They are general germplasm collection and pointed collection. A general collection is usually from a new and priority area of collection for the purpose of collecting and conserving random representatives of the available germplasm. A pointed collection is mounted in a well-known area where a special effort is made to recover specific characters with different agronomic background. Obviously, both types of collection are useful for specific purposes. The world collection can be enriched through cooperation of scientists and collaboration between national and international organizations and agencies. Nowadays, the thrust in germplasm collection and conservation is further strengthened by a number of national organizations in the areas of concern.

Table 1. Sorghum germplasm collection status at ICRISAT (May 1981).

S.No.	Source	Assembled by Rockefeller Foundation	Assembled by ICRISAT up to May 1981	Total
	Africa			
1	Angola	23	6	29
2	Benin	1	3	4
3	Botswana	28	162	190
4	Cameroun	1 753	82	1 835
5	Central African Republic	37	2	39
6	Chad	125	13	138
7	Egypt	15	7	22
8	Ethiopia	1446	2 667	4113
9	Gambia	1	—	1
10	Ghana	11	53	64
11	Ivory Coast	1	—	1
12	Kenya	313	448	761
13	Lesotho	—	7	7
14	Malagasy Republic	—	1	1
15	Malawi	58	312	370
16	Mali	95	16	111
17	Morocco	—	3	3
18	Namibia	—	1	1
19	Niger	25	383	408
20	Nigeria	897	276	1 173
21	Senegal	11	219	230
22	Sierra Leone	—	3	3
23	Somalia	5	120	125
24	South Africa	483	176	659
25	Sudan	855	1400	2 255
26	Swaziland	18	1	19
27	Tanzania	31	102	133
28	Uganda	471	141	612
29	Upper Volta	160	56	216
30	Zaire	24	—	24
31	Zambia	3	207	210
32	Zimbabwe	123	63	186
	Asia			
33	Afghanistan	5	1	6
34	Bangladesh	—	9	9
35	Burma	2	6	8
36	China	24	44	68
37	India	2 732	1 295	4 027
38	Indonesia	6	26	32
39	Iran	6	1	7
40	Iraq	2	2	4
41	Israel	22	—	22
42	Japan	106	5	111

Continued

Table 1. *Continued*

SNo	Source	Assembled by Rockefeller Foundation	Assembled by ICRISAT up to May 1981	Total
43	Lebanon	—	179	179
44	Nepal	7	1	8
45	Pakistan	18	11	29
46	Philippines	1	4	5
47	Saudi Arabia	—	1	1
48	South Korea	2		2
49	Sri Lanka	—	25	25
50	Syria	—	4	4
51	Taiwan	12	1	13
52	Thailand	5	—	5
53	Turkey	1	50	51
54	Yemen	—	27	27
55	Yemen D Ft	—	1	1
56	USSR	5	64	69
	Europe			
57	Belgium	—	1	1
58	Cyprus	1	—	1
59	France	5	—	5
60	Greece	1	—	1
61	Hungary	—	22	22
62	Italy	8	—,	8
63	Portugal	—	6	6
64	UK		1	1
	Americas			
65	Argentina	2	14	16
66	Cuba	1	2	3
67	El Salvador	—	1	1
68	Gautemala	—	6	6
69	Honduras	—	1	1
70	Mexico	207	27	234
71	Nicaragua	—	1	1
72	Spain	—	3	3
73	Uruguay	—	1	1
74	USA	1 208	659	1 867
75	Venezuela	—	1	1
76	West Indies		3	3
	Australia and Oceania			
77	Australia	6	22	28
78	New Guinea	—	1	1
	Unknown	370	27	397
	Total	11 778	9 486	21 264

At the international level, the sorghum collection and conservation effort is being undertaken by ICRISAT in close collaboration with several national programs, the IBPGR, and FAO. It is also most gratifying to note that the Semi Arid Food Grain Research and Development (SAFGRAD) program and the Institute du Sahel have recognized germplasm collection and conservation as one of their important objectives. The recent establishment of the Pan African Germplasm Collection and Conservation Committee is also considered a move in the right direction.

Experience has shown that well-planned germplasm collection missions are bound to be successful even though they may face some unexpected problems. The planning should be effected ahead of time and in close consultation with all concerned. The most successful and rewarding collection missions so far have been those that were launched jointly in close collaboration between ICRISAT (in our case) and national organizations in the country of collection. Those expeditions that are attempted without proper and advance planning are bound to fail and will become a rather frustrating and costly experience. They may also lead to misunderstanding and strain between cooperating agencies.

In most ICRISAT germplasm collection missions, several organizations, agencies, institutions and individuals have played key roles in the planning and implementation of the mission (Table 4.)

Assignment of I.S. Numbers

As a result of the 1978 recommendation of the IBPGR/FAO Advisory Committee on Sorghum and Millets Germplasm, ICRISAT has been given the responsibility to assign I.S. (International Sor-

Table 2. Progress made in covering specific geographical gaps in the world collection.

Priority area	Collection Organization	Remarks
Western Africa		
Mali	FAO/ORSTOM*	Collection not reached ICRISAT
Niger	FAO/ORSTOM	Mostly guinea sorghums
Togo	FAO/ORSTOM	Collection not reached ICRISAT
Eastern Africa		
Ethiopia (Gambella area)	ICRISAT/IBPGR	Good Zera-Zeras
Malawi	ICRISAT/IBPGR	Mostly guineas
Mozambique	ICRISAT/IBPGR	In transit. Few accessions
Somalia	ICRISAT/IBPGR	Mostly durras
Sudan (Eastern)	ICRISAT/IBPGR	Mostly caudatums and Zera-zeras
Tanzania	ICRISAT/IBPGR	Mostly guineas and caudatums
Zambia	ICRISAT/IBPGR	Mostly guineas
Southern Africa		
Botswana	ICRISAT/IBPGR	Good kafirs and half kafirs
Asia		
India	ICRISAT	Hill sorghums, primitive landraces, scented and pop sorghums.
Philippines	ICRISAT	Very few samples
Sri Lanka	ICRISAT	Very few samples
Yemen	USAID	Not reached ICRISAT

* ORSTOM = Office de la Recherche Scienttfique et Technique d'Outre-Mer.
Other accessions have recently been received from China. USSR, Turkey and Hungary.

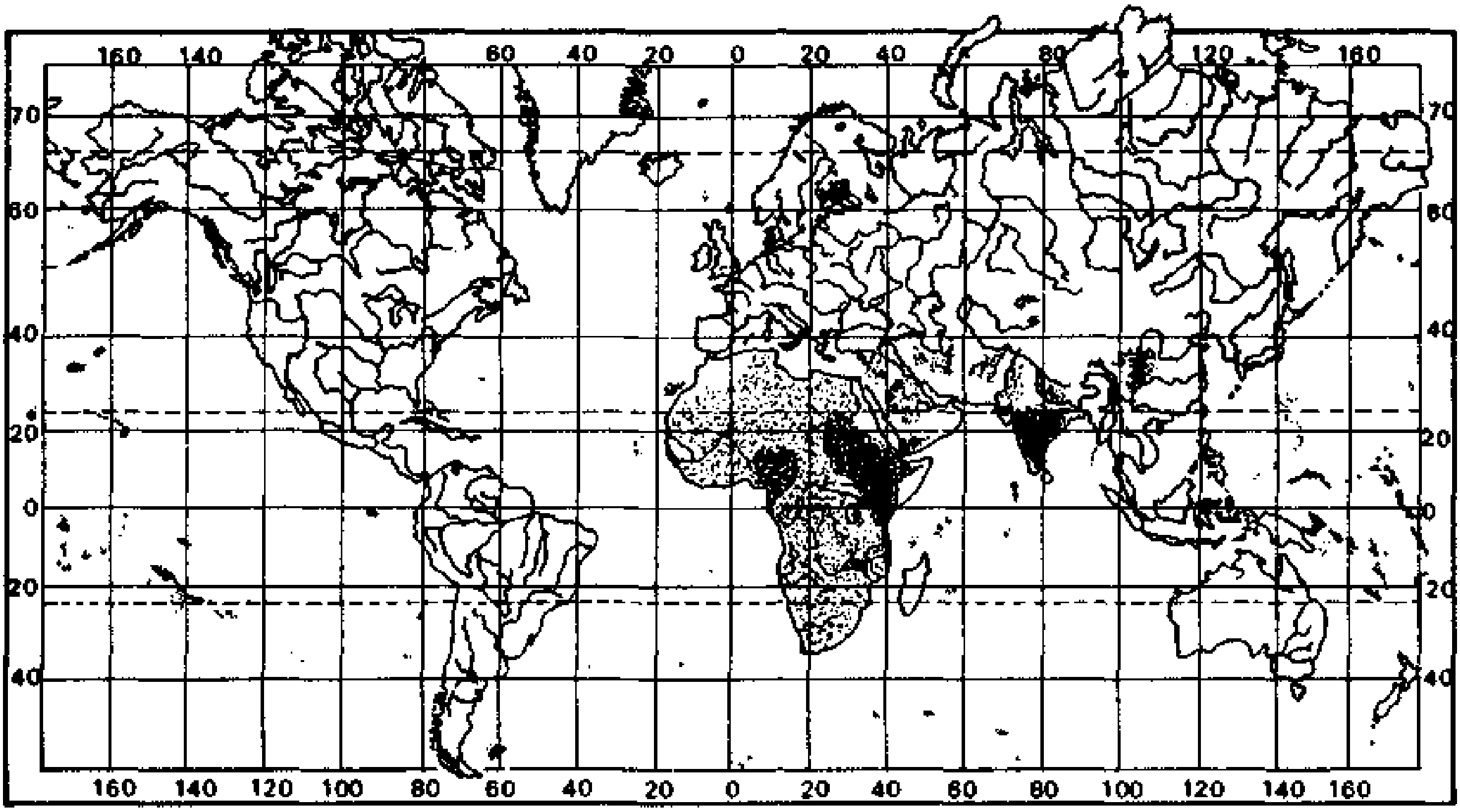

Figure 2. Important areas of sorghum germplasm collection.

Table 3. Priority araas for sorghum garmplasm collection.

Area	Status of Collection	Remarks
Africa		
Algeria	not collected	to be explored
Angola	few accessions	to be collected
Benin	very poor representation	to be collected
Burundi	not collected	to be explored
Cape Verde	not collected	to be explored
Central-African Republic	not collected	to be collected
Chad	few accessions	to be collected
Congo	not collected	to be explored
Egypt	few accessions	to be explored
Guinea	not collected	to be explored
Guinea Bissau	not collected	to be explored
Ivory Coast	not collected	to be collected
Libya	not collected	to be explored
Mali	collection not reached ICRISAT	to be assembled or recollected
Mauritania	not collected	to be collected
Mozambique	few accessions	to be collected
Nigeria (north)	partly collected	fuller coverage
Rwanda	not collected	to be explored
Sierra Leone	not collected	to be explored
S. W. Africa	not collected	to be explored

Continued

Table 3. *Continued*

Area	Status of Collection	Remarks
Togo	Collection not reached ICRISAT	to be assembled
Tunisia	not collected	to be explored
Uganda	partly collected	fuller coverage
Zaire	few accessions	to be collected
Zimbabwe	partly collected	to be recollected
Near East		
Syria	few accessions	to be explored
Lebanon	mostly experimental accessions	to be explored
Jordan	not collected	to be explored
Iran	few accessions	to be explored
Saudi Arabia	not collected	to be explored
Yemen	collection not reached ICRISAT	to be assembled or recollected
Asia		
Afghanistan	few accessions	to be explored
China	few accesions	to be assembled or collected
Pakistan	few accessions	to be collected
India	collected except Assam, Sikkim and some pockets	to be collected
Nepal	not collected	to be collected
Burma	few accessions	to be explored
Laos	not collected	to be explored
Cambodia	not collected	to be explored
Vietnam	not collected	to be explored
Indonesia	few accessions	to be collected
Philippines	few accessions	to be collected

Table 4. Cooperators involved in ICRISAT germplasm collection missions.

FAO/IBPGR	National Agencies
1. IBPGR — Rome	1. Ministries of Agriculture.
2. FAO —Country representatives	2 Agricultural Research Institutes.
3. Field-Consultants	3. Universities.
	4. District Agricultural and Administrative Officers.
	5. Crop Improvement Scientists and Students.
	6. Agricultural Extension Agents
	7. Farmers, above all.

ghum) numbers to the new collection in continuation to the world collection previously assembled by the Rockefeller Foundation. This important task is being implemented in broad consultation and without losing sight of the need to record the original pedigree references. So far, I.S. numbers have been assigned to new germplasm at ICRISAT from I.S. 16139 to I.S. 20887 in continuation of the catalog published by the Rockefeller Foundation. This assignment of I.S. numbers will continue and a catalog will soon be published.

Evaluation and Documentation

The importance of a broad genetic base in evolving new cultivars is well recognized. Consequently the careful evaluation of sorghum germplasm for morpho-agronomic characters—insect, disease, *Striga* and drought resistance—is the first step in the exploitation of genetic variability. The recent development of "List of Sorghum Descriptors" (IBPGR/ICRISAT 1980) will promote a more systematic and uniform system of evaluation around the world, which will in turn enhance a common language and better understanding among sorghum improvement scientists.

The evaluation and characterization of germplasm is continuing. Data tabulated for 7114 I.S. numbers in the 1974 postrainy season and the 1975 rainy season were computerized at IS/GR Colorado using the EXIR program. The same data were transferred to the ICRISAT computer through a magnetic tape and a computer printout was produced in the form of a catalog. The data for the remaining accessions are being compiled for documentation and computerization in a retrieval system. The delay in the documentation is caused by our desire to fill the missing gaps before computerization.

Screening the sorghum germplasm for insect, disease, *Striga* and drought resistance, etc., is being conducted in collaboration with other disciplines (Table 5).

Evaluation of sorghum germplasm in the rainy season *{kharif)* of Patancheru cannot give us complete information, for most of the tropical germplasm accessions are photoperiod sensitive. That is why we place much importance on future evaluation of germplasm near their original habitat. This project could be started at carefully selected regional centers in collaboration with national programs.

In order to have an effective and easy flow of tropical germplasm into various sorghum improvement programs around the world, an Introgression and Conversion Project was initiated in 1976 at ICRISAT Center. Exotic germplasm such as selected landraces from Ethiopia (ET numbers) were crossed and backcrossed to adapted cultivars, 109 selections of the introgressed material were supplied to ICRISAT breeders and the remaining seed is stored for future use by interested sorghum scientists anywhere in the world (Prasada Rao and House 1979). At present we are in the process of converting "Zera-zera" landraces from Sudan and Ethiopia which are highly prized for their superior agronomic characters but are of restricted utility because of their photoperiod sensitivity and plant height.

Table 5. Sorghum germplasm accessions screened at ICRISAT.

Screened for	No. of accessions	No. of promising lines	Described by
Disease resistance	7 429	64	Sorghum Pathology
Insect resistance	7 874	323	Sorghum Entomology
Striga resistance (Lab. screening)	15 504	671	Sorghum Breeding
Drought resistance	1 075	133	Sorghum Physiology & Breeding

Range of Variation

A wide range of variability has been observed in sorghum germplasm for several morpho-agronomic characters such as maturity, plant height, plant pigmentation, midrib colors, head length and width, head compactness and shape, glume color, covering, grain color, size and weight, etc. The range of variation is summarized in Table 6.

Types of Collection

The different types of collections maintained at ICRISAT are the following, which have been suggested by several sorghum workers (Harlan 1972).

1. Accessions collection: this includes the available world collection and new accession assembled by ICRISAT. A seed sample of about 500 g of each accession is maintained.
2. Spontaneous collection: these are the wild and weedy races that are being maintained separately; at present, the wild and weedy accessions being maintained at ICRISAT are listed in Table 7.

Table 6. Range of variation in selected characters of sorghum.

S.No.	Descriptors	Range of variation	
1	Days to 50% flowering (no. of days)	36	199
2	Plant height (cm)	55	655
3	Pigmentation	Tan	Pigmented
4	Midrib color	White	Brown
5	Peduncle exsertion (cm)	0	55.0
6	Head length (cm)	2.5	71.0
7	Head width (cm)	1.0	29.0
8	Head compactness and shape	Very loose stiff branches	Compact oval
9	Glume color	Straw	Black
10	Glume covering	Fully covered	Uncovered
11	Grain color	White	Dark brown
12	Grain size (mm)	1.0	7.5
13	100-seed weight (g)	0.58	856
14	Endosperm texture	Completely corneous	Completely starchy
15	Threshability	Freely threshable	Difficult to thresh
16	Luster	Lustrous	Nonlustrous
17	Subcoat	Present	Absent

Table 7. Wild and weedy sorghum germplasm accessions maintained at ICRISAT.

Sections	Species	Subspecies	Race	No. of accessions
Para' Sorghum	S. *versicolor*	—	—	2
	S purpureosericeum			4
	S. dimidiatum	—	—	4
Eu-Sorghum	*S. halepense*	—	halepense	9
			almum	9
	S. bicolor	*arundinaceum*	arundinaceum	6
			virgatum	2
			verticilliflorum	19
			aethiopicum	5
		drummondii	shattercanes	107
				167

3. Named cultivar collection: this collection includes 237 named cultivars released by private and public institutions in different countries. Two kg seed samples are maintained to meet seed requests.
4. Genetic stock collection: this collection includes all the resistant lines, stocks with known genes and cytoplasmic-genic male steriles. One kg seed samples are maintained by selfing except in the case of male-sterile lines which are maintained by hand pollination.
5. Conversion collection: 176 I.S. conversion

lines from USA are maintained. A conversion program at ICRISAT has been initiated and after conversion lines will be added.

6. Basic collection: a basic collection consisting of about a thousand accessions was selected from the world collection and stratified taxonomically. geographically and based on their ecological adaptation at Patancheru location. This exercise needs to be repeated at other locations for the selection of comprehensive basic collections for different regions.

Maintenance

All collections *are* maintained by selfing about 20 representative heads in each line. Seed harvested from these heads is mixed and a bulk of about 500 g is preserved in bottles. One to two kg samples are maintained for named cultivars and genetic stocks where seed demand is more. *Cytoplasmic male-sterile lines are maintained* by hand pollination with their counterpart B lines.

Distribution

If the world collection is to serve a useful purpose, it should be readily available to all the sorghum research institutions and agricultural universities. A principal service of the ICRISAT gene bank is to distribute viable and clean seeds to all sorghum improvement scientists who wish to utilize them in their research program. All export of seed material from ICRISAT must pass through the Indian Plant Quarantine Authority which is facilitated by the Export Quarantine Laboratory established at ICRISAT Center. Table 8 shows the magnitude of germplasm distribution by ICRISAT.

Conservation

Germplasm forms the base material for any crop improvement work. All the efforts for collection, evaluation and documentation would be a waste if the germplasm is not maintained and conserved properly. It is very difficult to grow the many thousands of sorghum accessions every 3 or 4 years for rejuvenation. This is an expensive procedure since it requires land, staff, and other facilities for growing and harvesting the crop. Furthermore it-is difficult to retain the original characteristics of each accession free from outcrossing, mutation and mechanical mixture. In order to avoid such extra work, time, money and energy, the material must be stored on a long-term basis. Three different types of storage are planned for sorghum germplasm—short-term, medium-term and long-term storages. Short and medium-term cold storage facilities are ready at ICRISAT. The long-term cold storage facility is under construction. In addition it is envisaged to use the National Seed Storage Laboratory (NSSL), Fort Collins, Colorado, USA and gene banks in Africa as backup (duplicate) storage for long-term conservation and safety.

The worldwide collection, mobilization and conservation of germplasm has lately caused anxiety in some developing countries. The main reason for that is the fear that the developing countries, where almost all of the sorghum landraces are found, are being robbed of their genetic resources. The paramount factor is that the entire world is gradually losing its landraces. Whatever landrace that still exists in nature must be collected and conserved without delay. That is exactly what the International Centers are trying

Table 8. Sorghum germplasm distribution up to June 1981.

Year	Within ICRISAT	To Indian Institutions	To Institutions abroad	Total no of samples
1973			3	3
1974	4 133	3	359	4 495
1975	6 574	2 102	1 090	9 766
1976	3 977	1 788	2 729	8 494
1977	11 691	2 841	3 429	17 961
1978	8 563	2 159	693	11 415
1979	7 870	3 720	5 785	17 375
1980	23 197	1 798	1 897	26 892
1981	14 534	2 489	3 807	20 830

to do. Not only do they collect and conserve the germplasm in their gene banks, but they also encourage and assist developing countries to do the same. In all cases, a duplicate of the collected germplasm is left with the host country. The assembled material in the ICRISAT gene bank belongs to all those who contributed and those who could utilize it in their own environment anywhere in the world. And its distribution from the ICRISAT gene bank is prompt and free of charge.

Our Outlook in the Eighties

1. Continuation of germplasm collection in the priority areas with some emphasis on wild relatives.
2. Evaluation, documentation, analysis and interpretation of the data generated.
3. Assessment of our collection efforts in terms of genetic conservation and utilization.
4. Development of regional germplasm evaluation and conservation centers primarily in Africa.
5. Promotion and implementation of special biological studies in germplasm viability, biosystematics, interspecific crosses, conversions and introgressions and population studies in close collaboration with universities and agricultural research institutes of the developed and developing nations.
6. Development and utilization of a long-term cold storage facility.
7. Establishment of institutional linkage in genetic resource activities between ICRISAT and other international and national organizations, universities and gene banks.

References

DE WET, J. M. J., and HARLAN, J. R. 1971 The origin and domestication of *Sorghum bicolor.* Economic Botany 25:128-135.

GEBREKIDAN, B. 1979. Sorghum genetic resources in Africa. Ethiopian Journal of Agricultural Science 1 :108 -115.

HARLAN, J. R. 1972. Genetic resources in sorghum. Pages 1-13 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co.

HARLAN, J. R., and STEMLER. A. 1976. The races of sorghum in Africa. Pages 465-478 *in* Origins of African plant domestication, eds. J. R. Harlan, J. M. J. de Wet, and A. Stemler. The Hague, Netherlands: Mouton.

HOUSE, L. R. 1980. A guide to sorghum breeding. Patancheru. A.P., India: ICRISAT. 231 pp.

IBPGR (International Board for Plant Genetic Resources). 1976a. Priorities among crops and regions. IBPGR/76/8. Rome, Italy: IBPGR.

IBPGR. 1976b. Proceedings of the Meeting of the Advisory Committee on Sorghum and Millets Germplasm, ICRISAT, 3-7 Oct, Hyderabad, India.

IBPGR. 1978. Proceedings of the 2nd Meeting of the Advisory Committee on Sorghum and Millets Germplasm, ICRISAT, 9-12 Jan, Hyderabad, India.

IBPGR. 1979. Proceedings of the 3rd Meeting of the Advisory Committee on Sorghum and Millets Germplasm, ICRISAT, 19-20 Sept, Hyderabad, India.

IBPGR/ICRISAT. 1980. Sorghum descriptors. Rome, Italy: IBPGR.

MENGESHA, M. H., PRASADA RAO, K. E., and APPA RAO, S. 1979. The status of cereals germplasm at ICRISAT. ICRISAT Genetic Resources Unit working paper.

MURTY, B. R., ARUNACHALAM, V., and SAXENA, M. B. L. 1967. Classification and catalogue of a world collection of sorghum. Indian Journal of Genetics and Plant Breeding 27 (Special Number): 1-312

PRASADA RAO, K. E., and HOUSE L. R. 1979. Introgression of exotic germplasm. Sorghum Newsletter 22:6.

PRASADA RAO, K. E., and MENGESHA, M. H. 1980. Sorghum and millets germplasm collection in Eastern Sudan. Genetic Resources Unit ICRISAT progress report-16.

ROCKEFELLER FOUNDATION 1970. World collection of sorghums. List of pedigrees and origins. Rockefeller Foundation, Indian Agricultural Program, New Delhi, India.

Utilization of Germplasm in Sorghum Improvement

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The amount of genetic variability available in sorghum *[Sorghum brcolor* (L) Moench] is immense. Much of this genetic variability is still available in areas of the first domestication of the crop (Africa) and regions of early introduction (Asia). In Africa, the genetic variability available is both in the cultivated species and the wild progenitors of the crop, de Wet and Harlan (1971) have reported on the distribution of both the wild varieties and the major cultivated races of the crop in Africa. The sorghum genetic resources situation of the continent has also been reviewed (Gebrekidan 1979).

In view of the tremendous genetic variability of sorghum in Ethiopia, Stemler et al. (1975, 1977) have examined and documented the evolutionary history of Ethiopian cultivated sorghums. On the basis of evaluation of about 2000 and 5000 Ethiopian sorghums, Gebrekidan (1973) and Gebrekidan and Kebede (1978), respectively, have reported on the distribution of major agronomic characters and races of sorghums in Ethiopia. The collection of the bulk of the 5000 Ethiopian sorghums was done by the Ethiopian Sorghum Improvement Project (ESIP) as part of our overall effort to develop high-yielding sorghums for the various ecological zones of the country. In the early seventies, much of the ESIP's attention was on the highland sorghums of Ethiopia. When the performance of introduced sorghums in the Ethiopian highlands resulted repeatedly in dismal failures, ESIP got stuck more and more with indigenous germplasm work. Consequently, we were involved in collection, evaluation, maintenance, and utilization of Ethiopian sorghum germplasm for most of the 1970s. In fact, as our program developed, our work on germplasm became an integral part of our overall national sorghum improvement effort. Even though most of our collections are normally biased in favor of agronomic eliteness, the aspect of evaluation and maintenance has become increasingly burdensome for our breeding program as the collection has grown in size.

In terms of utilization, the germplasm collection has been a source of high-yielding varieties for the Ethiopian highlands. The evaluation of the collection has involved not only the identification of high-yielding varieties per se, but also elite parents possessing special desirable traits for our crossing programs.

Germplasm Evaluation and Utilization

Much of the utilization aspects of the sorghum germplasm work has yet to be done. It is obvious that only a small fraction of the total available collection could be fully utilized by breeders at any one time. Crop improvement programs are often interested in portions of the collection which carry special desirable characters.

As a prerequisite to efficient utilization of the germplasm it must be properly evaluated, characterized, and documented with a workable retrieval system so that any group of entries carrying any desired characteristic could be easily pulled out and used in breeding programs. This means evaluation and utilization cannot be viewed separately. The obvious question that arises in this connection is: where should the evaluation of the germplasm be done? The physical and the biological environment of the location of evaluation must, of course, allow differential expressions of entries for the major characters of worldwide interest in sorghum. However, knowing the tremendous range of adaptation of the crop in

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altitude, temperature, moisture, fertility, disease and pest situations, it is impossible to get a single location anywhere that will allow the expression of all the economically important traits. Evaluation made on the world collection of sorghums at Hyderabad can give no information on resistance to weed, disease, pest, stress, and other problems not existing in Hyderabad but which are of importance elsewhere in the sorghum growing world. Examples are *Striga hermonthica, Busseola fusca.* birds, anthracnose, smuts, cold tolerance, general adaptation, food quality, etc. Such evaluations and screening are indeed being planned at other specific locations.

It is suggested that evaluations of the entire sorghum germplasm be done in at least three representative areas—one each in Africa, India, and the Americas, since these are the major regions growing the crop. Thorough evaluation, characterization, and documentation should be made so that the information will be of use to sorghum improvement programs everywhere. Not only should the information and easy retrieval be available in each of these regions but also the seeds of the entire collection. Seed movements to national and subregional programs within regions are expected to be much easier.

The growing and evaluating of some sorghum collections in areas where they are not adapted at all, changes the identity of the collection or may lead to the complete loss of the collection. An obvious case is the growing of photoperiod sensitive collections under long days. However, a specific case in point here is the growing of Ethiopian highland sorghums under the lowland environments of Hyderabad and New Delhi, India. Seeds of 1073 Ethiopian sorghums being maintained in the international sorghum collection and which have been repeatedly grown and maintained under lowland Indian conditions for over 15 years have been reintroduced to Ethiopia in 1978. These collections were grown in 1978 under the typical highland conditions of Alemaya and evaluated for major agronomic characteristics. Most of the entries appeared to have been converted to earlier and shorter types as a consequence of the grow-outs in India.

The Conversion Program

The broadening of the germplasm base and the availability of tropical sorghum germplasm to sorghum breeders in the temperate areas has received a major boost with the initiation of the conversion program. The conversion program has been designed for systematically converting tall, late, and photoperiod sensitive tropical sorghums to short, early, and photoperiod insensitive genotypes (Stephens et al. 1967). Materials coming out of the conversion program are dramatically changing the sorghum industry in the U.S. (Miller 1979). Economic characteristics obtained from the project are disease and pest resistance, a range of improved plant and kernel characteristics, and reduced genetic vulnerability (Miller 1979).

As a result of the experience with the southern corn blight of the early seventies in the U.S., interest in broadening the germplasm base of crops has widened. Webster (1975, 1976) and Brown (1975) have discussed sorghum vulnerability and germplasm resources and the need for increased genetic diversity in the crop. The conversion program certainly opens the door wide to the tremendous genetic diversity available in the tropical sorghum to breeders in the temperate areas.

The conversion program, by necessity, can handle only a small portion of the available world collection of sorghums. On the basis of characters of economic importance, it is only the best of the collections that could be selected to undergo the lengthy conversion program. The selection of these entries could be on the basis of the original collection notes, evaluation in the country of collection, and/or other evaluations done elsewhere. Continuous consultation with and collaborative work between sorghum workers in the tropics and those actively engaged in the conversion program has been most useful in the identification of materials for conversion. Lines to be converted could also be obtained from breeding programs in the tropical regions themselves. Elite materials obtained from such breeding programs would have gone through a good amount of evaluation locally and would be in elite agronomic background. Converted materials in elite agronomic background are expected to be of more use to both the tropical and temperate areas.

Singh (1977) has described a breeding method by which late and tall highland sorghums of Eastern Africa could be converted to shorter and earlier genotypes which could be suitable for the cool highlands of Latin America. Mass crossing was recommended to be done through genetic male sterility and earliness and reduced plant height were to be incorporated through appropriate maturity and height genes. This presumably has been the system used by CIMMYT/ICRISAT for developing highland sorghums for the Americas.

diversifying the Cytoplasm

In view of the use of the milo cytoplasm in the production of almost all hybrids in the world and the possible hazards associated with using this narrow cytoplasm, efforts have been made to develop additional cytoplasmic-genetic male sterility systems. Ross and Hackerott (1972) have released A-lines with cytoplasms derived from grassy sorghums. Ross and Kofoid (1979) have reported that the nonmilo cytoplasms in the six Kansas A-lines, compared with CK 60A, had no beneficial or adverse effect on major agronomic characters. They have, therefore, recommended that these lines be used in diversifying the cytoplasm in hybrid seed production. A new cytoplasmic-genetic male sterility system with cytoplasm derived from IS 12662C has been reported by Schertz (1977) and this has been released as A2 Tx2753. In comparison with other cytoplasmic-genic male sterility systems under development, A2 Tx2753 has been reported as currently suitable for use in breeding programs (Schertz and Ritchey 1978). These new cytoplasmic-genic systems will no doubt be instrumental in the much needed diversification of the milo-cytoplasm currently in use universally.

Introgression

In addition to the conversion programs, another method of broadening the source material for breeders has been and still is the work on introgression. There appears to be no well organized introgression program anywhere being done for the conversion program. The development of the new A-lines by Ross and Hackerott (1977) is a good case of the introgression of genes and cytoplasm from weedy species to cultivated sorghums. Introgression has been instrumental in the transfer of genes conferring resistance to greenbug from grassy sorghums to cultivated types (Johnson and Teetes 1979). Attempts have also been made to transfer shoot fly resistance from sugarcane (*Saccharum officinarum* L.) (de Wet et al 1976). Modified sorghums carrying sugarcane genes have been recovered. Whether or not these sorghums have any shoot fly resistance has not been reported. In areas where the cultivated and wild species of sorghum occur side by side, certainly introgression of genes from the weedy species to cultivated ones has been going on for a long time and it certainly is continuing. To accelerate such movement of genes from wild species to cultivated forms, a more organized and systematic introgression program is needed. Weedy species should be good sources of specific genes for a number of resistance and adaptation traits.

Utilization as an Indicator of Priorities of Collection

An example of utilization serving as an indicator of priorities of collection is the case of the Ethiopian high lysine sorghums. As soon as the discovery of the high lysine gene in two Ethiopian sorghums (IS 11758 and IS 11167) was announced by Singh and Axtell (1973), there was worldwide interest in these sorghums. In the mid-seventies, collection expeditions went to the Wollo region of Ethiopia (where IS 11758 and IS 11167 were originally collected) to make more thorough collections of these sorghums. Repeated sorghum collections have also been made in the Wollo region by the Ethiopian national program. Through all of these collection missions it has been possible to collect the *hi* gene in a range of agronomic backgrounds. The traditional culture and yield potentials of the Ethiopian high lysine sorghums in different agronomic and seed color backgrounds have been reported (Gebrekidan and Kebede 1979).

Utilization of germplasm by local farmers has partly served and could continue to serve as a very useful indicator of priorities of collection as well as an indicator of potentials of certain sorghums in other parts of the world. For example, the high altitude sorghums of Ethiopia are found in diverse and excellent agronomic backgrounds. They are adapted to cool growing conditions and their individual plant yields are very high. These sorghums are used very little outside of Ethiopia. With some modification, they should be useful in other highland sorghum areas and even perhaps the *rabi* season of India. Conversely, rabi sorghums of India are worth trying in the cool highlands of Ethiopia and elsewhere.

Another group of sorghums which have been used very little outside of certain regions of West Africa are the Muskwari (transplanted) sorghums on Vertisols. These sorghums are photosensitive, are transplanted at the end of the rains and have large flinty grains (Monthe 1977). In their present form, they may have use in other regions and they should certainly be useful as parents in crossing programs. Since these are special kinds of sorghums, a concerted effort should be made to collect them and enlarge their germplasm holding in the world collection.

Special types of sorghums which presumably should have potential for drought resistance and sandy soil condition breeding are the dune sorghums of Niger (Etasse 1977; Chantereau and Moussa 1977). Thorough collection and utilization of such sorghums in sorghum improvement programs for drought affected areas appear important. Worldwide drought is often considered as one of the most important problems of sorghum production. Mobilizing existing germplasm resources and making a concerted effort to accumulate more relevant germplasm to bear on this problem need urgent attention.

In some parts of Africa, ratoon cropping of sorghums is a traditional farming method. The use of ratoon cropping is dependent on the distribution of the rains. In some areas, such as the Konso and Borena Negelie areas of South Ethiopia, the ratoon crop often gives a higher yield than the main crop. It would be of interest to survey and collect sorghums particularly suitable for this type of farming system. The evaluation of collections and their utilization in this fashion could have broader significance than is presently realized.

A very important experience that is often ignored and underestimated is the tremendous knowledge about sorghums available with local farmers. In areas where the crop is a traditional one, farmers have accumulated time tested knowledge about types and cultures of sorghums. Often the local names given to sorghums describe the special characteristics of many sorghums. Some examples from Ethiopia are given in Table 1. These and many others could be used as guides to collection and utilization of sorghums.

With respect to the local name *tinkish* (sweet sorghum), in many parts of Ethiopia special types of sorghums are cherished for their sweet stalks. It is traditional to chew these sweet sorghums in most sorghum growing areas. Only special types are recognized for this purpose. With the growing interest in high sugar sorghums for gasohol production, it appears worthwhile to make a thorough collection of such sorghums and utilize them.

Table 1. Selected Ethiopian vernacular names of sorghums and their meanings.

ETS No.	Vernacular name	Meaning of vernacular name
ETS 1347	*Fendisha*	Sorghum that pops.
ETS 2283	*Bisinga Worabeisa*	"Hyena sorghum"—glumes protrude like hairs of a hyena.
ETS 2390	*Sende Lemine*	"Why take wheat"— as good as wheat for making bread.
ETS 2611	*Hafukagne*	"Shame on me if I do not head" —every plant produces head always.
ETS 2624	Wotet Begunche	"Milk in my mouth"— sorghum that is as good as milk.
ETS 2834	*Gebabie Muyra*	"Short *Muyra*"—short sorghum with compact panicle.
ETS 2861	*Tinkish*	"Sweet stem"—sorghum stalks used for chewing.
ETS 2970	*Marchuke*	"Gives honey like sweetness"—sweet seeds consumed roasted.
ETS 3133	*Gan Sober*	"Breaks the clay pot used for making local beer"—during the process of fermentation in local beer making, it ferments so strongly that it breaks the *gan* (clay container).
ETS 3147	*Cherekit*	"Moon like"—seeds are bright and white like the moon
ETS 3149	*Dirb Keteto*	"Twin seeded sorghum"
ETS 3252	*Wof Aybelash*	"Bird proof"
ETS 3780	*Alequay*	"Horse bean like seeds"—very large seeds with 1000 seeds weighing 70 gms.
ETS 4762	*Kitgn Ayferie*	"Unafraid of syphilis"—not affected by *Striga* (kitgn) which is locally referred to as *kitgn* (syphilis of sorghum).

Germplasm as a Source of Resistance and Other Useful Genes

Over the years, collections have been used as sources of resistance to pests and diseases, and environmental stresses as well as sources for special traits.

Insect Resistance

Johnson and Teetes (1979) have given several sources of resistance to the greenbug, midge. Banks grass mite, and shoot fly. Of the nine sources of resistance to greenbug *(Schizaphis graminum* [Rondani]), they have indicated that six are grassy sorghums. So far the inheritance of greenbug resistance has been shown not to be complex and incorporation of the resistance genes to agronomically elite lines is relatively easy (Johnson and Teetes 1979). Availability of resistance to the sorghum midge *(Contarinia sorghicola* [Coquillet]) in converted sorghum lines has been reported by these same workers. Out of the 31 converted lines presented as having high or moderate level of resistance to the sorghum midge, about two-thirds of them have been received from the East African region. Teetes (1975) has indicated that the most obvious morphological difference between the resistant and susceptible types is their small glumes and he continues that all lines identified with high levels of resistance have been caudatums. If additional sources of resistance to the sorghum midge are sought this region is likely to yield more lines conferring resistance. Sources of resistance to both the greenbug and the sorghum midge are also available in several agronomically improved lines with Tx numbers.

Probably the most amount of work on the sorghum shoot fly *(Atherigona soccata* Rondani) has been done in India. A list of 35 promising entries from the sorghum collection which consistently showed resistance to shoot fly in India has been given by Jotwani and Davies (no date). From their list, 25 of the 35 resistant entries are Indian durras. This is in contrast to the case of sorghum midge resistance where all the known resistance genes are confined to caudatums; sources of resistance to shoot fly appear to be mostly in durras. The resistant lines were reported tall, late, lodging, low yielding and photosensitive, and thus useful only as sources of shoot fly resistance genes.

Significant progress appears to have been made in India to incorporate shoot fly resistance to agronomically elite lines and hybrids. Work at ICRISAT has shown that the presnce of trichomes on the underside of leaves of sorghums is associated with nonpreference for oviposition and consequently conferred field resistance to the sorghum shoot fly (Maiti 1977). Maiti et al. 1980 have given a list (most entries are the same ones included by Jotwani and Davies, no date) of shoot fly resistant genotypes along with trichome count per mm^2. Selecting for the presence of trichomes promises to be a useful tool for screening sorghum collections for shoot fly resistance. The glossy character is often found in association with the presence of trichomes and this character also appears as a very promising method for screening for shoot fly resistance.

Internationally, the two most important borers attacking sorghum are *Chilo partellus* (India and Africa) and *Busseola fusca* (Africa). Jotwani and Davies (1979) have listed IS numbers of 26 sorghums found promising for resistance to *Chilo partellus* in India. All except three of these sorghums are of Indian origin. Whether this indicates true concentration of the genes for borer resistance in Indian sorghums, it is not possible to draw generalization from their data. Regardless of this point, the Indian sorghums appear to be very important sources of resistance to *Chilo.* No data are available to show whether lines identified as resistant to *Chilo* are also resistant to *Busseola* and vice versa. In view of the importance of borers as a sorghum pest both in India and Africa, more effort is needed to identify sources of resistance and to incorporate them into elite agronomic backgrounds both under the Indian and African conditions.

Germplasm entries possessing multiple resistnace to both shoot fly and stem borer have also been identified (Jotwani and Davies 1979). If genes from such lines could continue to be incorporated into elite agronomic backgrounds with adaptation and yield genes for the major shoot fly and borer problem areas in India and Africa, it will be a major contribution to improving sorghum yields in these regions.

Disease Resistance

Recent screening tests at ICRISAT have shown that sources of resistance are available for sorghum downy mildew, leaf blight, and rust. Dange et al. (1979) have reported that out of 437 sorghums, most of which were from collections, 135 were free from sorghum downy mildew (*Peronosclerospora sorghi*[Weston & Uppal] C. G. Shaw); for leaf blight (*Exserohilum turcicum* Leo and Sug.) and rust *{Puccinia purpurea* Cooke), 125 and 40 resistant sorghums, respectively, were found among the 930 tested. The relative concentrations of genes for leaf blight and rust resistance were in tan, zera zera, and a range of converted sorghums. In addition, for leaf blight resistance, *roxburghii* sorghums were also reported as important sources of resistance. Fourteen of these lines were resistant both to leaf blight and rust. For downy mildew, the immunity of the Australian variety QL-3 is specially noteworthy. Frederiksen and Rosenow (1979) have listed a number of sources of resistance to head smut, anthracnose. downy mildew, other leaf diseases, and charcoal rot.

Several sources of resistance for a whole range of diseases in sorghum have also been presented by several workers (ICRISAT 1978). Among the major sorghum diseases for which resistance sources have been listed in the Proceedings of this Symposium, are grain molds, downy mildew, a range of leaf diseases, charcoal rot, and smuts. The strategies that are needed to utilize resistances could be many. In general, the incorporation of multiple resistance to the important diseases of a region and the screening of segregating populations and parental lines under natural field conditions should be enough to maintain a sufficient level of resistance in most situations. This would best be done if the breeder and the pathologist could work as a team on the same material.

One plant characteristic that has been used effectively in many breeding programs is tan plant and glume color. This characteristic appears associated with resistance to leaf diseases and grain weathering. Seeds from tan plants usually appear to have cleaner and less molding seeds than plants with anthocyanin coloring.

Striga Resistance

Striga hermonthica Benth and *Striga asiatica* (Linn.) Kuntze are menaces to the sorghum crop with relative economic importance in Africa and Asia, respectively. Several cultivars resistant to *Striga* have been identified in India and several African countries, and have been listed by Ramaiah (1980,1981). Two lines which have been found resistant in most countries are N-13 of Indian origin and IS 8686 of African origin.

The established African varieties Dobbs, Serena, Framida, and Radar have been identified as resistant in a number of locations over the years and the resistances in these varieties appear to hold up (Doggett 1970; Kambal 1977). In discussing the two forms of resistance to *Striga,* Doggett points out Dobbs to be a good example of resistance based on barriers to the successful establishment of the parasite on the host, and Framida is an example of a *Striga* resistant sorghum producing low amounts of the germination stimulant factor. In various laboratories, efforts have been made to screen sorghum lines for stimulant production. However, there appear to be no solid data to correlate laboratory screening for stimulant production and field performance, under heavy *Striga* infestation, of the same lines.

Whether or not low stimulant factor production in the laboratory means resistance in the field has yet to be shown conclusively. For *Striga* resistance conditioned by a barrier to successful establishment of the parasite on the host, no laboratory screening method appears available. In view of the importance of *Striga* as a major limiting factor to sorghum production, particularly S. *hermonthica* in Africa, further efforts are needed to identify more sources of resistance, elaborate the mechanisms of resistance, and incorporate resistance into agronomically elite backgrounds. Screening and evaluating germplasm under heavily *Striga* infested soils in several places in Africa is necessary.

The use of the germplasm to tackle the very important problems of drought, heat, and other stresses has not been very significant. Effective methods for screening germplasms for environmental stresses have yet to be worked out. In many national and regional programs, drought resistance commands high priority in sorghum research. Therefore, all effort that could assist in identifying sources of resistance for drought and heat would be welcome.

Other Useful Genes

In addition to the range of resistances to diseases, pests, *Striga,* and drought, other important genes have also been obtained from the germplasm.

Singh and Axtell (1973) reported the discovery of a high lysine gene (hl) in two Ethiopian sorghum collections. IS 11758 and IS 11167. They reported that the high lysine contents in these sorghums were also associated with relatively high levels of protein and dented seed characteristic. According to their finding, the biological values of IS 11758 were three times that of an average normal sorghum. Featherston et al. (1975) conducted chick growth studies using IS 11758 and reported that the weight gains obtained with this *hl* sorghum was three times that of a normal commercial sorghum. Stimulated by these impressive gains in nutritional terms, attempts were made by several workers to transfer the *hl* gene into a plump seed background but without much success (Ken Riley, personal communication). It is now felt that the best way to utilize the *hl* gene of the Ethiopian sorghums is in its original dented form perhaps for special high nutritional needs such as for weanling children and pregnant mothers (House 1980). The grain yields of these *hl* sorghums are reasonably good if they are grown in environments of their best adaptation. Gebrekidan and Kebede (1979) have reported on the yield potentials of the original Ethiopian *hl* sorghums under highland Ethiopian conditions. Working with the two Ethiopian high lysine sorghums, Pant (1975) reported an unusually high nicotinic acid content in them and stressed the significance of his finding in respect of improving the niacin status of populations in the developing countries consuming sorghum.

Recently Prasada Rao and Murty (1979) reported the collection of basmati (scented) sorghums in India. The grains and the plants of these special sorghums emit a pleasant mild scent. Such special characteristics if used in breeding programs are expected to improve flavors of food sorghums.

Genetic Research in Germplasm Utilization

Adequate evaluation and genetic characterization of the germplasm collection is a prerequisite to utilization. Genetic research supportive to the activities of the germplasm work is essential. Such a genetic research function could identify sources of resistances for different needs on a routine basis. This could be done in collaboration with multidisciplinary teams. In the collection, the geographical and the taxonomic distribution and concentration of genes for selected traits need to be determined. Systematic intercrosses among races and/or intermediate races and/or wild types done on a large number of crosses could lead to a better understanding of the genetics of sorghum and consequently better utilization of sorghum germplasm. As a follow-up of this point, multilocational evaluation of collections is a necessary part of proper utilization of germplasm. It is obvious that a range of environments is needed to allow all entries in the collection to have good expressions somewhere.

The formation of different pools of sorghum populations on the basis of agronomic characters, ecological zones, geographical groups, etc., could make the collection more accessible to utilization and could also provide a systematic means of improving the populations. Recurrent selection schemes could be handy in the improvement of these populations.

Taxonomic Systems and Germplasm Utilization

Out of the several classification systems proposed for the cultivated sorghums by different workers, the major ones are Snowden (1936), Murty et al. (1967), de Wet and Harlan (1971), Harlan (1972), Harlan and de Wet (1972). On the basis of its simplicity, meaningfulness, and accuracy, the system proposed by Harlan and de Wet (1972). On the basis of its simplicity, meaningfulness, and accuracy, the system proposed by Harlan and de Wet (1972) has gained more and more popularity among sorghum workers. Their classification is essentially based on the knowledge of only the five basic races (bicolor, guinea, caudatum, kafir, and durra). All possible combinations between the five races are intermediate in character and are also easy to identify. The International Board for Plant Genetic Resources (IBPGR) Advisory Committee on Sorghum and Millets Germplasm has accepted and recommended this classification to be used in describing sorghum germplasm (IBPGR/ICRISAT 1980).

The simplified classification system allows any sorghum worker to classify sorghum into one of the 15 races. Proper classification and identification of materials in the germplasm is essential for proper utilization and understandable communication among sorghum workers. There are several genetic characteristics which are unique to a given race, and a reliable and repeatable classification will facilitate exploitation of these genetic characters. In the exchange of seed materials and information among sorghum workers, a meaningful and easily understood classification system will be of great assistance.

Interaction of Germplasm and Crop Improvement Scientists

In the overall activities of germplasm work, germplasm scientists are usually on the collecting and maintaining side, while crop improvement scientists are on the utilization end. Where, what, when, and why to collect could best be answered by the interaction of germplasm and crop improvement scientists. Often pointed collections, such as the zera zera sorghums collection expedition mentioned earlier, would materialize as a result of close and continuous interactions of germplasm and crop improvement scientists.

Priorities of collections could be on the basis of geography or taxonomic groups of sorghums desired. Evaluation, reporting, and utilization of germplasm as a team could often give a lead as to what priorities or pointed collections should be made. The physiologist-breeder working on problems of drought would know taxonomic group(s) and/or geographical area(s) which would be of interest to him. The breeder working on *Striga* could give clues to the germplasm scientist where to look for further resistance for this parasite, if the breeder working on sorghum has sufficient contact with germplasm work he would certainly know what taxonomic groups or georgraphical areas are sources of genes for the problem area on which he is working. Problems of diseases, insects, resistance to various stresses could be viewed in a similar fashion. The constant interaction of germplasm and crop improvement scientists could help make collections more useful.

As an example of the benefit of interaction between germplasm, pathology, and crop improvement disciplines I would like to mention one case. In 1977 the Ethiopian Sorghum Improvement Project received the International Sorghum Grain Mold Nursery (ISGMN) from the ICRISAT Sorghum Pathology Program and grew it at the Arsi Negelie and Alemaya stations (highland stations with about 2000 m altitude). As it turned out, 18 of the 22 entries looked completely unadapted for these cool growing conditions of Ethiopia. The reactions of these poorly adapted 18 entries confirmed our past observations which repeatedly pointed out that introduced materials in the form that they came to us have been completely useless under our highland conditions. However in the 1977 ISGMN, four entries, i.e., IS 9521. IS 9331, IS 9533, and IS 9544 caught us by surprise. Unlike all the other entries, they looked outstanding, well adapted, and agronomically elite and they looked as good as, or better than, the best of the local entries. In our interaction with the cereal germplasm botanist of ICRISAT we came to know that all four of the entries were kafirs originally collected from South Africa.

With that information as a starting point, we requested the ICRISAT cereals germplasm botanist to send us all available entries collected from the same general area as these four kafirs. Accordingly we received 286 such entries which we screened in 1978 in our highland areas. Most of them looked excellent and well adapted. We have had the very best of these in yield trials for the last 2 years. Out of these collections, we have obtained entries which have given as much as 70 q/ha under our highland conditions. Nine of these entries are in advanced agronomic and yield trials now and there are plans to release some of them for commercial production soon.

We are now convinced that the kafirs of Southern Africa have a lot to offer to the Ethiopian highlands. We are also using them as parents in our crossing program. On the basis of the interaction between germplasm and crop improvement scientists, we were able to exploit a group of alien sorghums which are uniquely suited to the special highland sorghum zones of Ethiopia. I am sure constant interaction like this one could give clues to other suitable germplasm for different zones and problems.

It is well known that most collections from tropical areas are late, tall, photosensitive, and difficult to be incorporated into breeding programs where early, short, and photoinsensitive genotypes are sought. The details and backgrounds on the early Texas work in the dramatic transformations of the traditional tropical sorghums to combine height and early versions through the use of the height and maturity genes have been well summarized by Quinby (1974). More recently the conversion program has been imaginatively conceived to get around these problems (Stephens et al. 1967). It makes more tropical sorghums accessible to sorghum breeders in the temperate zones and it can come up with modified and converted sorghum plants for use in the tropical areas also. The conversion program is covered in detail by the paper by Rao and Rana on "Selection in Temperate-Tropical Crosses of Sorghum" (These Proceedings). Partial conversion and modification of the sorghum plant geometry for use within the tropics needs to be done in some systematic way. Such a partial conversion obviously could be done only on selected elite genotypes from selected areas. Intercrossing between genotypes differing in maturity and plant height could be done with difficulty if the necessary arrangements in timing of planting and management of parents is done.

It is not universally true that dwarf sorghums are desired by all farmers. For the typical farmer of the semi-arid tropics often the leaves and sorghum stalks are very important too. The leaves are stripped off and fed to his livestock and the stalks are the year round source of fuel for cooking. Therefore intercrossing and improvement of tall sorghums are of crucial importance in these areas. Crossing between sorghums which are very tall (>3m) is often very difficult and inconvenient. One effective method of making a large number of crosses among very tall genotypes has been the use of the high lysine dented seed marker. The method we are using in the ESIP is referred to as the Dented Seed Breeding Method (DSBM) and has been described in the ESIP progress report of 1977 (Gebrekidan and Kebede). We are using the DSBM in conjunction with a population improvement and recurrent selection scheme.

Highlights and Projections

1. Thus far the greatest effort has gone into collection and maintenance; in the future there should be a greater input into utilization.
2. The recently developed sorghum descriptors should be used internationally to provide a common base for communication.
3. The conversion work on sorghum should continue.
4. Increased collection and more exhaustive utilization of collections in Africa are expected in the 1980s.
5. More imaginative use of select entries from the collection in drought prone areas is required.
6. Understanding and use of collections should be an integral part of training and educational programs.
7. Movement of breeding stocks and collections are expected to increase in the 80s in support of crop improvement. Policies encouraging such free movement are necessary.
8. Germplasm evaluation can best be undertaken by a team of scientists working in areas of different crop adaptation.
9. Emphasis in the 80s should be on sorghum as a food rather than a feed.
10. Heterosis between sorghums of different geographic origin and taxonomic traits should be included as part of the collection evaluation.
11. With respect to germplasm utilization, formation of populations and a systematic effort to improve them by recurrent selection methods are particularly attractive for handling germplasm earmarked for specific use.
12. As part of germplasm evaluation a systematic effort is required to exploit potentials of intergroup and interracial crosses.
13. A greater effort is required in the 80s to evaluate and exploit variability of sorghum adapted to cold, dry areas.
14. A continuing effort to find useful sources of cytoplasmic male-sterility is required.

To conclude, I would like to state that the most significant development of the seventies with respect to worldwide efforts on sorghum research has been the establishment of ICRISAT. For the Institute, the past decade has been one of establishment and development of appropriate contacts worldwide. It has successfully fulfilled these functions. ICRISAT is now a reality and a well-known Institute throughout the semi-arid tropics. Peoples and governments of countries of the semi-arid tropics look to ICRISAT to assist them in coping with food production problems under water stress situations. It is hoped that in the eighties, ICRISAT will make its presence felt more and more in the important ecological and geographical regions of the semi-arid tropics. Germplasm and its utilization is certainly going to be a major component of ICRISAT's package of methodologies for increasing and stabilizing sorghum production under the harsh environments of the semi-arid tropics.

References

BROWN, W.L. 1975. A broader germplasm base in corn and sorghum. Pages 81 -89 *in* Proceedings of the 30th Annual Com and Sorghum Research Conference.

CHANTEREAU, J., and MOUSSA, A. 1977 Principal results and orientation of sorghum research in Niger.

DAMON, E. G. 1962. The cultivated sorghums of Ethiopia. Experiment Station Bulletin No. 6, Alemaya College of Agriculture. Ethiopia.

DANGE, S. R. S., DARUNAKAR. R. I.. and WILLIAMS, R. J. 1979. Results of the sorghum downy mildew and leaf diseases resistance screening projects ICRISAT Sorghum Pathology departmental progress report.

DE WET, J. M.. and HARLAN, J. R., 1971. The origin and domestication of *Sorghum bicolor.* Economic Botany 25:128 135

DE WET, J. M. J,, GUPTA, S. C, HARLAN, J. R., and GRASSL, C. O. 1976 Cytogenetics of introgression from *Saccharum* into *Sorghum.* Crop Science 16:568-572

ETASSE, C. 1977. Summary of the work on sorghum Pages 85-102 *in* A translation: "L'IRAT et ('amelioration du sorgho" L'Agronomic Tropicale XXXII, 3, July-Sept.

FEATHERSTON, W. R., ROGLER, J. C, AXTELL, J. D., and OSWALT, D. L. 1975. Nutritional value of high lysine sorghum grain for the chick. Poultry Science 54:1220 -1225.

FREDERIKSEN. R. A., and ROSENOW, D. T. 1979. Breeding for disease resistance in sorghum. Pages 137-167 *in* Biology and breeding for resistance to arthropods and pathogens in agricultural plants, ed. M. K. Harris, College Station, Texas, USA: Texas A&M University.

GEBREKIOAN, BRHANE. 1973, The importance of the Ethiopian sorghum germplasm in the world sorghum collection. Economic Botany 27:442-445.

GEBREKIDAN, BRHANE. 1979. Sorghum genetic resources in Africa. Ethiopian Journal of Agricultural Sciences 1:108-115.

GEBREKIDAN, BRHANE, and KEBEDE. YILMA. 1977. Annual Progress Report No. 5. Ethiopian Sorghum Improvement Project. Addis Ababa University, Nazreth, Ethiopia.

GEBREKIDAN, BRHANE, and KEBEDE, YILMA. 1978. Annual Progress Report No. 6. Ethiopian Sorghum Improvement Project, Addis Ababa University. Nazreth, Ethiopia.

GEBREKIDAN, BRHANE, and KEBEDE. YILMA. 1979 The traditional culture and yield potentials of the Ethiopian high lysine sorghums. Ethiopian Journal of Agricultural Sciences 1 :29-40

HARLAN, J. R. 1972. A new classification of cultivated sorghum. Pages 512-516 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House New Delhi, India: Oxford and IBH Publishing Co. 638 pp.

HARLAN, J. R., and DE WET, J. M. J. 1972 A simplified classification of cultivated sorghum. Crop Science 12:172-176.

HOUSE, L. R. 1980. The ICRISAT sorghum improvement program. Report to the 5th joint meeting of the UNDP-CIMMYT-ICRISAT Policy Advisory Committee, ICRISAT, Patancheru, A.P., India.

IBPGR/ICRISAT 1980 Sorghum descriptors Rome. Italy: IBPGR

ICRISAT. 1980 Proceedings of the International Workshop on Sorghum Diseases. ICRISAT, 11-15 Dec 1978. Hyderabad. India. Patancheru. A.P., India: ICRISAT.

JOTWANI, M G., and DAVIES. J. C. 1979. Insect resistance studies on sorghum at international institutes and national programs with special reference to India. *In* Biology and breeding for resistance to arthropods and pathogens in agricultural plants, ed. M. K. Harris. College Station, Texas, USA: Texas A&M University.

JOHNSON. J. W., and TEETES. G. T. 1979. Breeding for arthropod resistance in sorghum. Pages 168-180 *in* Biology and breeding for resistance to arthropods and pathogens in agricultural plants, ed. M.K. Harris. College Station, Texas, USA: Texas A&M University.

KAMBAL, A. 1977. Progress and problems of sorghum research in the Sudan. Presented at the International Sorghum Workshop, ICRISAT, 6-12 Mar, Hyderabad, India.

MAITI, R. K. 1977. Leaf trichomes on sorghum in relation to shoot fly resistance. Presented at the International Sorghum Workshop, ICRISAT, 6-12 Mar, Hyderabad, India.

MAITI, R. K.. BIDINGER, F. R., SESHU REDDY K. V., GIBSON, P.. and DAVIES, J. C. 1980. Nature and occurrence of trichomes in sorghum lines with resistance to the sorghum shoot fly. ICRISAT Sorghum Physiology and Entomology joint progress report no. 3.

MILLER, F. R. The breeding of sorghum. 1979. Pages 128-136 *in* Biology and breeding for resistance to arthropods and pathogens in agricultural plants, ed. M. K. Harris. College Station. Texas, USA: Texas A&M University.

MONTHE, E. 1977. Present state of sorghum selection activities in North Cameroon. Pages 4-22 *in* A translation: "L'IRAT et l'amelioration du sorgho" L'Agronomic Tropicale XXXII. 3, July-Sept.

MURTY, B. R., ARUNACHALAM, V., and SAXENA, M B. L. 1967. Classification and catalogue of a world collection of *sorghum.* Indian Journal of Genetics and Plant Breeding 27 (Special Number): 312

PANT. K. C. 1975. High nicotinic acid content in two Ethiopian sorghum lines. Journal of Agricultural Food Chemistry 23:608-609

QUINBY, R. J. 1974 Sorghum improvement and the genetics of growth. College Station, Texas, USA: Texas A&M University. 108 pp.

RAMAIAH, K. V. 1980. *Striga* program in Africa Presented at the First SAFGRAD Sorghum and Millet Workshop. Mombasa. Kenya

RAMAIAH. K V. 1981 *Striga* program in Africa Presented at the Second SAFGRAD Sorghum and Millet Workshop, Gaborone, Botswana.

PRASADA RAO, K. E.. and MURIV, D. S. 1979 A basmati (scented) sorghum from Madhya Pradesh Current Science 48:824-825.

Ross, W. M.. and HACKEROTT, H. L. 1972 Registration of seven isocytoplasmic sorghum germplasm lines Crop Science 12:720.

Ross, W. M., and KOFOID, K. D 1979 Effect of non-milo cytoplasms on the agronomic performance of sorghum. Crop Science 19:267-270

SCHERTZ, K. F. 1977. Registration of A2 Tx2753 and B Tx2753 sorghum germplasm. (Reg. No GP. 30 and 31) Crop Science 17:983.

SCHERTZ, K. F„ and RITCHEY, J M. 1978 Cytoplasmic-genic male-sterility in sorghum. Crop Science 18 : 890 -893.

SINGH, S. P. 1977. Use of genetic male sterility for simultaneous conversion and improvement of alien sorghums. Crop Science 17:482-484,

SINGH, R., and AXTELL, J. D. 1973. High lysine mutant gene (*hl)* that improves protein quality and biological value of grain sorghum. Crop Science 13:535-539.

SNOWDEN, J. D. 1936. The cultivated races of sorghum. London, UK: Adlard and Son. 274 pp

STEPHENS, J. C. MILLER. F. R., and ROSENOW, D. T. 1967. Conversion of alien sorghums to early combine genotypes. Crop Sciece 7 : 396.

STEMLER, A. B. L, HARLAN. J. R.. and DE WET. J. M. J. 1975. Evolutionary history of cultivated sorghums (*Sorghum* bicolor[Linn.) Moench) of Ethiopia. Bulletin of the Torrey Botanical Club 102:325-333

STEMLER. A. B. L, HARLAN, J. R., and DE WET, J. M. J. 1977. The sorghums of Ethiopia. Economic Botany 31 : 446-460.

TEETES, G. L. 1978. Insect resistance in sorghum. Pages 167-189 *in* Proceedings, Thirty-Third Annual Corn and Sorghum Research Conference.

WEBSTER, O. J. 1975. Use of tropical germplasm in a sorghum breeding program for both tropical and temperate areas Pages 1-12 *in* Proceedings. 30th Annual Corn and Sorghum Research Conference.

WEBSTER, O. J. 1976. Sorghum vulnerability and germplasm resources. Crop Science 16:553-556

Session 4 Genetic Resources

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The two papers on genetic resources presented at this symposium treated the subject in a nice complementary manner. The paper by M. H. Mengesha and K. E. Prasada Rao summarized the status of the world collection of over 21 000 accessions in the gene bank at ICRISAT in terms of recent acquisitions from several priority regions, and general comments on the strategies of sampling, maintenance and evaluation. Their narrative is largely a broadbased statistical survey of the ICRISAT holdings which show an impressive gain in making new collections. Collecting trips by these authors in Malawi, Tanzania, Eastern Ghats of India and other regions, reported in separate publications, showed the usefulness of their planning, field experience, ethnobotanical know-how, and other tactics required for success in such explorations. The second paper by B. Gebrekidan, in contrast, reviewed several specific agronomic and breeding issues in the particular context of the Ethiopian genetic resources, adding in conclusion "the bulk of the resources and efforts in germplasm work seem to have gone to collection and maintenance without sufficient attention to utilization." Accordingly, Gebrekidan's paper discusses the usefulness of population breeding in which diverse resources could be utilized, the need for cytoplasmic diversity in male-sterile systems, and the use of different kinds of local materials in various breeding programs. I shall now discuss some specific points of these papers.

Mengesha and Rao report that nearly 10 000 new accessions have been added from 68 countries. Their own collecting missions have covered several high priority regions although they still list a rather large number of areas to be explored. Several other collecting efforts have been reported in the International Board for Plant Genetic Resources (IBPGR) Plant Genetic Resources Newsletter (e.g., Damania and V. R. Rao; Arora and others; also see J. Toll; N. M. Anishetty; and W. G. Ayad (1981) in the Directory of Germplasm in Sorghum and Millets published by the IBPGR). Only a total of 167 accessions of wild and weedy taxa are in the ICRISAT collection which still leaves a serious gap, as noted also by Harlan (1972) and Webster (1976). Screening of germplasm for disease, pest, parasite *Striga* and drought resistance at ICRISAT has been extensive as noted by Mengesha and Rao; no reader would fail to be impressed on this issue from a survey of the ICRISAT annual reports. The need for regional and multilocation evaluation is noted by several workers in the past and again here. Mengesha and Rao comment briefly on the issues of sampling, maintenance and documentation. Both random and nonrandom sampling procedures (they use the terms general and pointed collections) were used, although information on them is often scanty. For example, Appa Rao (1980) sampled one to four random heads per field during his Zambia trip, but the type descriptions give no information on variation *within* populations. Denton (1979), however, noted that each field in Malawi had a mixture of races. The races are described in their expedition reports by the local vernacular names and by the nomenclature proposed by Harlan and de Wet. However, the proposal of the Sorghum and Millets Advisory Committee (cf Webster 1976) and of Harlan (1972) that most collections from within a small region could be maintained as a few representative individual entries and the remainder as one or more bulks of subraces, has not yet been adopted. The collections might have a lot of "duplicates" but we must recognize that identifying duplicates is never easy or fully reassuring as it would depend on some certain subset of traits

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and one or more numerical taxonomic procedures. Admittedly, some ways of handling such large collections are needed. Burton (19801 reviewed this topic recently with reference to the pearl millet germplasm. (A detailed brainstorm session for sorghum is needed at this meeting.) Three of the basic issues here are: classification, different kinds of collections, and gene pool management.

The classification of cultivated sorghum races devised by Harlan and de Wet is based on glume appearance and the grain size-shape characteristics that underlie the basic evolutionary changes toward domestication. Fifteen races and biracial intermediates are named. This is simple, rapid and meaningful as it gives a good start in the geographical analysis of variation pattern (cf., Harlan 1975). However, as the authors of this scheme have themselves shown in various other genera, further use of multivariate taxonomy can be helpful in (a) identifying a few more diagnostic character associations, (b) describing geographical variation in terms of the evolutionary processes, and (c) refining the racial nomenclature. However, no amount of purely statistical or numerical work could replace the biological insight and the use of authentic collections (Jain 1981a). A classification scheme (in fact, several can be devised) must meet the hierarchy rule, i.e., higher ranked groups should show more or atleast as much divergence as the lower ranked groups (with some exceptions allowed). Moreover, modern biosystematics warrants the comparative use of several approaches: simple keys, numerical taxonomy, estimation of genetic distances using allozyme variation, etc. (Jain 1981b). This should not be construed as a call for a lot of time-consuming and unwieldy basic research. But the critics will hopefully recognize the fact that a good scheme like the one of Harlan and de Wet could have been conceived only with their deep level of knowledge of the variation and evolution in sorghums. Professor C. M. Rick's classical work on tomato genetic resources (several references. see Eucarpia 1979 volume) has also demonstrated the scientific partnership between simplicity and complexity.

Our work on the systematics of amaranth genetic resources began with a simple scheme due to Professor J. Sauer, but now require many further revisions based on new findings and would probably end up with another more natural and simpler system of classification and nomenclature. Also, note that the definitions of primary and secondary gene pools in sorghum (Harlan 1975) have already become outdated—cf de Wet et al.'s (1976) work on the *Sorghum* x *Saccharum* cross. With the inclusion of wild and weedy races and natural hybrid swarms, sorghum races might need further classification.

Harlan (1972) and others have emphasized that besides accessions of landraces, the subject of primary focus in Mengesha and Rao's paper, we need to pay special attention to other categories (e.g., genetic stocks, named varieties, populations, and of course, wild/weedy races). Different male-sterile stocks, isogenics, induced polyploids, converted "tropical" and "temperate bulks" (Rosenow 1972), and any known genetic variants with apomixis, anther nondehiscence. and endosperm color, ratooning ability, etc.. should be conserved as well. The facts that an *arundinaceum* accession may have higher photosynthetic efficiency at moderate light intensities or a liguleless variety has better leaf canopy characteristics, are of potentially as much interest as any large-scale computerized descriptor list. As noted by Harlan (1972). "the time is approaching when we must go through *all* material within genetic reach with a fine comb to find genes or genetic complexes of value." An understanding of genetic variants in a population background would enrich our designs for incorporating new genetic resources into the source and elite populations (e.g., dented seed with hl gene; Gebrekidan). This was also distinctly recognized in a recent Rockefeller Foundation publication (Rachie and Lyman 1981) on the use of new genetic engineering technology in crop improvement; here, too, available specific genes and full knowledge of their expression in population contexts would be critical.

The idea of bulk populations or some kind of synthesized gene pool for genetic conservation has had rather little support as several authors (e.g., Burton 1980; Frankel and Soule 1981) warn against the losses of variability as well as note the problem of retrieval of desirable specific genes. However, one might argue that breeders are interested in various recurrent selection programs for the population improvement so that some dynamic gene pools would be available anyway and may be conserved as "mass reservoirs" of new gene combinations, of materials for adaptation studies and for monitoring changes during seed storage. Gene pools are *not* a substitute for the accessions, cultivars or genetic stocks conserved individually, but can be useful materials as an adjunct to certain conservation programs. Their genesis, parentage, propagation methods, and breeding value are issues that obviously warrant closer attention.

Several points taken from the quinquennial report of the IBPGR are relevant here; (a) "The basis of the priorities designated are the economic and social importance of particular crops, the risks of loss, the requirements of plant breeders and research workers in both developed and developing countries, and the size, scope and quality of existing collections."(b) "The Board's work will generate, partly as by-products, many services to crop improvement on the one hand, and to an understanding of the ecological and evolutionary bases of the diversity of cultivated plants (genetic resources science) on the other."

Simmonds (1981) and others have advocated the need to separate characteristics and evaluation to focus on primarily the taxonomists' and breeders' interests respectively. Hopefully, this will lead to a new comprehensive look at our objectives in the "genetic resources science" (cf., Brown 1978; Jain 1979). We should note that there are numerous examples of biosystematic studies and basic genetic discoveries of certain mutants that have found uses in plant breeding. Even ("neutral") taxonomic characters like leaf pubescence, peduncle shape, monoecy and seed coat colors in various crop species are now of considerable interest.

Gebrekidan's paper reviewed extensively many aspects of African genetic resources from a more local point of view; he noted how Ethiopian soghums in the ICRISAT collections after several growouts in India, and reintroduction to Ethiopia showed conversion to earlier and shorter types (natural conversion!). He emphasized that sampling by local people as part of the collecting team, and a certain amount of evaluation, documentation and utilization be carried out locally within each region, are all needed along with international programs. He recommends that "evaluations of the entire sorghum germplasm be done in at least three representative areas—one each in Africa, India and the Americas." Among other key recommendations are (a) an organized introgression program to utilize more of the wild and weedy germplasm, (b) interdisciplinary research on evaluation and characterization so as to balance "the bias for agronomic eliteness", (c) good ecological and ethnobotanical understanding of the sources of drought resistance; specialized use types (e.g., high sugar types and chewing sorghums; responses to ratooning and transplanting), and (d) diversified breeding approaches including population improvement goals. This paper thus provides a good survey of many basic as well as applied research needs on sorghum genetic resources. Several papers at the 1971 symposium (Rao and House 1972) discussed many aspects of population improvement research in sorghum. Numerous advances have been made in terms of new recombination systems, stability vs productivity evaluation, response to mass selection, etc. (Ricelli-Mattei, 1968; Foster et al. 1980). A survey of these advances will undoubtedly reinforce Gebrekidan's conclusions.

In conclusion, these two papers on genetic resources and a survey of recent sorghum literature show that sorghum as a crop with new emphasis on productivity and food use has exciting prospects for improvement by breeding. Yield, stability, wider adaptability, basic genetic studies—all these will require new and more extensive uses of genetic resources which should be urgently expanded to include wild and weedy relatives, as well as other races (e.g.. Kaoliang, Feterita). A review of numerous sorghum germplasm collections outside Ethiopia and India would be valuable. For instance, has the ORSTOM/IBPGR collection from West African countries been incorporated into the "world collections"? Are numerous national collections readily distributed to an international center? And vice versa? Mengesha and Rao, in fact, briefly touched upon the issue which some critics have raised about the open and fair exchange of genetic resources. Here, undoubtedly, ICRISAT has played an admirable role as a world trustee of sorghum genetic resources. Genetic variation in landraces and other collections, utilizing most of the descriptors, and local efforts of documentation (cf Howes 1981) would be very helpful in developing one or more schemes for the grouping of accessions, a rationale for gene pool synthesis, and an understanding of the evolutionary origins of various racial characteristics. With the advanced molecular genetic methodology now emerging rapidly, the time gap between a basic discovery of variant genotype or of new genetic mechanisms and their practical use has narrowed. Therefore, any rigid distinction between the goals of biosystematists and plant breeders would seem unnecessary. To set aside certain genetic resource management activities in a designated center or administrative unit might be essential but there should be a free flow of ideas and materials among the stewards of genetic resources and the researchers.

References

APPA RAO, S. 1980. Germplasm collecting mission to Zambia. ICRISAT.

BROWN, A. H. D. 1978. Isozymes, plant population genetic structure and genetic conservation. Theoretical and Applied Genetics 52:145-157.

BURTON, G. W. 1980. Handling cross-pollinated germplasm efficiently. Crop Science 19:685-690.

DENTON. I. R. 1979. Sorghum and millets in Malawi. Plant Genetic Resources Newsletter 39: 20-22.

OE WET, J. M. J., GUPTA, S. C. HARLAN, J. R., and GRASSL, C. O. 1976. Cytogenetics of introgression from *Saccharum* into *Sorghum.* Crop Science 16:568-572.

FOSTER, K. W., JAIN, S. K., and SMELTZER, D. G. 1980. Responses to 10 cycles of mass selection in an inbred population of grain sorghum. Crop Science 20:1-4

FRANKEL, O. H., and SOULE, M. E. 1981. Conservation and evolution. Cambridge, UK: Cambridge Universitiy Press.

HARLAN, J. R. 1972. Genetic resources in sorghum. Pages 1-13 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co. 638 pp.

HARLAN, J. R. 1975. Crops and man. Madison, Wisconsin, USA: American Society of Agronomy.

HOWES, C. W. 1981. Genetic resources documentation: A progress report. Presented at the FAO/UNEP/IBPGR Technical Conference,April 1981, Rome.

JAIN, S. K. 1979. Biosystematic studies of populations in germplasm collections. Pages 103-110 *in* Proceedings, Conference on Broadening the Genetic Base of Crops, Wageningen, The Netherlands.

JAIN, S. K. 1981a. Principles of sampling. Presented at the FAO/UNEP/IBPGR Technical Conference, April 1981, Rome.

JAIN, S. K. 1981b. Principles of evaluation. Presented at the FAO/UNEP/IBPGR Technical Conference, April 1981, Rome.

RICCELLI-MATTEI, M. 1968. Estimation of genetic parameters related to mating systems in populations of sorghum *[Sorghum bicolor* (L.) Moench). Ph.D. Dissertation, University of California. Davis, USA.

RAO. N. G. P.. and HOUSE, L. R. (eds.). 1972. Sorghum in seventies. New Delhi, India: Oxford and IBH Publishing Co. 638 pp.

ROSENOW, D. T. 1972. Discussion. Pages 39-42 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co. 638 pp.

SIMMONDS. N. W. 1981. Characterization and evaluation. Presented at the FAO/UNEP/IBPGR Technical Conference, April 1981. Rome.

WEBSTER, O. J. 1976. Sorghum vulnerability and germplasm resources. Crop Science 16:553-556.

Session 4 Genetic Resources

O. J. Webster* Discussant—2

The authors of the two papers presented in this session are to be commended for giving a thorough report on germplasm collections and their utilization. We need only to check the dates of the references cited to realize the magnitude of the activity in these areas during the past decade. We must, however, realize that a good start has been made but that a continued effort needs to be pursued in these two areas of work.

Current Situation and Future of Sorghum Germplasm

Dr. Harlan (1972) in his paper given at the 1972 sorghum conference outlined a number of deficiencies in our collections. A number of these gaps have been breached but there are a number of geographical areas yet to be surveyed. These are given by the authors.

Special attention should be given to collecting additional accessions of wild and weedy races. Such material has survived in the 'wild', growing under a wide range of environmental conditions and should be a good source of genes for resistance to a number of pests and diseases not found in known cultivated races. A good example are the genes for resistance to biotype C of greenbug, *Schizaphis graminum* (Rondani) found in *S. virgatum* and transferred to cultivated sorghums (Hackerott et al. 1969; Starks et al. 1976). Because of their shattering habit, wild races are difficult to maintain. They also require special care so as not to become a 'weed' in the nursery where seed is increased. For these reasons most breeders prefer not to be bothered with these species.

I note that the collection has been increased to more than 21 000 accessions. Harlan (1972) presented a recommendation from the Committee on Sorghum and Millet Germplasm that a basic collection be made of approximately 2000 lines carefully chosen to represent race, subrace, geographical distribution and ecological adaptation. Mengesha and Prasada Rao report about 1000 accessions have been selected at Patancheru. This is a good start but I believe a better approach would be to have sorghum specialists working in their respective countries help in this effort by providing seed of the major genotypes being grown. For example, I note that there are 1173 accessions in the collection from Nigeria. Based on my experience in traveling in Nigeria and seeing this collection being grown, I believe that there are no more than 50 distinct accessions which would adequately represent that country. I was also privileged to grow the Cameroun Collection in Puerto Rico in 1970 and based on morphological characteristics, there were relatively few distinctly different types. I also saw the first increase of 1500 of the 4000 accessions from the Yemen Arab Republic in Puerto Rico. In my classification I put the first 500 into three groups.

In a number of countries where sorghums have been grown for centuries as a traditional crop I know of no person better qualified to survey the crop than the trained sorghum specialist, if one is available. When a specialist begins to work in a country, his first endeavor is to tour the area and collect the major types which will be the basis for his breeding program. At the same time it would be most useful if the specialists in each country would prepare a paper on sorghums, describing the type of "races" being grown in each ecological zone, their uses, and note any special characteristics such as resistances to insects, diseases, etc. Such information would help pinpoint the areas where intensive collections should be made.

I found in looking at a third of the Yemen collection that there are types unique to that part

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of the world not found at least in West Africa. I was surprised to find in the collection a number of accessions with yellow endosperm, a characteristic which I thought to be indigenous to northern Nigeria. Although the grain on the plant from the two countries is similar the plant types are very different.

One constraint which breeders must contend with is the problem of moving seed between countries. A good plant quarantine agency is essential but we need more scientific evidence as to what potential diseases or pests with which we need to be concerned. Good progress has been made in the identification of insects and diseases found in each country. More information is needed on the variation in physiologic races and mode of infection in order to know the care which must be taken not to transmit a disease from country to country. When a disease specific to an area is found, such as long smut, a concentrated effort should be made on the spot to learn more about its mode of infection, economic losses, environmental effects, and possible sources of resistance.

At present there are strict quarantine regulations against the movement of sorghum seed from Africa and parts of Asia into some countries of the western hemisphere and such importations must first be increased in greenhouses. Suggestions have been made for the development of a quarantine station where introductions could be increased.

Utilization of Germplasm in Sorghum Improvement

A sorghum breeder working anywhere in the world must first survey the variations in the genotypes being grown and determine the factors which limit production. Once this is done then he should draft his specifications for a new genotype and collect the germplasm to be used in his program to accomplish his objectives. This may take considerable time and there will be disappointments. When I first went to Nigeria in 1951 I had many preconceived ideas as to what steps should be taken to improve the local cultivars. Since the local sorghum is planted in May and matures in October I planted early USA material in July expecting it to mature with the local crop. I soon learned that shoot fly could be a problem and there was a soil fertility problem when planting in mid season. I also learned that when the material in the nursery headed at different times there could be a midge problem. Also if the maturity cycle were in phase with the stem borer cycle the crop could be lost. In this one year I learned a number of constraints put on the sorghum breeder.

When I returned in 1963 I noted that Curtis, Andrews, and Abifarin had made a survey of the sorghums in the country and had selected six or eight major types for reselecting. From their effort they were able to select genotypes superior to the parent stocks as measured by carefully designed experiments. Unfortunately when these improved cultivars were planted by farmers in the traditional manner they looked and performed no better than the farmer's variety. The next step was to introduce a dwarfing gene in the tall locals and plant at relatively high rates with fertilizer. These practices gave significant increases in yield if the rains at the end of the season were adequate. In a year when the rains "finished" early, the crop went into moisture stress and failed. The traditional method of planting is to wide space the plants to be assured of adequate soil moisture at maturity. The next step was to develop slightly earlier varieties but with rains and heavy dews at the end of the season grain molds damaged the seed. Another constraint was grain feeding which can be a problem during the rains.

The traditional sorghums growing in the tropics have good resistance to foliar diseases and are tolerant to the indigenous insects which may attack them. Most are photoperiod sensitive which is essential in areas where the planting season at the beginning of the rains can vary as much as a month and the crop must complete its cycle at the end of the rains. A study of agronomic practices to improve production may increase yields more than plant breeding. The breeder can help stabilize yields by breeding for resistance to covered kernel smut and introduce genotypes tolerant to *Striga* sp. I was advised by the Ministry of Agriculture in Nigeria to guard against any sorghum release whose grain quality differed from that of the traditional varieties.

Eventually the breeders of the tropics will produce hybrids which will be accepted by the local farmers and who will also learn that they must purchase F, seed each year. Some say that this cannot be done but what can be accomplished by education is illustrated by the acceptance of hybrid maize by the small farmers of Kenya.

When hybrids become a reality, seed production will not be without its problems. We found in Nigeria that male-sterile florets were highly vulnerable to ergot during the rainy season. The only answer to this potential problem is to produce seed under irrigation during the dry season. The areas in West Africa where this is practical are limited.

The constraints on the sorghum breeder in the tropics are many and for the most part he will have to build his program using local germplasm. In some cases he may wish to reduce plant height for which tropical bulks from the Conversion Program may be of help.

The breeders in the temperate zones will benefit the most from the germplasm from the Conversion Program. Before hybrids were introduced in 1956, nearly all grain sorghum cultivars in the USA were derived from crosses between kafirs and milos. The lines from the conversion program have greatly enhanced the source material available to the breeders, particularly by giving them resistance to many insects and diseases. It has been reported by F. Miller (personal communication, Texas A&M University) that 1283 lines are in the program and the conversion has been completed on 403.

The converted lines are being used extensively in the development of breeding populations. This breeding system has its merits as a simple means of producing a gene pool from which a breeder can draw the genotypes which will best fit his environment. The person using a population must know the characteristic of the source material in order to anticipate the recombinants. I believe the population approach should be tried in the tropics particularly where manpower is limited and environments are diverse. In 1971 (Webster 1975) I assembled 41 elite lines from West Africa and synthesized a population using male sterile-7. My plan was to have seed of this population grown at a few locations in northern Nigeria and the breeder at harvest time would select the types best suited to each environment.

Sorghum improvement specialists are all members of an international program. The coordination was initially with FAO but now ICRISAT plays the leading role. ICRISAT has research personnel posted in a number of countries who function as a part of a regional team as well as giving assistance to national programs. One function of INTSORMIL is to arrange for cooperative work between scientists in developing countries with the experts available in one of a dozen universities of the USA. The library facilities at the headquarters of ICRISAT are available to all.

As far as plant quarantine regulations permit, the growing of International Nurseries is to be encouraged. Such nurseries not only are a means of distributing elite germplasm, but the disease nurseries also serve as a means of monitoring the presence of a disease in an area, or a physiological race.

It is imperative that we diligently continue in our efforts to increase sorghum production in the world in order to alleviate hunger. If we do not do this and improve the livelihood of the sorghum producers, particularly the peasant farmer in the developing countries, we will have failed in our calling.

References

HACKEROTT, H. L, HARVEY, T. L, and Ross, W. *M* 1969. Green bug resistance in sorghum. Crop Science 9:656 -658

HARLAN, J. R. 1972. Genetic resources in sorghum. Pages 1-13 *in* Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co.

STARKS. K. J., EBERHART, S. A.. CASADY, A. J., and WEBSTER, 0. J. 1976. Developing green bug resistant lines from KP2BR sorghum breeding population. Crop Science 16:360-362.

WEBSTER, 0. J. 1975. Use of tropical germplasm in a sorghum breeding program for both tropical and temperate areas. Pages 1-12 *in* Proceedings, 30th Corn and Sorghum Research Conference.

Session 4 Genetic Resources

Discussion

K. E. Prasada Rao

This is with reference to the comment made by Dr. Gebrekidan regarding the change that occurred in the original accession sent to ICRISAT. I may have to clarify what has actually happened, otherwise this could give a wrong impression that Hyderabad may not be a suitable center for maintenance. At Hyderabad we have two seasons. One a long day and the other a short day. When a part of the Ethiopian collection was first brought by Dr. Doggett in 1973, we were not aware of the photoperiod sensitive problem of the Ethiopian collection. We planted the material in February 1974 and the material segregated for sensitive and insensitive types. The insensitive ones were given by number (E-35-I, etc). In that way, part of the Ethiopian collection lost its identity. When we planted in the *rabi* (postrainy season) everything flowered including collections from Ethiopia as well as highly sensitive Nigerian types. There was no problem of maintenance.

Vidyabhushanam

Dr. Gebrekidan in his presentation mentioned types for transplantation used in West Africa. I wish to know the identity of these types and their characteristics.

Gebrekidan

As this practice is prevalent in West Africa, I would rather request someone from West Africa to say more about this.

Obilana

The varieties Masakwa and Moskwaris are the Harmattan dry season sorghums with special traits like:

1. Very large, hard endosperm, high quality grains which are considered as a delicacy.
2. Heat tolerance at the seedling stage.
3. Cold tolerance at the vegetative and reproduction stages.
4. Drought resistance or tolerance flourishing on residual moisture in heavy clay soil.

Niangado Ouman

In the central Nigerian delta, sorghum is grown in receding flood water, which in practice is locally called "Sorgho en decrue" These sorghums are usually sown directly but sometimes they are transplanted by some farmers. We are planning an expedition to this region this year.

Mengesha

This is an interesting comment. We have heard of these types of sorghum in different parts of Africa, i.e., Cameroon, Chad, Nigeria, etc. We are planning to explore those areas and collect those types in the near future. As Mr. N. Ouman is planning to collect this year, we will be grateful if he could send us samples of this collection.

Jain

Dr. Gebrekidan cited Zera Zera sorghums as an example of finding a cluster of useful accessions within a small region. But if we survey all known resistance sources for geographical origins, do we find that resistance to a given disease or insect pest is found localized? My guess from other crops is that it varies with different diseases or pests. Now, given that resistance is found scattered at random, are we not led to maintaining all the accessions basically as a game of numbers for maximizing the probability of including a rare genotype? The claim that observationally a few accessions from each of the areas would represent the variability seems questionable.

Mohamane

How can I get some seeds of Zera Zera, the variety from Ethopia? Does this variety grow well on sandy soils? What is the rainfall necessary for its growing? What is the period of cultivation? How many days from sowing to anthesis and so on?

Gebrekidan

E-35-1 (Gambella 1107) is the best available Ethiopian Zera Zera sorghum. Seeds of this variety should be easy to get from ICRISAT, Ouagadougou, Upper Volta. I have no information on its performance under sandy soils but ICRISAT, Upper Volta has indicated that it has done well there. Under Ethiopian conditions, it is a medium maturity variety, taking about 75 days from planting to flowering and about 4 months to maturity. In Ethiopia it is grown in areas where the annual rainfall is about 600 mm and the altitude is below 1600 m.

Goud

What sources of cytoplasm have been used to develop a cytoplasmic genetic male-sterility mechanism other than milo?

Gebrekidan

Several sources have been used, the major ones of which are caudatum, Durra, Guinea—Bicolor, Guinea—Caudatum. Details on this are given in the symposium paper by Shertz and Pring "Cytoplasmic sterility symptoms in sorghum".

Chaudhary

Does the sorghum germplasm program of ICRISAT include grain as well as forage sorghum, or does it deal only with grain sorghum?

Mengesha

We do have several forage types of sorghum germplasm maintained at the ICRISAT gene bank.

Bapat

Looking to the possibility of using sorghum for industrial uses, there is a need to collect cultivars from different countries, which are known for their quality characters. Such collections should be maintained separately (e.g., sugary types—grain and sweet stemmed types; pop sorghum; starchy types, etc.)

Mengesha

Yes, we are maintaining such types separately.

Maiti

I want to make a general comment. The "glossy" traits which are found to be related to insects and drought resistance could be included in future as one of the descriptors of sorghum germplasm. In this connection I want to inform the Symposium that at ICRISAT, in collaboration with Mr. K. E. Prasada Rao, Genetic Resources Unit, 21 000 germplam lines were evaluated for glossy trait. About 500 lines have been identified. These lines showed variability in taxonomy and geographical distribution. They will be tested for different crop establishment traits.

Rana

1. Last year, I made 60 collections from Western Kenya. To my surprise, some of them yielded fairly well with 300 mm rain, during the short rainy season. They have BSR (Busia Sorghum Roa) numbers and can be included in the world collection.
2. How do you meet nonspecific seed requests? If sources of resistance and economic characters are known, they can be documented for ready reference.

Ravindranath

Nonspecific requests of seed supply can also be made based on:

1. The behavior of the entry of germplasm in the native country or country of collection if the pest/disease is found there.

2. Some information has already been collected in various trials such as the ISRON, ISCRN etc. Thus it is possible that some information from past testing would be available before providing germplasm lines.

Mengesha

Yes, we will soon be able to provide detailed information as we complete our computerization and documentation effort as stated in our presentation. This is a very useful question and we *are* taking action.

Niangado Ouman

I would like to put two questions to Dr. Mengesha and to the phytopathologist. Yesterday, these gentlemen spoke about the existence of several physiological races of certain diseases of sorghum. They also remarked that the resistance mechanisms often observed can be overcome by new physiological races. My first question is: Given this state of affairs, is not the long-term conservation which was proposed, risky in the sense that we might keep varieties which will soon be overcome and destroyed by parasites? Would it not be desirable to combine the long-term conservation with a dynamic conservation? Good cooperation with the countries having samples would guarantee this dynamic conservation. Does not the preservation of a sample by saving seed from 20 panicles bring about a genetic change compared with the original strain.

Mengesha

Yes it does,and that is why we are also planning to form bulks and populations to maintain the original strain as much as possible.

Session 5

Genetics and Breeding for Improvement

Chairman: M. V. Rao

Co-Chairman: D. T. Rosenow

Rapporteurs: B. V. S. Reddy

M. J. V. Rao

The Problems of Apomixis and its Prospects in the Eighties

U. R. Murty[1], N. G. P. Rao[1], P. B. Kirti[1], and M. Bharathi[1]

Apomixis results in and can be used for the fixation of heterozygosity and consequently heterosis. This possibility was discussed as early as the thirties by Navaschin and Karpechenko (cf Solentzeva 1978). Nearly 50 years have passed and during this period, the various attempts of breeders have resulted in some progress, most notable among them being the manipulation of obligate apomixis in the breeding of Buffel grass, *Cenchrus ciliaris* (Taliaferro and Bashaw 1966). Less spectacular achievements are those involving its application in citrus, berries, guayule, and numerous perennial forage grasses. Apomixis has been reported in grain sorghum and pearl millet and is believed to be present in several other important crops (Rao and Narayana 1968; Hanna et al. 1970; Bashaw 1980).

Among the cereals, the maximum amount of information has been obtained in sorghum. However, research work on apomixis in sorghum was hampered for a number of reasons. Most workers are either professional geneticists or breeders, who are handicapped by lack of a thorough knowledge of embryology, or orthodox embryologists, who have no knowledge of genetics. The support for apomixis research is also being received in the form of temporary and short-term grants. In addition, the phenomenon of apomixis in sorghum is the most complicated so far encountered in any flowering plant. All these reasons together with an inadequate understanding of the phenomenon (Rana et al. 1981; Narasa Reddy 1979) have resulted in limited success. However, a few devoted attempts made in recent years have produced a reasonably clear picture of the phenomenon and the procedures to be followed in this field of study (Murty et al. 1979; Murty and Rao 1979; Murty et al. 1981a). An account of the problems inherent in this field, the progress made so far, the program that can be profitably followed in the future, and the prospects accompanying such research are dealt with in this paper.

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2. ICRISAT, Ahmadu Bello University, Samaru-Zaria, Nigeria.

The Problems

The chief problems encountered in apomixis work are: (1) the confusion regarding the wide variety of terminology used in reference to this phenomenon; (2) the difficulties in the estimation of its frequency; (3) the low frequency with which it occurs in several sorghum lines; (4) the delicate balance between sexuality and apomixis influenced by the environment; and (5) the difficulties encountered in maintaining genetic stocks.

1, The Terminology

The term apomixis means only the production of offspring without the fusion of the male and female gametes. This phenomenon can occur in several ways, not all of which are useful as far as fixation of heterozygosity is concerned.

The theoretical details of such processes are discussed in a number of reviews (Gustafsson 1946, 1947 a and b; Fagerlind 1940; Maheshwari 1950; Stebbins 1950; Nygren 1954; Battaglia 1963; Khokhlov 1976; Asker 1980). There are two processes needed for fixation of heterozygosity: (a) production of unreduced female gametes and (b) development of such gametes into viable embryos.

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Production of Unreduced Female Gametes

Unreduced female gametes can be produced in several ways. Only two of the methods are useful, i.e., apospory (production of unreduced embryo sacs from nucellar cells) and diplospory (production of unreduced embryo sacs directly from the archesporial cell). These two phenomena may-lead to the production of diploid embryo sacs, the type of divisions through which they give rise to such sacs having a bearing on their usefulness. Conventionally, there are three types of divisions that lead to diploid cells. These are: (1) the formation of a restitution nucleus; (2) pseudo-homeotypic division, and (3) mitosis. Rosenberg (1927) described the phenomenon of meiotic nuclear restitution as the formation of a single nucleus with unreduced chromosome numbers owing to a failure of either the first or the second division referred to as the first division restitution (FDR) and the second division restitution (SDR), respectively. Cytologically, there are important differences between these two types. In the case of FDR the nucleus does not undergo the normally expected disjunctional separation of homologous chromosomes at anaphase I (AI). Instead, the entire diploid complement divides mitotically, giving rise to a diad with two unreduced spores. The two daughter nuclei are by and large similar. In SDR, the nucleus restitutes after anaphase I (AI). Each product of the normal disjunctional separation—a haploid set—divides mitotically but the sister chromatids do not separate to poles. Therefore, the doubled chromosomes of a haploid set constitute the second division restitution gamete. Since SDR is preceded by a disjunctional separation of homologous chromosomes which leads to genetic segregation, the SDR gametes may be quite dissimilar.

Thus FDR preserves heterozygosity and fixes heterosis. SDR leads to homozygosity and to dihaploid production. In addition to FDR and SDR, normal mitosis could also replace meiosis and is the ideal phenomenon for perpetuating heterozygosity.

There are other possible ways of producing diploid embryo sacs. One such mechanism, "synkaryogenesis" or "automixis", which occurs in sorghum, is dealt with in the next section.

Once a diploid embryo sac is formed, further development could be either autonomous (without the stimulation of pollen) or pseudogamous (with the stimulation of pollen).

2. Estimation of the Level of Apomixis

The frequency of apomixis has two components. One of them is the frequency of diploid embryo sacs. The other is the frequency of progeny obtained without the fusion of the male and female gametes. In fact, the latter can only be more correctly termed as the true apomictic frequency.

(1) Study of Serial Sections of Ovules

The classical procedure for the estimation of the frequency of diploid embryo sacs involves the cytological screening of sectioned ovules during megasporogenesis. This procedure provides a direct and accurate estimate of the relative frequencies of the normal (sexual) and the aposporous, and diplosporous types of embryo sacs, provided the investigator makes comparative studies of his material with normal sexual material. Overenthusiasm on the part of the observer results in erroneous observations. In several reports on apomixis in sorghum, the degenerating megaspores were interpreted as representing the degenerating megaspore mother cell and the sexual functional megaspore as a nucellar cell giving rise to aposporus embryo sacs (Narasa Reddy et al. 1979). To be accurate, this procedure involves sectioning of a large number of ovules since all sections do not contain the required stage of development. Also, estimation of the frequency of the different types of development from only the clearly discernible preparations is likely to introduce some bias. It should also be realized that the relative frequency of apomictic embryo sacs may not accurately reflect the relative apomictic seed, particularly when pollination is uncertain or there is marked zygotic competition (Barlow 1958). Not all the potential diploid sacs may develop into seed through apomixis and not all the sexual embryo sacs develop sexually. The frequency of apomixis depends on the relative efficiency of these two types of embryo sacs. In order to distinguish between the frequency of apomictic embryo sacs and the frequency of apomictically formed offspring we propose two terms, structrual apomixis and functional apomixis.

Structural apomixis is defined as the phenomenon by which an organism produces unreduced embryo sacs. Functional apomixis refers to the phenomenon by which an organism produces offspring without the fusion of gametes. Structural apomixis is purely under genetic control and has two components: genotype and genotype x environmental interaction. Functional apomixis may or may not be under genetic control. It has three components: genotype, environment, and genotype x environmental interaction. Functional apomixis can be induced easily through environmental factors like heat treatments, cold treatments, distant pollinations and delayed pollinations. Apomixis reported in maize, wheat and potato are all due to functional apomixis. Structural and functional apomixis are independent phenomena that can operate alone but when they occur together, they complement each other. Classical cytological techniques provide for the estimation of the former only. The latter can be estimated by progeny tests.

(2) Progeny Tests

The advantages of progeny tests have been known for several years. These methods allow for scoring of large numbers of individual plants (Tinney and Aamodt 1940). These procedures are also ideal to study the effect of environmental factors on the incidence of sexuality in facultative apomicts. Such studies have been previously restricted by limitations of cytological methods (Knox and Heslop-Harrisson 1963; Knox 1967; Evans and Knox 1969). Progeny tests, when used in conjunction with morphological marker loci, reduce the need for specialized equipment and expertise. These procedures are of special value for field stations and experiment farms, where both equipment and expertise are often lacking. Progeny tests provide a direct measure of the relative frequency of apomictic seed. Such an estimate is of greater populational significance than the prezygotic estimate afforded by cytological techniques (Marshall and Weir 1979).

Progeny tests also have some disadvantages. The frequency of apomixis could be biased upward due to accidental selfing and tight linkage of the marker genes. Also the possibility of autosegregation should be ruled out before definite conclusions are reached. Moreover, the frequency of apomixis is not constant and is subject to environmental effects.

Application of both these methods in sorghum is difficult. If we consider the classical microtome method, the difficulties faced are the absence of differences between the sexual and apomictic embryo sacs, and the great time and energy to be spent if careful analyses of large populations have to be made. Till recently, progeny tests could not be performed on R-473, because it is cross sterile. The phenomenon of cross sterility was first described in corn (Demerec 1929). Cross sterility refers to the inability of certain varieties of corn to set seed with foreign pollen and was shown to be controlled by a gametophytic locus (ga) located on the short arm of chromosome 4. Alleles of this locus prevent certain pollen genotypes from fertilizing the female gamete or give one pollen genotype a competitive advantage over the other. The same phenomenon occurs in sorghum. As of today, no single line of sorghum has been found that can induce seed set on emasculated spikelets of genuine R-473 earheads. Only recently did Murty and his colleagues find a procedure for performing progeny tests (Murty et al. 1979; Murty and Rao' 1979).

The difficulties in the detection and estimation of apomixis in R-473 has prompted development of some indirect methods (Marshall and Downes 1977; Reddy et al. 1980). The validity of these conclusions is discussed in item number eight in the section entitled Progress Made During the Seventies.

3. The Facultative Nature of Apomixis

Apomixis has so far been reported in five lines of sorghum. Details of the various materials are discussed in the next section. The most investigated line so far is. R-473 from India. Although it was initially believed that this line is an obligate apomict (Murty and Rao 1972; Rao and Murty 1972), under cross pollination at least, it does not behave as an obligate apomict. The frequency of apomictically produced offspring varies from 30 to 50% (Murty et al. 1981b). For apomixis to be useful in the fixation of heterozygosis, it has to be obligate or nearly so as in Buffel grass. The sexual potential in this line, whatever may be its extent, should be decreased to the minimum to achieve complete fixation of heterozygosity. Breeding of facultative apomicts is much more difficult than breeding of obligate apomicts, although some useful cultivars have been produced in forage grasses like Kentucky blue grass, guinea grass, blue stem, etc., (Bashaw 1980). The presence of some sexuality makes the progenies segregate in each generation. Also, the most important factor is to determine the stability of each line through several generations.

4. Environmental Effects on Apomixis

The frequency of apomixis,especially in facultative apomicts.is subject to environmental influences like locations, seasons and years. Day length has been found to have a significant effect on the frequency of apomixis in *Dichanthium aristatum* (Poir.) C. E. Hubb (Knox and Heslop-Harrison, 1963; Knox 1967). The line R-473 was investigated at one tropical (India) and one temperate location (Texas) and showed different frequencies of apomixis in the two environments. Similarly, even in the same location, the frequency of apomixis in field-grown and glasshouse-grown plants differs. The *kharif, rabi* and summer crops at Hyderabad have also given different results (Murty, unpublished). Generally, seed set on apomicts is greater in summer than in other seasons.

5. Maintenance of Pure Genetic Stocks

When N. G. P. Rao made his first observations at the time of the isolation of R-473, he noticed the absolute absence of seed set on emasculated heads of R-473 pollinated by alien pollen. However, later workers could find sporadic seed set under cross-pollination. In fact, J. Roy Quinby isolated two types of R-473 lines, one of them being completely cross sterile and the other giving up to 50% hybrids when crosses were made using the plastic bag method. We found that the frequency of multiple embryo sacs in the former line is much greater, the frequency of pollen penetration much lower and that no seed is set on cross-pollination in the former. Observations of chromosome morphology at pachytene indicated that R-473 carries structural heterozygosity for some chromosomal segments, especially the nucleolus organizing chromosome and a few others (Kirti et al.. In press). In such an individual carrying structural heterozygosity, sexually produced offspring may not reproduce the genotype. In such a case, it is possible to get offtypes even under selfing. Maintenance of delicately balanced, structurally heterozygous R-473, therefore, poses some problems. A practical method is to cross-pollinate a part of the earhead and collect only selfed seed from the plants that do not give any seed set. This is because all cross sterile plants maintain structural heterozygosity.

Progress Made During the Seventies

1. Source Materials for Apomixis

The first report of apomixis was in the line R-473 (Rao and Narayana 1968). This is an F_4 line from the cross of an Indian line Aispuri with a yellow endosperm kafir, IS 2942. The next report of apomixis was in the line 'Polygynaceous' by Hanna et al. (1970). A few more lines were tested in recent times and were found to have a low level of apomixis (Table 1). The other lines were tested at Hyderabad in progeny tests using hand crosses. All crosses yielded only hybrids and no maternals. This indicates that they may have

Table 1. The source material for apomixis.

Line	Origin	Frequency of apomixis	References
R-473	F, derivative of IS-2942 x Aispuri.	30-100%	MurtyandRao 1979; Murtyetal. 1979.
Polygynaceous	Multiple ovaried male sterile line derived in radiation experiments.	25.0	Hannaetal. 1970.
Polygynaceous (PGY)	A single ovaried selection from a cross of polygynaceous line x Colby	Very low	Tangetal. 1980
White Seed (WS)	A white seeded mutant of Experimental 3	" "	" "
South Dakota Mutant 3-58(SD)	A mutant of Experimental 3	" "	" "
Doubled Haploid (DH)	A doubled haploid line derived from Tx 403.		

some prezygotic apomictic potential, but none of this potential is realized in the progeny tests. White Seed, however, was observed to have a prefertilization embryological behavior similar to that of R-473. In addition, White Seed is the line that was helpful in the studies of apomixis in R-473. The extent of its usefulness in apomictic studies is given in the next section. The discussion in the following pages will be mainly about R-473.

2. Breakthrough in the Performance of Progeny Tests on R-473

The cross-sterility exhibited by R-473 was a great hindrance in the study of apomixis. In their attempts to overcome this hurdle at College Station, Texas, Murty et al. (1979) performed several bud pollinations with pollen from other lines including Dakota Amber, White Seed and Colby but with no success. The ovaries enlarged slightly and developed some green color when emasculated florets were pollinated with a mixture of live alien pollen of Colby and radiation killed pollen of R-473. But such ovaries did not continue to develop. These methods did not overcome the cross fertilization barrier of R-473.

In order to induce seed set on emasculated R-473, the methods adopted with self-incompatibility studies were followed. These included pollinating R-473 spikelets with pollen from individual plants of F_1, F_2 and BC F_1 of crosses in which R-473 was the male parent. Surprisingly, seed developed in two combinations. These involved the F,s (White Seed x R-473) and (Dakota Amber x R-473) and F_2s and BC F_1s of (White Seed x R-473). This induction of seed set provided an opportunity for the performance of progeny tests on R-473. The resulting progenies had two types of individuals—maternals and hybrids. Hybrids in these progenies could be distinguished from matemals (identical to R-473) by differences in height and panicle characters.

Subsequently, we have performed several progeny tests at Hyderabad. The procedure for performing a progeny test has been given in detail by Murty and Rao (1979). For accurate results, the female parents and the F, hybrid should be clearly identifiable morphologically. We found that in addition to White Seed, individual F_2 plants of the crosses (Kafir B x R-473) and (IS-84 x R-473) have also induced seed set. In fact, the seed set induced by these is much greater than that of White Seed x R-473 at Hyderabad (Table 2).

3. Frequency of Apomixis

By far, frequency of apomixis is the most important factor for the successful fixation of heterozygosity. The greater the frequency, the more advantageous it will be in breeding. The frequency of apomixis in facultative apomixis is, however, not only a function of the genetic potential but also of environmental factors. In sorghum, the frequency of apomixis is dependent upon four factors: (a) type of pollination, self or cross; (b) type of pollinator, cross sterile or cross fertile; (c) location; and (d) season.

The frequency of apomixis is greater under self-pollination than under cross-pollination. Under cross-pollination, the frequency is greater if a cross-sterile plant is used as the pollinator than if a cross-fertile plant is used. Apomixis was also found to occur in a greater frequency under the glass-house conditions of College Station, Texas than under the field conditions of Hyderabad (Tables 3, 4 and 5).

Table 2. Seed set on R-473 heads by individual F_2 plants from crosses of R-473 with IS-84. Kafir-B, and White Seed.

F_2 progeny	Number of plants: Giving seed set	Number of plants: Not giving seed set	Seed set %: Range	Seed set %: Mean
White Seed x R-473	8	6	0-10.00	1.73
Kafir-B x R-473	17	1	0-38.46	1400
IS-84 x R-473	11	4	0-43.90	13.25

The lower frequency of apomixis under cross pollination is probably due to defective endosperm formation. Endosperm in R-473 is derived in several ways and could, therefore, have different genetic constitutions. The relation genome: plasmon in the endosperm is normally 3:1 in sexual plants. In R-473, this relation instead could be either 2:2 or 2:5 in addition to 2:3; and this deviation from the normal ratio might cause degeneration of potential apomictic endosperms and embryo, and lower the frequency of apomixis realized. Under self-pollination, the relation might have existed in a perfectly balanced state.

4. Mechanism of Apomixis

There are at least three types of mechanisms for the production of diploid embryo sacs in R-473.

1. Apospory: A diploid embryo sac is formed from a nucellar cell.

Table 3. Frequency of apomixis—cross-pollination. Backcrosses at College Station, Texas (19751.

Male parent	Seed Set	Frequency of Maternals	Frequency of Hybrids
A Kafir x R-473	0	—	—
South Dakota x R-473	0	—	_
Polygynaceous derivative x R-473	0	—	—
Double haploid x R-473	1/300	0	1
R-473 x S. Colby	0	—	—
Dakota Amber x R-473	8/50	6 (75.00)	2
White Seed x R-473-1	16/480	2 (50.00)	2
White Seed x R-473-3	58/180	20 (39.21)	31
White Seed x R-473-5	23/170	10 (66.66)	5
White Seed x R-473-7	16/95	2 (50%)	2
White Seed x R-473-8	20/91	12 (75.00)	4
White Seed x R-473-9	8/50	4 (50.00)	4
Mean (%)		52.33	47.66

a. Numbers in parentheses are percentages.

Table 4. Frequency of apomixis—cross-pollination. Progeny tests on R-473 by F, and backcross plants at College Station, Texas (1975).

No. of seeds sown	No. ger-minated	No. of hybrids	No. of matemals	Percentage of matemals
21	15	10	2	16 66
12	3	1	2	66.66
8	4	1	3	75.00
7	6	2	4	66.66
6	3	3	0	0.00
9	3	1	2	66.66
17	13	7	6	46.15
24	8	0	8	100 00
33	12	3	9	75.00
24	11	1	10	90.99
29	3	2	1	33 33
46	13	5	8	61 54
20	16	16	0	0.00
Mean				53.74

Table S. Frequency of apomixis under cross-pollination. Progeny tests on R-473 at Hyderabad, *rabi* 1979.

Seed set range	0-100%
Mean	9.7%
Number of total seeds	886
Plants which survived	234
Percent apomixis	33.76

2. Diplospory: A diploid embryo sac is formed from an archesporial cell.
3. Synkaryogenesis or Automixis: These terms are used *sensu lato* in this publication. From haploid nuclei of the embryo sac, diploid nuclei are formed through fusion. This can involve fusion of sister nuclei of the egg apparatus (Murty et al. 1981b) or sister nuclei of the antipodals.

Normally, both apo- and diplosporous embryo sacs are identical to the sexual type sacs (Polygonum type). The synkaryotic sacs, however, are atypical. Even more atypical sacs with six nuclei were found in some derived apomicts.

Regarding the development of endosperm and embryo in aposporous embryo sacs, the endosperm in some ovules develops by the independent fusion of each of the polar nuclei with separate sperm nuclei (Murty et al. 1979). Sometimes endosperm arises from nuclei other than the polar (Murty et al. 1981a). The development of the embryo is autonomous. The stimulus of pollination, however, is necessary for the formation of the seed.

5. Isolation of True Breeding Lines

The objective of apomixis research is the production of uniform and vigorous lines that breed true. For this, single plant progenies from F_2 and BC F_1 plants that gave good seed set on R-473 and also those that were cross-sterile were grown on an extensive scale along with some untested plants. Three types of progenies were obtained: (a) those that were segregating freely, (b) those in which only two morphological types were found, and (c) those that were completely uniform.

The first type of progenies apparently indicated occurrence of normal sexual reproduction in the heterozygous parent. The second type apparently indicated the existence of facultative apospory.

Progenies of this type always have two types of individuals. A majority of them (up to 80%) are identical with their parent. A small frequency of offtypes are always encountered. The maternal types are presumably produced through apospory and the offtypes through sexual reproduction. Individual progenies from the maternals always behave in a similar manner. The cytological behavior of these plants was similar to R-473. All such plants were found to be cross sterile.

The third type of progenies was found to be 100% homozygotes, reproducing sexually.

6. The Concept of Vybrids—Definition, Production and Significance

Heterozygous individuals with facultative apomixis produce a population containing: (a) F_1 genotypes derived through apomixis, and (b) F_2 genotypes developed through sexual reproduction. The frequency of F, genotypes will be equal to the frequency of apomixis. If the next generation is derived through the F, genotype plants only, then the population mean will remain the same. If the procedure is repeated, it is possible to maintain heterozygotic vigor in subsequent generations and to keep the mean constant.

A peculiar type of population was produced using two derived facultative individuals. The F, was uniform and vigorous. The F_2 had two types of individuals—(a) those carrying the F, genotype, and (b) those carrying genotypes resulting from segregation. Individuals looking like the F, were selfed and carried over. The same type of behavior was noticed. These observations led to the concept of "vybrids". Vybrids are superior varieties in that their yield levels will be greater than those of conventional varieties although they may not be equal to those of their F,. Some more comments on vybrids are made later in the section entitled Program and Prospects of the Eighties.

7. The Concept of Dihaploids—Production and Significance

The possibility of parthenogenetic development of reduced egg cells followed by reduplication or fusion or development of embryos from secondary diploid cells of the embryo sac derived through fusions, is interesting from the breeder's point of view. It would give rise directly to homozygous diploids. The formation of such diploids has been presupposed by several authors. Automixis, fusion of two haploid nuclei in a meiotic embryo sac to give rise to diploid homozygous progeny, has been claimed to occur in *Rubus* (Thomas 1940). This possibility has now been realized in sorghum. These dihaploids. for all practical purposes, can be considered identical to those produced by anther culture techniques.

Several dihaploids were produced in our experiments. Some of them were cross-sterile and some were cross-fertile. The homozygosity of these lines was tested by crossing them to a pure line and observing the uniformity in the F, progeny.

8. The Interfering but Helpful Cross Sterility

Detection, estimation and manipulation of apomixis in R-473 has been much hampered because of cross sterility. We have made several attempts to isolate apomictic segregates without cross sterility. Such attempts were never successful. It was also noticed that in addition to R-473, White Seed also exhibited the formation of multiple embryo sacs, nucellar activity and antipodal differentiation. But White Seed never exhibited apomixis in progeny tests. In addition to this, we have also examined several other lines. Among them, 302 was found to have similar anomalies but no realizable apomixis.

The difference between these lines and R-473 is obligate cross sterility. Cross sterility in some way affects the reproductive system and promotes apomixis.

The different constituents of apomixis are known as the elements of apomixis (Petrov 1976). The elements of apomixis lie within the reproductive potentiality of sexual plants. They play a greater part only when the normal sexual process is impaired. Cross sterility is one such mechanism.

Long ago, Powers (1945) suggested the existence of three essential elements of apomixis: (a) failure of reduction of chromosome number; (b) failure of fertilization of egg cells, and (c) development of the egg cell to an embryo without its being fertilized. Production of diploid embryo sacs is one element of apomixis. The prevention of fertilization of unreduced embryo sacs leads to the stimulation of such embryo sacs to apomictic seed formation.

It appears, therefore, that apomixis in sorghum may not occur without cross sterility. In view of this, the conclusions reached by Reddy et al. (1980) need some modifications. They concluded that if mutation for male sterility caused a loss of apomixis, such a loss would have had to occur as five distinct events, once in each progenitor of the five M_2 progenies in which male steriles were derived. It was not realized that loss of cross-sterility makes a line reproduce sexually although it may have some potential for apomixis.

Program and Prospects of the Eighties

1. Rapid Methods for Estimating Prezygotic Potential of Apomixis

Estimation of the prezygotic potential of apomixis in a segregating population is almost impossible if one uses the serial section method. The ovule squash method used extensively by Murty et al. (1979) is the only method available for such a purpose. Estimation of the relative amount of DNA of Feulgen stained nuclei of embryo sacs using a microscope spectrometer (integrating densitometer; microphoto meter) should provide a rapid and easy alternative. If such an instrument is provided with a computerized recording device, large numbers of populations can be screened in a short time. A procedure for the estimation of apomixis based on the existing information and using the embryo sac squash method is given below:

1. Emasculate the spikelets of the suspected parent.
2. Pollinate abundantly with pollen from sister plants.
3. Fix material 4 hours after pollination.
4. Examine embryo sacs in ovule squashes.
5. Approximate apomictic potential = frequency of ovules with unfertilized embryo sacs (single) + frequency of ovules with multiple embryo sacs + frequency of ovules with degenerating embryo sacs and antipodal activity.

In recent years. Zein isoelectric phoretic patterns are being used for evaluation of genetic purity.in hybrid seeds (Motto and Salamini 1979). Similar techniques can also be easily perfected for apomictic studies in sorghum.

2. Rapid Methods for Performing Progeny Tests

Conventional progeny tests involve slow and tedious procedures of emasculation and pollination and visually observable morphological criteria. The utilization of grain characters (e.g., shrivelled vs plump endosperm or color of the endosperm) should help make for easy performance of progeny tests. The use of chemical dyes that can effectively distinguish between sexually and asexually produced seed should be an ideal method for apomictic research.

3. Utilization of Facultative Apomixis for the Production of Vybrids

The vybrids so far produced by us are agronomically inferior. They were synthesized only for testing the theoretical possibility. Future investigations should aim at exploiting the partial fixation of heterozygosity for yield advantage. The following steps are involved in the production of agronomically desirable vybrids.

1. Select adapted and desirable sorghum genotypes and cross with one or more facultative apomicts.
2. Produce and grow large BC F_1 progenies. Make individual selections.
3. Grow head to row progenies, keeping remnant

seed. Pick up uniform lines that have maintained vigor.
4. Sow the remnant seed of the uniform lines and make as many crosses as possible among themselves.
5. Select the good F_1s and carry over to the next generation.
6. Save the seed of only F_1-type plants for the next generation. Test the performance in yield trials.

Good hybrids will be those that have a high frequency of facultative apomixis, a high degree of yield heterosis, and a minimum of negative transgressive segregation.

Theoretically the performance of vybrids will be intermediate between those of F_1 hybrids and of the parental lines from which they have been synthesized.

4. Utilization of SDR, Automixis, and Synkaryogenesis

SDR, synkaryogenesis, and automixis could be profitably put to use for the production of dihaploids. The significance of dihaploids could be realized when one considers the tremendous opportunities for obtaining true breeding desirable lines in one step from heterozygous plants. Since the release of 'Maris Haplona' variety of rape, *Brassica napus* (cf Riley 1974), excellent commercial varieties like F-211 in tobacco (Nakamura et al. 1974), the Tanu and Huayu varieties of tobacco, and the Haupei and Lunghua varieties of wheat (Hu et al. 1978) have been produced using anther culture techniques. However, in sorghum, although several devoted research projects have been carried out in tissue culture (Brettell et al. 1980; Werinicke and Brettell 1980), anther culture techniques are yet to yield positive results. The present method of obtaining dihaploids, therefore, indicates a potential breeding tool in sorghum.

5. Achieving Obligate or Near Obligate Apomixis

By far, the real achievement of research on apomixis in sorghum, centers around attaining obligate apomixis. A perfectly operating gametophytic apomixis is usually not likely to arise in one single step. In nature, genes promoting effective apomictic reproduction are successively incorporated by mutation or recombination.

Apomixis obviously involves fixation of heterosis. It is not surprising, then, that induction of apomixis in sexual crops has been considered by breeders. According to Solentzeva (1978). this possibility was discussed by Navashin and Karpechenko as early as in the thirties. During later years, work of this type has been carried out in different materials (Asker 1980).

Several possibilities exist for increasing the frequency of apomixis through genetic means. The frequency of unreduced egg cells varies strongly among inbred lines of maize (Alexander and Beckett 1963). It is well known that in genera like *Saccharum* and *Citrus,* some clones or stocks produce unreduced female and male gametes to a much greater extent (Harlan and de Wet 1975).

The possibility of obtaining apomicts through means like wide crosses, mutations, etc., has been discussed by several authors. However, the following specific methods should prove fruitful in the case of sorghum.

(a) Selection Following Matings of Cross Sterile Facultative Apomicts

Several apomictic plants have been shown to have a simple genetic control. However, in many cases, it appears that there is certainly a polygenic control. The results in sorghum also indicate such a quantitative gene action. As such, it appears probable to increase the frequency of apomixis by mating facultative apomicts, selecting for increased apomictic frequency, and by repeating the process.

(b) Effect of Cytoplasms and the Search for Apomictic Restoration

In recent years, diverse cytoplasmic sources have been identified (Rao 1962; Nagur et al. 1965; Schertz 1978). On milo, R-473 is a restorer but it is nonrestoring on some of the new cytoplasms. If continuous backcrossing is involved, there are three possibilities:

1. Selection of spontaneous mutations that result in restoration due to mutation of the restorer genes.
2. Selection of spontaneous mutants that promote apomixis.
3. Selection of lines with altered frequency of apomixis due to gene-cytoplasm interactions (see J. R. Quinby, These Proceedings).

The second and third possibilities need to be tested during the eighties.

(c) Effect of Growth Regulators

Auxins and gibberellins are known to be involved in the postpollination reproductive events of plants. Various chemical treatments have been tried in order to induce parthenogenesis in plants but generally without success. However, parthenocarpy is easily induced by treatment with plant hormones. Deanon (1957) reported a significantly increased frequency of monoploids in maize after treatment with dimethyl sulphoxide (DMSO). The diploids were homozygous, resulting from haploid parthenogenesis followed by chromosome doubling (see J. R. Quinby, These Proceedings).

(d) Effect of Spontaneous and Induced Mutations

There exists the possibility of inducing apomixis by a combination of suitable spontaneous and artificial mutations with strong effects upon the reproductive system. Mutations are known that induce either FDR or SDR. Induction of mutations, screening for apomixis and selection of near obligate types is a possibility.

Summary

The progress of research work on apomixis is reviewed, the problems are stated and suggestions are made for the efficient utilization of the phenomenon in breeding. Maximum frequency of apomixis occurs in the Indian grain sorghum line R-473. Under self-pollination, apomixis occurs to the extent of 80%. Under cross pollination, it varies from 30 to 50%. Most apomictically produced offspring were heterozygotes resembling the female parent. However, a small frequency of individuals were obtained that are for all practical purposes dihaploids. These dihaploids arose from the phenomenon of second division restitution, automixis or synkaryogenesis.

Using facultative apomixis, it has been possible to obtain what are known as vybrids. Vybrids are the first and subsequent generation progenies of the F, hybrids of two facultative apomicts. In each generation, F, genotypes could be recovered and the mean of the population in any generation remains constant. Rapid techniques and procedures were outlined for the production and utilization of vybrids and dihaploids.

References

ALEXANDER, D. E., and BECKETT, J. B 1963. Spontaneous triploidy and tetraploidy in maize. Journal of Heredity 54:103-106.

ASKER, S. 1980 Gametophytic apomixis: Element and genetic regulation. Hereditas 93:277-293.

BARLOW, B. A. 1958. Heteroploid twins and apomixis in *Casuarina nand* Australian Journal of Botany 6:204 -219

BASHAW, E. C. 1980. Apomixis and its application in crop improvement. *In* Hybridization of crop plants. Madison, Wisconsin,, USA: Crop Science Society of America 677 pp.

BATTAGLIA, E. 1963. Apomixis. *In* Recent advances in embryology of angiosperms, ed. P. Maheswari International Society of Plant Morphologists

BRETTEL, R. 1. S., WERMICHE, W., and THOMAS. E. 1980. Embryogenesis from cultured immature inflorescences of *Sorghum bicolor* Protoplasms 104:141-148

DEANON. J. R. JR 1957 Treatment of sweet corn silks with maleic hydrazide and colchicine as a means of increasing the frequency of monoploids Philippines Agriculture 41 :344.

DEMEREE, M. 1929. Cross sterility in maize. Zeits. i. Abst U. Vereb. 50:281-291.

EVANS, L T., and KNOX, R. B. 1969. Environmental control of reproduction in *Themeda australis.* Australian Journal of Botany 17:375-389.

FAGERLIND, F. 1940 Die terminologie De apomixis Prozesse Hereditas 26:1-22.

GUSTAFSSON, A. 1946. Apomixis in higher plants Part I The mechanism of apomixis. Lunds University Arsskr NF Ard 2.

GUSTAFSSON, A. 1947a. Apomixis in higher plants. Part II The causal aspect of apomixis. Lunds University Arsskr NF Ard 43:71-178.

GUSTAFSSON, A. 1947b. Apomixis in higher plants. Part III. Biotype and species formation. Lunds University Arsskr NF Ard 2, 43:183-370.

HAGBERG, A„ and HAGBERG, G. 1980. The high frequency of spontaneous haploids in the progeny of an induced mutation in barley. Hereditas 93:341-343.

HANNA, W. W„ BASHAW, E. C, and SCHERTZ, K. F. 1970.

Apospory in *Sorghum bicolor* (L). Science 170:338 -339.

HARLAN, J. R., and DE WET, J. M. J 1975. The origins of polyploidy. Botanical Review 41 : 361-390

Hu, H., Hsi. T. Y., TSENG, C C, CUYANG, T. W. and CHING, C. K. 1978 Application of anther culture to crop plants. Pages 123-130 *in* Frontiers of plant tissue culture, ed T. A. Thorpe. Calgary. Alberta, Canada: International Association of Plant Tissue Culture

KHOKLOV, S. S. 1976 Evolutionary-genetic problems of apomixis. Pages 179-189 *in* Apomixis and breeding, ed. S. S. Khoklov New Delhi, India: Amerind

KIRTI, P. B., MURTY, U. R . BHARATHI, M , and RAO, N G. P. (In press). Chromosomal studies of cross sterile and cross fertile sorghum *[Sorghum bicolor* (L). Moench 1 Genetica.

KNOX, R. B. 1967 Apomixis: Seasonal and population differences in a grass. Science 157:325-326

KNOX, R B , and HESLOP-HARRISON, J 1963. Experimental control of aposporous apomixis in a grass of the *Andropogoneae* Botaniska Notiser 116:127-141.

MAHESWARI, P. 1950 An introduction to the embryology of angiosperms. New York, USA: McGraw Hill

MARSHALL, D R , and DOWNES, R W. 1977 Test for obligate apomixis in grain sorghum R-473 Euphytica 26:661-665

MARSHALL, D. R , and WEIR, B. S. 1979. Maintenance of genetic variation in apomictic plant populations I. Single locus models Heredity 42:159-172.

Mono, M . and SALAMINI. F. 1979 Evaluation of genetic purity in hybrid corn seed production through zein isoelectric phoretic patterns. Maydica 24 : 233-235

MURTY, U. R , and RAO, N. G. P. 1972. Apomixis in breeding grain sorghum Pages 517-523 *in* Sorghum in seventies, eds N. G P. Rao and L. R. House New Delhi, India: Oxford & IBH. Publishing Company. 638 PP.

MURTY, U. R.. and RAO, N. G. P. 1979 Progeny tests on apomictic *Sorghum bicolor (L.)* Moench. Current Science 48:1041-1042.

MURTY, U. R., RAO, N. G. P.. KIRTI, P. B., and BHARATHI, M. 1981a. Apomixis and sorghum improvement. National Research Centre for Sorghum, IARI-Regional Station, Hyderabad, India.

MURTY, U. R. RAO, N. G. P., KIRTI, P. B., and BHARATHI, M. 1981b. In vivo production of dihaploid *Sorghum bicolor* (L.) Moench'. Current Science 50:142-143.

MURTY, U. R., SCHERTZ, K. F.. and BASHAW, E. C. 1979. Apomictic and sexual reproduction in sorghum. Indian Journal of Genetics and Plant Breeding 39: 271-278.

NAGUR, T., MURTY, K. N., and PARTHASARATHY, A. V. 1965. A note on male sterile yellow grained jowar. Andhra Agricultural Journal 11 : 183-184.

NAKAMURA, A., YAMADA, T., KODOTANI, N , ITAGAKI. R., and OKA, M. 1974. Studies on the haploid method of breeding in tobacco Society for the Advancement of Breeding Research in Asia and Oceania (SABRAO) Journal 6: 107-131.

NARASA REDDY, R 1979 Studies of apomixis and cytoplasmic genetic male sterility systems in sorghum. Ph.D. Thesis. Kakatiya University, Warangal, India.

NARASA REDDY, R., NARAYANA, L. L, and RAO, N. G. P 1979. Apomixis and its utilization in grain sorghum II. Embryology of F1 progeny of reciprocal crosses between R-473 and 302 Proceedings of Indian Academy of Sciences Section B 88:455-461

NYGREN, A 1954. Apomixis in the angiosperms. Botanical Review 20:577-649.

PETROV, D. F. 1976. Genetically regulated apomixis as a method of fixing heterosis and its significance in breeding. Pages 18-28 *in* Apomixis and breeding, ed. S. S Khoklov. New Delhi, India: Amerind

POWERS, L. 1945 Fertilization without reduction in guayule (*Parthenium argentatum* Gray) and a hypothesis as to the evolution of apomixis and polyploidy. Genetica 30:323-346.

QUINBY, J. R 1981. Interaction of genes and cytoplasm in sex expression in sorghum These Proceedings: ICRISAT.

RANA, B. S, REDDY, C. S., JAYAMOHAN RAO, V. S., and RAO, N. G. P. 1981. Apomixis in grain sorghums: Analysis of seed set and effects of selection Indian Journal of Genetics and Plant Breeding 41 :125-130.

RAO, N. G P. 1962. Occurrence of cytoplasmic genetic male sterility in some Indian sorghums. Indian Journal of Genetics and Plant Breeding 22:257-259.

RAO. N. G. P., and MURTY, U. R. 1972. Further studies of obligate apomixis in grain sorghum. Indian Journal of Genetics and Plant Breeding 32 :379-383.

RAO, N. G. P., and NARAYANA, L. L. 1968. Apomixis in grain sorghums. Indian Journal of Genetics and Plant Breeding 28:121-127

REDDY, C. S., SCHERTZ. K. F.. and BASHAW. E. C. 1980. Apomictic frequency in sorghum R-473. Euphytica 29:223-226.

RILEY. R. 1974. The status of haploid research in haploids in higher plants—advances and potential, ed. K. J. Khasha. Ontario. Canada: University of Guelph.

ROSENBERG. O. 1927. Die Semi-heterotypische Teilung und thre Bedeuturg fur die Entstehung verdoppetter chromosomen zahlen. Hereditas 8:305—358.

SCHERTZ. K. F., and RITCHEY. J. M. 1978. Cytoplasmic genetic male sterility systems in sorghum. Crop Science 18:890-892

SOLENTZEVA, M. P. 1978. Apomixis and hemigamy as one of its forms. Proceedings of Indian Academy of Sciences Section B. 44:78-90.

STEBBINS, G. L. 1950. Variation and evolution in plants. New York, USA: Columbia University Press.

TALIAFERRO. C. M., and BASHAW. E. C. 1966. Inheritance and control of obligate apomixis in breeding buffel grass. Crop Science 6:474-476.

TANG, C. Y„ SCHERTZ, K. F., and BASHAW. E. C. 1980. Apomixis in sorghum lines and their F, progenies. Botanical Gazette 141:294-299.

THOMAS, P. T. 1940. Reproductive versatility in Rubus. II. The chromosomes and development. Journal of Genetics 40:119-128.

TINNEY, F. W.. and AAMODT, G. S., 1940. The progeny test as a measure of the type seed development in *Poa pratensis* L. Journal of Heredity 31 .457-464.

WEINICHE. W„ and BRETTEL. R. S. 1980. Somatic embryogenesis from *Sorghum bicolor* leaves. Nature 287:138-139.

Cytoplasmic Sterility Systems in Sorghum

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This symposium reflects an increasing international collaboration on sorghum, *Sorghum bicolor* (L.) Moench. Through this collaboration we have the potential to dramatically improve sorghum, its production, and its utilization in the 80s and beyond. An important result of increased multinational and multi-agency research will be more effective identification and use of genetic variability. Enhanced exchange of information and germplasm should result in more rapid progress than previously possible.

An expected effect of such widespread collaboration will be increased yield and uniformity. We are all aware of some of the past dramatic problems created by widespread plantings of the same or similar varieties, for example, the Irish potato famine in the 1840s, the coffee rust epidemic in the 1870s, wheat rust epidemics, and more recently, corn leaf blight. Uniformity of genotype or of cytoplasm can predispose a crop to widespread damage. In a crop like sorghum, on which people's lives depend, not even one year's crop loss is acceptable. Both stability and productivity are very important.

We must be wise as well as cooperative. We must not only strive for high yields but must also understand the mechanisms involved and the alternative ways to achieve that yield. We must understand the genetic control of the characters of interest and be aware of and use alternate sources of those characters. We must develop and use breeding methods to produce varieties with the necessary diversity and physiological homeostasis to withstand biological and environmental hazards.

Let us now focus our attention on the cytoplasms of sorghum as related to the questions of diversity and vulnerability and consider needs, progress, and a perspective.

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Needs

Concern regarding uniformity or diversity of cytoplasms is usually related to hybrids because of the use of cytoplasmic-nuclear male sterility in F, hybrid production. We should have a similar concern regarding uniformity of cytoplasm of self-pollinated varieties whenever a single or a few related varieties predominate in a geographic region.

A single cytoplasm is present in nearly all sorghum hybrids, as we now depend almost entirely on a single cytoplasmic-nuclear male-sterility system for the production of hybrids. Nearly all hybrids have milo cytoplasm because it is the cytoplasm that induces male sterility in most of the female parents.

The discovery of cytoplasmic-nuclear male-sterility in sorghum by Stephens and its development for hybrid seed production by Stephens and colleagues Quinby, Holland, Kramer, and others (Stephens and Holland 1954; Quinby et al. 1958; Quinby and Schertz 1970; Quinby 1971) made possible the mass producton of F_1 hybrids. Male sterility in this system is caused by the interaction of milo cytoplasm and kafir nuclear genes. The milo cytoplasm which induces male-sterility in the female parent is passed to the hybrid. No matter which male parents are used to produce the hybrids the cytoplasms of those hybrids are all from milo. Many female parents are similar because they must be sterilizable in milo cytoplasm. In addition to causing uniformity of cytoplasms in the hybrids, the use of milo cytoplasm restricts nuclear diversity. Male parents are restricted to those that will restore fertility to the hybrids produced when crossed to those females.

Other cytoplasmic-nuclear sterility systems are

International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru, A.P.. India. Patancheru. A.P. India: ICRISAT.

being sought. One purpose is to improve germplasm diversity so as to avoid hazards that might be related to a cytoplasm. The use of female parents with different cytoplasms would provide hybrids with different cytoplasms and a measure of security associated with diversity. Another purpose is to add flexibility and nuclear diversity to breeding programs. With additional cytomplasmic-nuclear sterility systems, new parental combinations should be possible.

Progress

Cytoplasms have been sought and studied at several locations. Some commercial companies as well as public research agencies are seeking and evaluating new cytoplasms. Quinby (1980) reported on the isolation of new cytoplasms and presented an hypothesis regarding the genetic and hormonal control of male sterility.

Indian Lines

Considerable progress has been made in India, where several male-sterile lines have been isolated. The lines studied and their cytoplasmic identities are listed in Table 1. Mital et al. (1958) reported the occurrence of a male-sterile in line IC 2360. A male-sterile plant in this line was sibpollinated to produce the sterile line.

Rao (1962) reported male-sterile plants in varieties W. E. 1, Bilichigan, Red Jonna, Indore local. GJ. 103, B.D. 8, Burma black, Norghum. and C. 10-2. Hussaini and Rao (1964) reported two additional male-sterile plants in PJ 22 K and a white-seeded variety from Warangal.

N. G. P. Rao and his colleagues identified some of the male-sterility inducing cytoplasms (Rao 1962) and reported that information in a subsequent series.

Appathurai (1964) isolated a sterile from G.1 and designated it G. 2-S. Apparently the cytoplasm of G. 2-3 differs from that of G. 2-S. Cytoplasmically affected self-incompatibility was found by Rao et al. (1971). They studied this incompatibility in the varieties Swarna, IS 84, and M35-1 and Kafir B. ail in indigenous *maldandi* cytoplasm. The variety IS 84 was crossed with an indigenous *(maldandi)* male-sterile line..

Nagur (1971) and Nagur and Menon (1974) reported on six male-sterile lines including CK60. In the latter report, they distinguished four different cytoplasm (S1 to S4) based on sterility response. They were S1 in ms CK 60-A, S2 in ms G-1-G and ms M35-1-G, S3 in ms VZM-1-V and ms VZM-2-V, and S4 in ms M31-2-R. Additional details were provided on sterility of these lines and on cytoplasmic effect on agronomic characteristics (Nagur and Menon 1974).

Rao (1972) in the "Sorghum in Seventies" symposium reviewed the work on male sterility in India and provided information of new male-sterile lines developed with milo cytoplasm. He also gave the following details regarding the new sterility-inducing cytoplasms: (a) The new cytoplasmic source reported in 1962 (Rao 1962) was used to convert M35-1 (an Indian winter sorghum) and IS 3691, a yellow hegari, into sterile lines. Both M35-1 and IS 3691 are restorers in the milo-kafir system; (b) additional sources of cytoplasmic sterility have been reported by Hussaini and Rao (1964) in durra (G2. VZM-1, and VZM-2); (c) sterile lines with feterita cytoplasm are being developed at Parbhani; and (d) at Raichur. another indigenous sterile line, M31-A, is said to owe its origin to induced mutation.

Tripathi (1979) and Tripathi et al. (1980) provided additional information regarding sterility as well as other characteristics on six male-sterile lines, some of which differed only in cytoplasms. The male-sterile lines included CK60A and NagpurA, the latter based on milo cytoplasm. Tripathi (1979) concluded that CK60A was identical to NagpurA, M35-1A was identical to M31-2A, and G1A was identical to VZM2A in sterility responses. Tripathi et al. (1980) gave a tentative designation of A, to the cytoplasms of M35-1A and M31-2A, and of A_3 to VZM-2A and G1A. Tripathi and colleagues also provided information on agronomic, genetic, biochemical, and scanning electron microscopy characteristics of these lines.

The male-sterile lines from India are being backcrossed to BTx 398 in our USDA-Texas program to produce additional lines differing only, in cytoplasms for comparison with the steriles we derived. We made mitochondrial and chloroplast DNA analyses of the cytoplasm of M35-1 male sterile (Pring et al., in press) and Dixon and Leaver (personal communication) found a line with M35 -1 cytoplasm to differ from milo in polypeptide formation. Details are presented later.

9E Cytoplasm

A male-sterile plant was discovered by Webster

Table 1. Cytoplasmic-nuclear male-sterile and incompatible sorghum lines studied by scientists in India.

Authority	Line	Source
Mital et al. (1958)	IC 2360	
Rao (1962)	W E. 1	
	Bilichigan	
	Red Jonna (Plants 1 & 2)	
	Indore local (Plants 1 & 2)	
	G J 103	
	B D. 8	
	Burma black (Plants 1 & 31	
	Norghum (Plants 1 & 2)	
	C 10 2	
Hussaini and Rao (1964)	PJ 22 K	
	White seeded variety from Warangal	
Appathurai (1964)	G 2 S	G I Strain, Guntur, India
Rao and Gouda (1966)	M 31 2	M 31-2
Nagur (1971)	ms CK60 milo cytoplasm	from USA
	ms G1 durra cytoplasm	from Guntur, India
	ms VZM1 durra cytoplasm	from Vizianagaram, India
	ms VZM2 durra cytoplasm	from Vizianagaram, Inda
	ms M35-1 dochna cytoplasm	from Kovilpatti, India
	ms M31 2 cernuum cytoplasrr	from Dharwar. India
Nagur and Menon (1974)	ms CK 60-A (S1)	
	ms G-1-G (S2)	from Guntur, India
	ms M-35-1 G (S2)	
	ms VZM-1-V (S3)	from Vizianagaram, India
	ms VZM-2-V (S3)	from Vizianagaram. India
	ms M-31-2-R (S4)	from Raichur. India
Rao et al. (1971)	Swarna indigenous maldandi cytoplasm	
	IS84 indigenous maldandi cytoplasm	
	M35-1 indigenous maldandi cytoplasm	
	Kafir B indigenous maldandi cytoplasm	
Tripathi (1979)	CK60A milo cytoplasm	
	NagpurA based on milo cytoplasm	Maharashtra (India)
	G1A unidentified cytoplasrmic source	Guntur (AP) (India)
	VZM2A unidentified cytoplasmic source	Vizianagaram (AP) (India)
	M35-1A unidentified cytoplasmic source	Maharashtra (India)
	M31-2A unidentified cytoplasmic source	Raichur (Karnataka) (India)
	CK60A, NagpurA } same sterility response	
	G1A, VZM2A } same sterility response	
	M35-1A, M31-2A } same sterility response	

Continued

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Authority	Line		Source
Tripathi et al. (1980)	CK60A	milo cytoplasm	
	NagpurA	based on milo cytoplasm	
	M35-1	A_2 (Tentative)	
	M31-2A	A_2 (Tentative)	
	VZM-2A	A_3 (Tentative)	
	G,A	A_3 (Tentative)	

and Singh (1964) in 9E, a selection made in Ghana. Reciprocal differences were observed; 9E x Leoti was sterile and Leoti x 9E was fertile (Webster, personal communication). Sterility in this line is maintained by kafirs and also by milos (Webster and Singh 1964).

Several lines, including D. D. Sooner Milo, have been sterilized in 9E cytoplasm and the sterility of those A lines was evaluated in tests at five locations (Webster 1980). The 9E sterile line is being test crossed and compared with other steriles in our USDA-Texas program. Our studies of mitochondrial and chloroplast DNA of 9E reveal that it differs from milo (Pring et al., in press) as did polypeptide studies of Dixon and Leaver (personal communication).

USDA-Texas Lines

The sorghum lines in our USDA-Texas-Florida studies represent diverse types or origins, or were reported by other breeders to be male steriles. Lines from others include male-sterile lines from India, 9E from Webster, and the KS lines from Ross (Ross 1965; Ross and Hackerott 1972). Those chosen for diversity were from the USDA -Texas Agricultural Experiment Station Conversion Program (Stephens et al. 1967). Lines from the world collection (IS lines) were converted from photoperiod sensitive to less sensitive by backcrossing and selecting. Each of these converted lines had the cytoplasm of the IS (Indian or International Sorghum) line from the world collection. The lines we used were collected in 13 countries and represented 10 races (4 basic and 6 intermediate) or 36 groups (16 basic and 20 intermediate). Two main approaches were used to identify diverse cytoplasms. One involved determining sterility differences among test-cross progenies of lines differing only in cytoplasms. The other was an analysis of mitochondrial and chloroplast DNA.

Sterility

In the sterility studies, converted lines were reciprocally intercrossed, the progeny were advanced to F_2 and male steriles were selected and repeatedly backcossed by the male parent. Male-sterile backcross progeny were backcrossed by a single sterility-maintaining line (BTx 398) so as to produce lines differing only in cytoplasms. We are backcrossing lines from India to the same maintainer line. The KS lines already differed only in cytoplasms, having been backcrossed to CK60 by Ross (Ross and Hackerott 1972). Each of the male-sterile lines will be crossed by a series of tester lines and fertility of F, progeny will be determined.

Twenty-four male steriles (Table 2) have been isolated from converted lines. We do not know how many of their cytoplasms differ from milo or among themselves. Male steriles were isolated in 10 races (4 basic and 6 intermediate) from 7 countries (Table 2). Fourteen of the 24 male-steriles now have at least four backcrosses to BTx 398. These crosses for definitive comparisons of some of these cytoplasms were made in 1981. Probable differences among cytoplasms for the induction of sterility were detected in preliminary test-cross and other progenies.

A few male-sterile lines were crossed by testers before the male steriles were backcrossed to nuclear uniformity. The purpose of making these crosses was to identify the most desirable testers but the results of such preliminary tests do provide some indication of possible differences among cytoplasms. The sterile with IS 12662C cytoplasm was identified by Schertz and Ritchey (1977) as probably different from milo (A1) and released as A2 (Schertz 1977; Rosenow et al. 1980; Schertz et al., 1981). The sterile from IS 1112C probably has a different cytoplasm and was designated A3 by Quinby (1980).

The sterile lines differ considerably. Some have

Table 2. Sorghum lines with male-sterile inducing cytoplasm.

IS no.*	SC no *	Group	Race	Place of origin
5322C	250	Roxburghii	Guinea	India
1116c	195	Roxburghii	Guinea	India
7920C	299	Conspicuum	Guinea	Nigeria
7007C	268	Conspicuum-Nigricans	Guinea	Sudan
2266C	93	Caudatum	Durra	Sudan
7506C	407	Caudatum-Guineense	Bicolor	Nigeria
2573C	64	Caudatum-Kafir	Caudatum	Sudan
12662C	171	Caudatum-Nigricans	Caudatum	Ethiopia
2816C	120	Zera zera	Caudatum	S Rhodesia
7498C	353	Caudatum-Conspicuum	Caudatum	Nigeria
12565C	50	Caudatum-Conspicuum	Caudatum	Sudan
1112C	193	Durra-Subglabrescens	Durra-(Durra-Bicolor)	India
12645C	154	Durra-Bicolor	Durra-Bicolor	Ethiopia
3620C	303	Margaritiferum	Guinea	Nigeria
12680C	217	Dochna-Leoti	Bicolor	India
12539C	19	Dochna-Amber	Bicolor	Ethiopia
6271C	317	Dochna-Roxburghii	Guinea-Caudatum	India
2757C	319	Dochna-Nigricans	Caudatum	Uganda
6882C	320	Caffrorum	Kafir-Caudatum	—
8232C	642	(Caffrorum-Durra)-(Caudatum-Nigricans)	(Kafir-Caudatum)-Caudatum	India
2169C	331	Nigricans-Durra	Durra	—
6964C	411	Caudatum-Dochna	Bicolor	Nigeria
2177C	215	Cernum	Guinea-Bicolor	India
12600C	91	S nitidum	—	N. Rhodesia

* IS = International sorghum numbers assigned to world collection
SC = Number asssigned during conversion

extremely minute anthers, with no functional pollen but others have nondehiscent anthers with pollen. Lines also differ in stability of sterility under various environmental conditions. High temperature is a main cause of a decrease in sterility in some of these lines just as it is with male-steriles having milo cytoplasm.

A few original IS fertile lines produced male-sterile F_1s. Reciprocal differences in F, sterility were observed (Table 3). Note particularly that IS 1112C (A3) frequently produced F, steriles when it was the female parent.

DNA

In the analysis of mitochondrial and chloroplast DNA, comparisons were made of DNA fragmented by restriction endonuclease (Pring et al.. in press). Lines used in the isolation of male steriles as well as others were analyzed. Included were several milo varieties. Mitochondria and chloroplasts were isolated from leaf-blade and leaf-sheath tissue of seedlings. DNA was fragmented by a series of restriction endonucleases and electrophoretic patterns on slab gel agarose were determined by methods reported by Pring et al. (1972) and Pring and Levings (1978).

Mitochondrial DNAs (mtDNAs) from kafir and milo cytoplasms were distinguished by four restriction endonucleases *Hind* III, *Sal* I, *BamHI,* and *Bgl* II, three patterns of which are shown in Figure 1 (Pring et al., in press). Note the extra band in milo (Fig. 1D) as compared with kafir (Fig IC) at 58 and 74 mm and in milo (Fig. IF) versus kafir (Fig. 1E) at 37 mm. Chloroplast DNAs (ctDNAs) of kafir and milo were distinguishable by

Table 3. Sorghum female parents that produced male-sterile F_1s and fertile reciprocals from specific crosses.

Female parents IS no.*	Frequency**	Group	Race	Country of Origin
5322C	1	Roxburghii	Guinea	India
1116C	1	Roxburghii	Guinea	India
5821C	4	Roxburghii	Guinea	India
7534C	1	Conspicuum	Guinea	Nigeria
12605C	1	Conspicuum	Guinea	Nigeria
2266C	1	Caudatum	Durra	Sudan
7382C	1	Caudatum	Durra	Nigeria
12662C	1	Caudatum-Nigricans	Caudatum	Ethiopia
12666C	1	Zera zera	Caudatum	Ethiopia
1022C	3	Durra	Durra	India
1056C	3	Durra	Durra	India
12683C	1	Durra	Durra	India
1112C	10	Durra-Subglabrescens	Durra-(Durra-Bicolor)	India
12645C	1	Durra-Bicolor	Durra-Bicolor	Ethiopia
12673C	1	Durra-Dochna	Durra-Bicolor	Ethiopia

*IS = International sorghum numbers assigned to world collection lines
Number of parehtal combinations that produced male-sterile F_1s with the noted female parent but fertile F_1s from the reciprocal cross

restriction endonucleases BamHI, EcoRI, *Hind* III, *Bgl* II and HaeIII (Fig. 2) (Pring et al., in press). Note differences between kafir (Fig. 2A) and milo (Fig. 2B) at 70 mm and between kafir (Fig. 2C) and milo (Fig. 2D) at 60 mm.

Several other milo cytoplasms and alternative sterility-inducing cytoplasms were observed in a similar manner using the previously mentioned and other restriction endonucleases (Pring et al., in press). The distinctions made by these analyses are recorded in Table 4.

Ten groups of cytoplasms were differentiated by restriction endonuclease analyses of mtDNAs. The milo cytoplasms, except for Millo Blanco, were all indistinguishable. A2 (A2Tx 2753) from IS 126622C was distinguished from milo by only one endonuclease *(Pst* I) of the seven used. A3 (IS 1112C) was distinguished by *Hind Ill* digestion. A3 (IS 1112C) cytoplasm also was found to contain two plasmid-like DNAs (Pring et al., in press).

These groups were differentiated by use of *Hind* III, EcoRI, and *BamHl* on chloroplast DNA. Some lines differentiated by analysis of mtDNA were not differentiated by analysis of ctDNA. It must be remembered, however, that negative results are not conclusive in studies of this sort. Restriction by other endonucleases might have revealed additional differences.

As indicated previously, M35-1 and 9E were distinguished from milo (A1) cytoplasm by DNA analyses (Table 4). This is consistent with the sterility observations of Rao and his colleagues and of Webster regarding these two steriles respectively. The DNA analysis also distinguished M35-1 and 9E cytoplasms from each other. No data are yet available comparing the sterility responses of these two steriles (M35-1 and 9E).

Dixon and Leaver (personal communication) have corroborating data from studies of translation products. They classified the male-steriles they studied into four groups. A male sterile with kafir nucleus and milo cytoplasm had an extra polypeptide with a molecular weight of 65 000. Martin with 9E cytoplasm has a variation in mobility of subunit I of cytochrome oxidase. A line with kafir nucleus and IS1112C cytoplasm synthesized an extra polypeptide with molecular weight of 82 000 and one with molecular weight of 12 000. A line with Yellow Feterita nucleus and

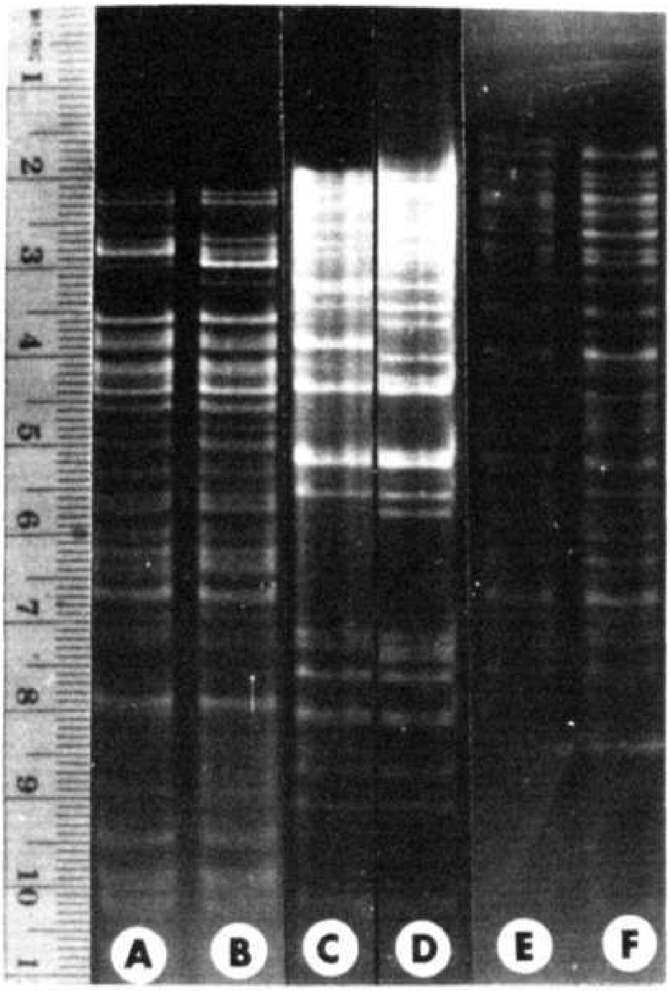

Figure 1. Agarose gel electrophoretogram of kafir (A, C, E.) and milo (B, D, F) sorghum cytoplasm mitochondrial DNA digested with Hind *///* *(AM* Sal */ (CD), and* BamHI *(E,F) restriction endonucleases.*

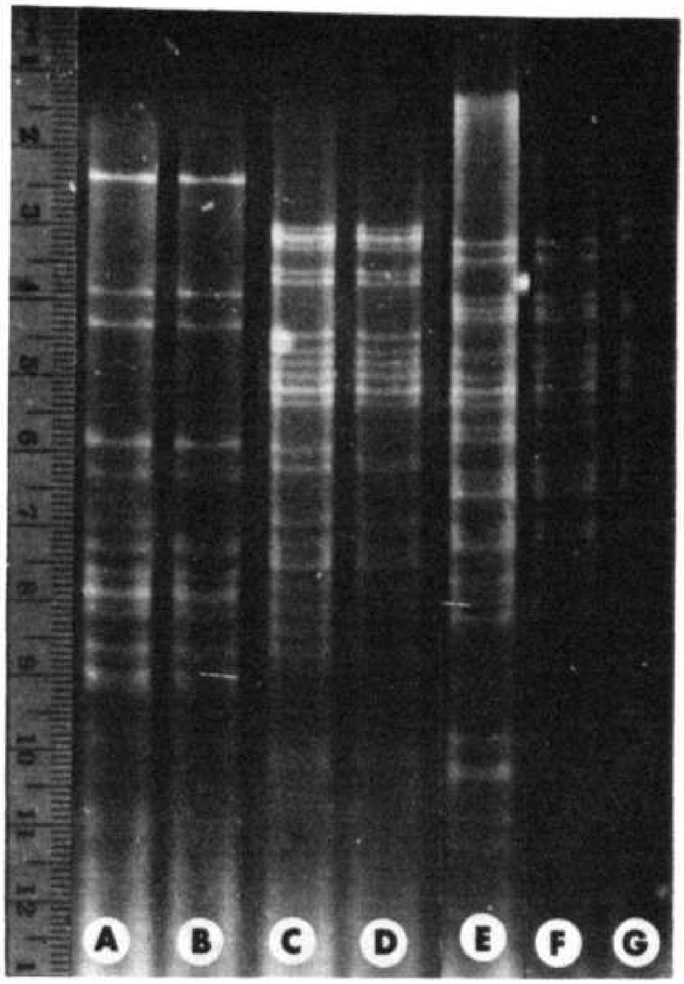

Figure 2. Agarose gel electrophoretogram of kafir (AC,F), milo (B.D.G) and 9E (E) sorghum chloroplast DNAs digested with EcoRI (AM Hind/// *(CD), and* Bam *HI (E,F,G) restriction endonucleases.*

M35-1 cytoplasm synthesized a polypeptide with molecular weight of 82 000. Each of the latter two lines contained plasmid-like DNAs.

KS Lines

Sterility

The KS lines developed by Ross (Ross 1965; Ross and Hackerott 1972) have cytoplasms from grassy sorghums. Early test crosses of these lines with CK60 nuclei did not reveal any cytoplasmic differences in sterility response. We decided that the availability of increased diversity in the world collection lines from the Conversion Program warranted another study of these cytoplasms. Each of the KS male steriles and CK60 (milo cytoplasm) was crossed by a series of testers. The test-cross progenies of male steriles KS35, KS36, and KS37 by specific male parents were more fertile than the progenies of the CK60, KS34, KS38, and KS39 male steriles by the same testers (Table 5). These tests were conducted in 2 years in Texas and Nebraska (Conde et al., in press).

DNA

Restriction analyses of mtDNA from the six KS male-sterile lines using several endonucleases revealed two subgroups. The patterns of KS34, KS38, and KS39, corresponded to that of milo as represented by CK60 male sterile. The patterns of KS35, KS36, and KS37 differed from that of milo and the other KS male-sterile lines. SsfEII digests of KS35, KS36 (Fig. 3D) and KS37 mtDNAs were

Table 4. Differentiation of sorghum cytoplasms into groups by restriction endonucleasa fragment analyses of mitochondrial and chloroplast DNA.

MtDNA Group	Members	CtDNA Group	Members
1	Milo	1	Milo
	IS 6705C		IS 6705 C
	IS 1116C		IS 1116C
	IS 2801C		IS 2801C
	IS 3063C		IS 3063C
	Standard Yellow Milo		Standard Yellow Milo
	Dwarf Yellow Milo		
	Early White Milo		
	IS 6271 C		
	KS34		
	KS38		
	KS39		
2	A2Tx 2753 (IS 12662C)		A2Tx 2753 (IS 12662C)
3	IS 1112C	2	IS 1112C
4	M35-1 (A line)		M35-1 (A line)
5	IS 1056C		IS 1056C
	IS 2483C		IS 2483C
6	Millo Blanco		Millo Blanco
7	Tx 398 (9E)	3	Tx 398 (9E)
8	IS 7920C		IS 7920C
9	KS35	1	KS35
	KS36		KS36
	KS37		KS37
10	Kafir	2	Kafir

Table 5. Percentage fertility of test-cross progenies of KS male-sterile sorghum lines.

			Male				
Female	Source of cytoplasm		Early hegari SA281	IS12673C SC182	IS7382C SC344	IS2169C SC331	IS12587C SC78
CK60	Milo		56	38	2	1	0
KS34	*S. arundinaceum*	PI 208190	45	5	1	2	0
KS35	*S. arundinaceum*	PI 258806	97	64	6	10	22
KS36	*S. verticilliflorum*	PI 208190	91	58	9	12	11
KS37	*S. sudanense*	PI 247722	88	52	8	10	15
KS38	*S. conspicuum*	PI 155140	60	30	1	1	1
KS39	*S. niloticum*	Kenya 53262	50	23	1	1	1

characterized by one obviously missing fragment (uppermost band in Fig. 3C of KS38) and probably two other missing fragments when compared to KS34. KS38, and KS39 mtDNAs. With *XhoI.* KS35 (Fig. 3F), KS36, and KS37 yielded three fragments not present in digests of KS34 (Fig. 3E), KS38, and KS39, e.g., at 27 mm in Fig 3. Additional differences were obtained with other endonucleases (Conde et al., in press).

These three, KS35, KS36, and KS37, are the same lines that differed from CK60 and the other KS lines in fertility of test-cross progenies (Table 5). The correspondence of fertility and mtDNA data supports the idea that the cytoplasms of KS35, KS36, and KS37 differ from the cytoplasms of milo and the other three KS lines.

Perspective

As we increase international collaborative sorghum research we must utilize the genetic diversity available and assure diversity among improved self-pollinated varieties and F, hybrids.

Diversity among cytoplasms is an important aspect of this consideration, particularly among cytoplasms used to induce male-sterility for hybrid production. The diversity of germplasm that became available during the past two decades provides an excellent opportunity for advancement in the future. Work is in progress and several potentially useful diverse cytoplasms have been isolated. Scientists in India and the USA have identified cytoplasms with sterility responses different from milo, the cytoplasm now used to induce sterility in nearly all female parents of hybrids. In both countries the effect of other cytoplasms are being studied. Other characteristics, including mitochondria, chloroplasts, and polypeptides, are being studied in India, the USA, and Scotland. These combined studies are providing information and lines useful to diversify germplasm in sorghum breeding programs.

Additional information is needed: (1) The identities of many of the cytoplasms must be determined by definitive studies of lines differing only in cytoplasms. (2) The inheritance of the cytoplasmic-nuclear interaction causing sterility needs to be understood. (3) Cytoplasms found to differ need to be checked for sterility response with many other lines so as to identify potential parents of hybrids with the new sterility systems. (4) The new cytoplasms need to be evaluated for their effect on characteristics other than sterility. (5) Methods of breeding and hybrid production need to be devised and evaluated so as to efficiently utilize new cytoplasms. (6) We need to evaluate ways to more efficiently identify diverse and potentially useful cytoplasms. Can DNA analyses, scanning electron microscopy, or other analyses be used to identify cytoplasms differing for sterility response or even for response to hazards?

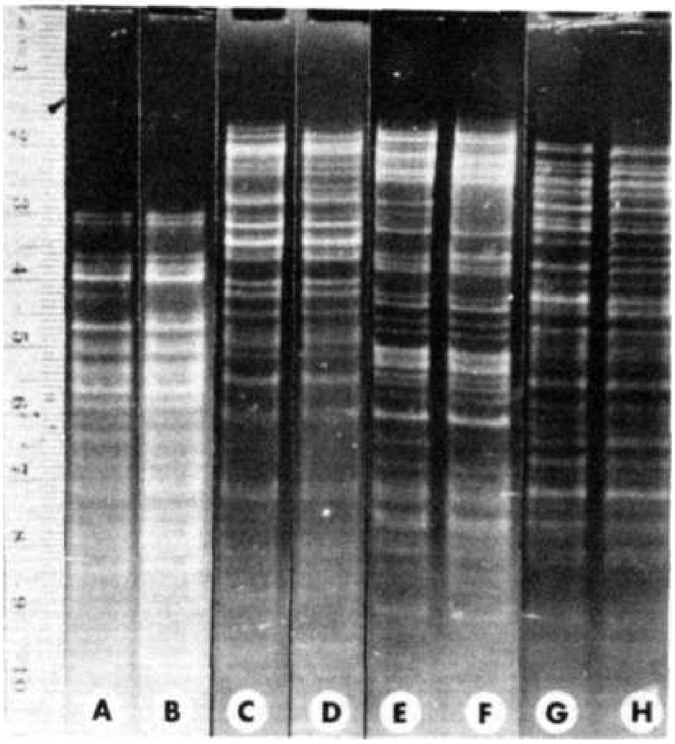

Figure 3. Agarose gel electrophoretogram of restriction endonuclease fragment analyses of the KS series cytoplasm mtDNAs of sorghum. Hind III *digestion of KS-34 (A) and KS-37 (B), BstEII digestion of KS-38 (C) and KS-36 (D),* Xho/ *digestion of KS-34 (E) and KS-35 (F), and* Bam *HI digestion of KS-34 (G), and KS-35 (H). DNAs digested with different enzymes were run on separate electrophoresis gels.*

It is essential that there be a coordinated collaborative approach to these studies. We must exchange information and lines but we must do more. We must actually conduct research together so that comparisons of results are most meaningful. We must agree on and use a uniform system of nomenclature so that we can understand each other and so avoid confusing those who might use our lines.

But will a new cytoplasmic nuclear system be used, and if so, how? (1) Presently used lines could be sterilized in new cytoplasms and held until a need for their use arises. Some breeders are doing that now. (2) Certain present hybrids could be produced in new cytoplasms. A very limited amount of seed is produced in this manner. (3) Hybrids could be produced with a blend of cytoplasms. (4) Entirely different hybrids with different cytoplasms could be produced. The potential to use new parents not usable in the milo-kafir system could be a strong impetus for adopting a new cytoplasm .The potential to increased nuclear diversity may be as important as cytoplasmic diversity per se.

Whether new cytoplasms are used and how they are used will be influenced by how well we fulfill our responsibilities. We must anticipate the needs and have answers to the important questions. As hybrid sorghum production increases, it will become increasingly critical that we have correct answers regarding cytoplasms.

References

APPATHURAI, R. 1964. Diverse plasmons in male sterile sorghum. Madras Agricultural Journal 51 :276-278.

CONDE, M. F., PRING, D. R., SCHERTZ, K. F., and Ross, W M. (In press). Correlation of mitochondrial DNA restriction endonuclease patterns with expression of fertility in KS cytoplasms of sorghum. Crop Science.

DIXON, L, and LEAVER, C. J. (personal communication). Department of Botany, University of Edinburgh, Edinburgh, Scotland, EH9 3JH.

HUSSAINI, S. H„ and RAO. P. V. 1964. A note on the spontaneous occurrence of cytoplasmic male sterility in Indian sorghums. Sorghum Newsletter 27 : 27-28.

MITAL, S. P., SWARUP, V., and JOSHI, A. B. 1958. Cytoplasmic male sterility in jowar *[Sorghum vulgare* Pers.). Current Science 27 : 314.

NAGUR, T. 1971. Studies on fertility restoration and combining ability in relation to genetic diversity and cytoplasmic constitution in sorghum. Ph.D. Thesis, Tamil Nadu Agricultural University, Coimbatore, India.

NAGUR, T., and MENON, P. M. 1974. Characterization of different male sterility-inducing cytoplasms in sorghum. Sorghum Newsletter 17:18.

PRING, D. R., CONDE, M. F„ and SCHERTZ, K. F. (In press). Organelle genome diversity in sorghum: male sterile cytoplasms. Crop Science.

PRING, D. R., and LEVINGS. C. S., III. 1978. Heterogeneity of maize cytoplasmic genomes among male-sterile cytoplasms. Genetics 89:121-136.

PRING, D. R„ LEVINGS, C. S., III. Hu, W. W. L, and TIMOTHY, D. H. 1972. Unique DNA associated with mitochondria in the "S"-type cytoplasm of male-sterile maize. Proceedings National Academy of Science, USA. 74:2904-2908

QUINBY, J. R. 1971. A triumph of research .... sorghum in Texas. Texas Agricultural Experiment Station Commemorative Publication.

QUINBY, J. R. 1980. Interaction of genes and cytoplasms in male sterility in sorghum. *In* Proceedings, 35th Corn and Sorghum Research Conference, American Seed Trade Association. Chicago, Illinois, USA.

QUINBY, J. R., KRAMER, N. W.. STEPHENS, J. C, LAHR, K. A., and KARPER, R. E. 1958. Grain sorghum production in Texas. Texas Agricultural Experiment Station Bulletin 912.

QUINBY, J. R., and SCHERTZ, K. F. 1970. Sorghum genetics, breeding and hybrid seed production. Pages 73-117 *in* Sorghum production and utilization, eds. S. S. Wall and W. M. Ross. Westport, Connecticut, USA: AVI Publishing Co.

RAO, M., and GOUDA, S. 1966. Occurrence of male sterile characters in Maldandi, M31-2. Sorghum Newsletter 9:43-44.

RAO, N. G. P. 1962 Occurrence of cytoplasmic-genetic male sterility in some Indian sorghums. Indian Journal of Genetics and Plant Breeding 22 :257-259.

RAO, N G. P. 1972. Sorghum breeding in India: recent developments. Pages 101-142 *in* Sorghum in seventies, eds. N G. P. Rao and L. R. House. New Delhi, India: Oxford & IBH Publishing Co. 638 pp.

RAO, N. G. P., HARINARAYANA, G., MURTY, U. R., TRIPATHI, D P., and KOTAIAH, K. B 1971. Self-incompatibility in grain sorghums. Indian Journal of Genetics and Plant Breeding 31 : 153-155.

ROSENOW, D. T., SCHERTZ, K. F., and SOTOMAYOR, A. 1980. Germplasm release of three pairs (A and B) of sorghum lines with A2 cytoplasmic-genetic sterility system. Texas Agricultural Experiment Station, MP-1448:1 -2

Ross, W. M. 1965. Cytoplasmic male sterility and fertility restoration relations of some major sorghum groups. Pages 57-62 *in* Proceedings, Grain Sorghum Research and Utilization Conference, Amarillo, Texas, USA.

Ross, W. M., and HACKEROTT, H. L. 1972. Registration of seven iso-cytoplasmic sorghum germplasm lines. Crop Science 12 : 720.

SCHERTZ, K. F. 1977. Registration of A2 Tx2753 and B Tx2753 sorghum germplasm. (Reg. No. GP 30 and 31.) Crop Science 17:983.

SCHERTZ, K. F., and RITCHEY, J. R. 1977. Cytoplasmicgenie male-sterility systems in sorghum. Crop Science 18:890-893.

SCHERTZ, K. F., ROSENOW, D. T., and SOTOMAYOR-RIOS, A. 1981. Registration of three pairs (A and B) of sorghum germplasm with A2 cytoplasmic-genic sterility system. Crop Science 21 :148.

STEPHENS, J. C, and HOLLAND. R. F. 1954. Cytoplasmic male-sterility for hybrid sorghum seed production. Agronomy Journal 46 : 20-23.

STEPHENS, J: C, MILLER, F. R., and ROSENOW, D. T. 1967. Conversion of alien sorghums to early combine genotypes. Crop Science 7 : 396.

TRIPATHI, D. P. 1979. Characterization of diverse cytoplasmic genetic male steriles in sorghum *[Sorghum bicolor (L.)* Moench!. Ph.D. Thesis, Indian Agricultural Research Institute, New Delhi. India.

TRIPATHI, D P., MEHTA, S. L, RANA, B. S., and Rao, N. G. P. 1980. Characterization of diverse cytoplasmic genetic male steriles in sorghum *[Sorghum bicolor* (L) Moench]. Sorghum Newsletter 23:107-108.

WEBSTER, O. J. 1980. Seed set under bags of A and B lines, 9E type cytoplasmic sterility Sorghum Newsletter 23:37-38.

WEBSTER, O. J., and SINGH, S. P. 1964. Breeding behavior and histological structure of a nondehiscent anther character in *Sorghum vulgare* Pers. Crop Science 4:656-658.

Interaction of Genes and Cytoplasms in Sex Expression in Sorghum

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Sorghum *(Sorghum bicolor* [L] Moench) is a species with perfect, or hermaphroditic, flowers but male sterility, partial male sterility, indehiscent anthers, antherlessness, pollen and stigma incompatibility, female sterility, and apomixis have been reported in the species.

I recognized all of these abnormalities, except female sterility, in segregating populations while searching for additional male-sterile inducing cytoplasms. Also, I came to realize that hormones might be involved in producing perfect flowers or floral abnormalities as well as in the control of plant growth and time of floral initiation. The following is a presentation of theories that evolved in an effort to explain the genetic and cytoplasmic inheritance of the abnormal sexual expressions observed, including apomixis. Also presented is the genetic and cytoplasmic identity of several strains and the sexual phenotypes of certain Fl hybrids.

A Review of the Literature

Heslop-Harrison (1957) has reviewed the literature and discussed chemical and hormonal effects on sexuality in plants. Thimann (1963) has reviewed the literature on the many influences of plant hormones on plant growth and has pointed out that auxin favors formation of pistillate flowers or femaleness, and gibberellin of staminate flowers or maleness. In contrast to Thimann's conclusion, Rood et al. (1980) have reported that, in *Zea mays* L, high gibberellin levels favor femaleness whereas low gibberellin levels favor maleness. However, Sladky (1969) has reported that a low level of auxin and a high level of gibberellin are present at the time of differentiation of the female sterile but male fertile maize tassel.

Oehlkers (1964) studied cytoplasmic inheritance in the genus *Streptocarpus,* a plant native to Africa. In one species, he recognized a weak genetic tendency toward maleness and a strong tendency toward femaleness. He assumed in that species, that has normal, hermaphroditic flowers, that, in the cytoplasm, there existed a strong male tendency and a weak female tendency. But, in a second species, the opposite situation existed. He also recognized a neutral cytoplasm in a third species that was neither female nor male promoting. One significance of these observations is that both nuclear and cytoplasmic genes affect maleness and femaleness.

Sex Expression Genes and Cytoplasms

The gene symbols assigned to floral abnormalities in sorghum have been compiled by Schertz and Stephens (1966). Sorghum is reported to be an allotetraploid (Endrizzi and Morgan 1955) and two genes might logically be expected to control any genetic character.

Maunder and Pickett (1959) recognized one nuclear gene and Erichsen and Ross (1963) and Appadurai and Ponnaiya (1967) recognized a second nuclear gene that interacts with cytoplasms to cause male sterility. The two genes have been assigned designations of ms_{c1} and ms_{C2} by Schertz and Stephens.

Casady et al. (1960) recognized two genes whose complementary action produced female sterility. Malm (1967) thought he recognized a third female inducing gene because of a linkage of female sterility with a height gene. But Malm's material included a dwarfing gene that was not

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru, A.P., India. Patancheru, A.P. India: ICRISAT.

present in Casady's material and it is possible that only two female inducing genes were involved in both studies. The genetic and cytoplasmic interactions that result in female sterility are not yet understood. Nevertheless, two female inducing genes appear to exist and, because cytoplasms are involved, it seems reasonable to assign Fs_{c1} and Fs_{c2} to the two female inducing genes.

A designation "A" was assigned to the cytoplasm in which Stephens and Holland (1954) male-sterilized the first cytoplasmic male sterile. This cytoplasm came from the Milo variety. The designation "A2" was given to the female inducing cytoplasm that was recognized by Schertz (1977) in the Ethiopian variety IS12662C. The designation "A3" was given to the female inducing cytoplasm in the Indian variety Nilwa, IS 1112C (Quinby 1980). The male inducing cytoplasm in Texas Blackhull Kafir was designated "B" by Stephens and Holland (1954).

The Theories Involved

Plant hormones are assumed to control sexual expression in plants. It is assumed that nuclear genes and genes carried in cytoplasmic inclusions control levels of the female and male hormones in the developing florets that cause perfect flowers, male sterility, female sterility, or other floral abnormalities. The assumption is that perfect flowers develop when female and male hormone levels are in balance, but that abnormalities develop when female and male hormones are out of balance. In other words, it appears that any sexual genotype will have perfect flowers in one cytoplasm but will be male sterile or be otherwise abnormal in all other cytoplasms.

As mentioned previously, two female inducing genes are thought to exist in sorghum and two male inducing genes have been recognized. These things being true, there should be two genes controlling male hormone levels and two controlling female hormone levels. And if a perfect balance between the male and female hormones is needed to produce perfect flowers, there should be two female promoting cytoplasms and two male promoting cytoplasms. In addition, if four genes are involved in sex expression, there must be six genotypes that are genetically in perfect balance. It follows then that there must be a neutral cytoplasm that promotes neither femaleness nor maleness. The two female inducing cytoplasms, the neutral cytoplasm, and one male inducing cytoplasm have been recognized. Work is under way to identify the second male inducing, or fifth, cytoplasm that should exist.

As shown in Table 1, it is assumed that "A" cytoplasm is neutral and contributes to neither female nor male hormone levels. Because genotypes 1, 8, 9, 10, 11, and 16 are in perfect genetic balance, they should have perfect flowers in "A" cytoplasm. It is assumed that "A2" cytoplasm furnishes an amount of the female hormone great enough to compensate for the presence of one recessive female inducing nuclear gene. For that reason, it is assumed that genotypes 4, 5, 14 and 15 have perfect flowers in "A2" cytoplasm. It is assumed that "A3" cytoplasm furnishes an amount of the female hormone great enough to compensate for the presence of two recessive female inducing nuclear genes. Only genotype 7 would be expected to have perfect flowers in "A3" cytoplasm.

It is assumed that "B" cytoplasm furnishes an amount of the male hormone great enough to compensate for the presence of one recessive male inducing nuclear gene and, for that reason, genotypes 2, 3, 12, and 13 should have perfect flowers in "B" cytoplasm.

The second male inducing cytoplasm has not yet been identified, but genotype 6 would be expected to have perfect flowers in that cytoplasm.

The hormones involved in maleness and femaleness have not yet been identified in sorghum and it is not yet known which plant hormone is being controlled by the Fs_c genes and which by the Ms_c genes. However, it seems logical to assume that the Fs_c genes control auxin levels and that the Ms_c genes control gibberellin levels.

Materials and Methods

The search for additional male sterile inducing (female inducing) cytoplasms began with the crossing of strains that were the first 63 tropical conversions released by the Texas Agricultural Experiment Station. F1 plant and F2 populations were grown and observed. A little later, a few other strains and a few additional tropical conversions from India were added to the study. A four-dwarf kafir, CKP, was male-sterilized in cyto-

Table 1. Phenotypea that result from combinations of genotypes and cytoplasms and the identity of several strains.

Genotype	Phenotype* of genotypes and strains in cytoplasms			
	A3($2Fh_c$)*	A2($1Fh_c$)*	A(0)*	B($1Ms_c$)*
1 Fs_{C1} Fs_2 $Ms_{c1}Ms_{c2}$	FF ms	FF MF (near perfect)	perfect IS 1122C	
2 $Fs_{c1}Fs_{c2}Ms_{C1}$ ms_{C2}	FF ms CKP(A3)	FF ms CKP(A2)	FF ms CKP(A), BK(A)	perfect CKP, BK
3 $Fs_{c1}Fs_{c2}s_{c1}Ms_{C2}$	FF ms	FF ms	FF ms	perfect IS 12683_c
4 Fs_{Cl} $fs_{C2}Ms_{c1}Ms_{C2}$	FF ms	perfect IS 2816C		
5 $fs_{c1}Fs_{C2}Ms_{Cl}Ms_{C2}$				
6 Fs_{c1} $Fs_{C2}ms_{c1}ms_{C2}$	FF ms	FF ms	FF ms	FF ms BK ms_2
7 $fs_{c1}fs_{C2}Ms_{C1}Ms_{c2}$	perfect IS 1112C		FF MF R473	
8 Fs_{Cl} fs_{C2} ms_{Cl} Ms_{C2}	FF ms SM100(A3) IS84(A3)	FF ms	perfect SM100 IS84 Day	
9 $fs_{c1}Fs_{c2}ms_{c1}Ms_{C2}$				
10 $Fs_{c1}fs_{C2}Ms_{C1}ms_{C2}$	FF ms IS 1151C(A3)	FF ms	perfect IS 1598C IS 1151C	
11 fs_{Cl} $Fs_{C2}Ms_{Cl}$ ms_{c2}				
12 $Fs_{Cl}fs_{C2}ms_{C1}$ ms_{C2}	FF ms	FF ms	FF ms Day ms	perfect
13 $fs_{c1}Fs_{C2}ms_{Cl}ms_{C2}$				
14 $fs_{c1}fs_{C2}Ms_{Cl}ms_{C2}$	FF ms IS 1056C(A3)	perfect IS 1056C		
15 $fs_{c1}fs_{c2}ms_{c1}Ms_{c2}$	FF ms	perfect IS 12662C		
16 $fe_{c1}s_{C2}ms_{Cl}ms_{C2}$			perfect NM13	

* Genetic equivalent.
a. FF = female fertile, fs = female sterile, MF = male fertile, ms = male sterile.

plasms from several sources and "A2" and "A3" cytoplasms were then recognized. The tropical conversions and a number of other strains were then crossed to the CKP(A), CKP(A2), and CKP(A3) females and the F1s observed. If the phenotype of a combination of genotypes and cytoplasm is unknown, those spaces are left blank in Table 1.

In the tables and in the discussions that follow, genotypes are identified by single gene symbols per locus. The International Sorghum (IS) numbers can be found in the publications of Johnson et al. (1971). Scheuring and Miller (1978), and (Murty et al. 1967).

The Genetic and Cytoplasmic Identity of Certain Strains

Studying the genetics of sexuality in sorghum is made more difficult by the fact that many F1 plants are either male or female sterile and F2 populations cannot be grown. In addition, height and duration of growth are undoubtedly controlled by hormone levels and it is apparent that the sexual phenotypes of F1 plants are different if the plants are 2-dwarf rather then 3-dwarf. It is also apparent that the percentage of male-sterile plants in segregating populations is influenced by heterozygosity for height and maturity.

In view of the difficulties encountered in studying the genetics of sexuality, I am presenting the identity of certain strains and their phenotypes in other cytoplasms without presenting data from segregating populations (Table 1). The identifications were made based largely on the cytoplasms of the strains and in which cytoplasms they could apparently be male sterilized. However, in 1981 I did obtain some good genetic information from F2 populations in "A" and "A2" cytoplasms.

Crosses were made using CKP(A), CKP(A2). and CKP(A3) as female parents and the male parents and the phenotypes of their F1 hybrids are shown in Table 2. The phenotypes of the Fls were useful in identifying the strains and their phenotypes in other cytoplasms.

The Identity of Strains in "B" Cytoplasm

CKP is known to be in "B", or Kafir, cytoplasm and has been male sterilized in "A", "A2", and "A3" cytoplasms. CKP, like Combine Kafir 60, is recessive at one ms_c locus, is combination 2B, and can be male sterilized in "A" cytoplasm for that reason.

The variety IS 12683C is apparently combination 3B. The CKP(A) x IS 12683C F1 hybrid is male fertile (Table 2.) Nevertheless, IS 12683C can be male sterilized in "A" cytoplasm because it is recessive at one ms_c locus.

Texas Blackhull Kafir (BK) is combination 2B and mutated to *ms,* (Stephens 1937). Genetic ms_2 is

Table 2. Tha Sexual phanotypas of F1 hybrids in thraa cytoplasm*.

Male Parent		Sexual phenotype* of F1 when female parent is		
Strain	Identity (combination)	CKPIA3)	CKP(A2)	CKP(A)
CKP	2B	FF ms	FF ms	FF ms
IS 12683C	3B	FF ms	FF ms	FF MF
Tex. Bh. Kafir ms_2	6B	FF ms	FF ms	FF ms
IS 1122 C	1A	FF ms	FF MF	FF MF
SM100	8A or 9A	FF ms	FF ms	FF MF
IS 84 or Tx 7529	8A or 9A	FF ms	FF ms	FF MF
IS 1151C	10A or 11A	FF ms	FF ms	FF ms
IS 1598C	10A or 11A	FF ms	FF ms	FF ms
IS 2816C	4A2 or 5A2	Ff ms	FF MF	FF MF
IS 1056C	14A2	FF ms	FF ms	FF ms
IS 12662C	15A2	FF ms	FF MF	FF MF
IS 1112C	7A3	FF MF	FF ms	FF ms
R473	7A	FF ms	FF MF	FF MF
NM13	16A	fs ms	fs ms	fs MF

* FF = female fertile, fs = female sterile, MF = male fertile, ms = male sterile.

combination 6B and is recessive at both ms_c gene loci. BK ms_2 is maintained in the heterozygous condition. BK ms_2 is female fertile and male sterile in "A", "A2", and "A3" cytoplasms as well as in "B" cytoplasm (Table 2).

Perfect flowered strains of combinations 12B and 13B have not been identified. Such strains crossed to BK ms_2 should produce male sterile F1 plants, but no such plants have been observed.

The Identity of Strains in "A" Cytoplasm

The variety IS 1122C is converted Karad Local from India and is apparently combination 1A because 25% of the plants of the F2 population of CKP(A) x IS 1122C and CKP(A2) x IS 1122C are male sterile. These populations were apparently segregating only at the ms_{C2} locus. F1 of CKP(A2) x IS 1122C is male fertile and of CKP(A3) x IS 1122C is male sterile (Table 2).

One of the Milo maturity genotypes, SM100, and IS84 (the male parent of CSH-1), have been male sterilized in "A3" cytoplasm. Both strains can probably be male sterilized in "A2" cytoplasm because their F1s with the CKP(A2) male-sterile are male-sterile (Table 2). These two strains are either combination 8A or 9A.

Even though combinations 10A and 11A produce male sterile F1 plants when crossed to CKP(A1), they should not male sterilize in that cytoplasm. An effort was made to male sterilize IS 1598C in "A" cytoplasm. But, as male sterilization proceeded, the male sterility disappeared. It is likely that IS 1151C and IS 1598C are either combination 10A or 11 A.

The origin of the Day male sterile was recounted by Stephens et al. (1952). The Day cultivar is known to be in "A" cytoplasm and, like Dwarf Yellow Milo, is thought to be either combination 8A or 9A. The Day male sterile is either combination 12A or 13A.

The strain New Mexico 13 crossed to CKP(A) is female sterile but male fertile (Table 2). NM13 crossed to CKP(A2) and CKP(A3) results in plants that are both female sterile and male sterile. NM13 is thought to be combination 16A.

The Identity of Strains in "A2" Cytoplasm

A converted line from Zimbabwe, IS 281C, is known to be in "A2" cytoplasm (Quinby 1980) and restores male fertility to CKP(A2) hybrids (Table 2). For these reasons, IS 2816C is thought to be combination 4A2 or 5A2.

A line from India, IS 1056C produces male-sterile F1s when crossed to CKP(A) (Table 2). It is known to be in "A2" cytoplasm and has been male sterilized in "A3" cytoplasm. For these reasons, it is assumed to be combination 14A2.

A strain from Ethiopia, IS 12662C, furnished the cytoplasm that Schertz (1977) designated "A2". IS 12662C is apparently combination 15A2 (Table 2).

A Perfect Flowered Strain in "A3" cytoplasm

IS 1112C, or converted Nilwa, is the strain that furnished the A3 cytoplasm. Because it has perfect flowers, it is assumed to be combination 7A3. CKP(A3)x IS 1112C F1 hybrids are male-fertile or near male-fertile. Surprisingly, CKP(A) x IS 1112C F1 plants are male-sterile (Table 2) and the interactions that bring this about are not understood.

Maldandi 35-1 and its male sterile counterpart were sent to Texas by Dr. N. G P. Rao and was one of the pairs worked with by Tripathi (1979). The male sterile inducing cytoplasm in the M35-1 male sterile has been called the Maldandi source and appears to be similar to the "A3" cytoplasm from Nilwa.

Restoration of Male Fertility to Hybrids

Information presented in Table 2 shows the genetic and cytoplasmic identity of certain strains that restore male fertility to hybrids made using female parents in three cytoplasms. All CKP females are genotype Fs_{c1} Fs_{C2} Ms_{C1} ms_{C2} The genotype CKP(A) is in neutral cytoplasm. CKP(A2) is a super-female because of the contribution of the female component from "A2" cytoplasm. CKP(A3) is an ultra-female because of a still greater contribution of the female component from "A3" cytoplasm.

Numerous strains restore male fertility to CKP(A) hybrids and those strains need only to be dominant at the Ms_{C2} locus. Apparently, because the CKP(A2) female is a super-female, strains that restore fertility to CKP(A2) hybrids must be dominant at both Ms_{C2} and Ms_{C2} loci. Only IS

1112C (Nilwa) is shown to restore male fertility to CKP(A3) hybrids (Table 2) and CKP (A3) x IS 1112C hybrids are not completely male fertile. CKP(A3) is an ultra-female and IS 1112C, that is genetically fe_{c1} fe_{c2} Ms_{c1} Ms_{c2}, apparently reduces femaleness in the F1 enough for it to be a near-perfect male fertile.

Apomixis

R473 is a facultative apomict recognized by Rao and Narayana (1968) and worked with by Murty and Rao (1972); Murty. et al. (1979; 1981). R473 is in Aispuri (IS 1151) or "A" cytoplasm and its male parent is IS2942. An F2 population of IS 1112C x R473 at Plainview in 1981 contained no male-sterile plants. For that reason, it is reasonable to assume that R473 is genotype 7 {fs_{C1} fs_{C2} Ms_{C1} Ms_{C2}) in "A" cytoplasm. It appears, from this information, that apomixis must result from a low level of the female hormone in comparison with a higher level of the male hormone.

R473 is considered to be a facultative apomict because hybrids can be produced using it as a female parent. Perhaps the R473 genotype in "B" cytoplasm might be an obligate apomict. CKP(B) has been crossed by R473 to see if apomicts can be found in the progeny. If and when "B2" cytoplasm is identified, obligate apomicts should be searched for in that cytoplasm.

Incompatibility

Most male-steriles in "A3" cytoplasm have large anthers that do not dehisce. However, male-steriles in "A3" cytoplasm have occasionally been seen to shed pollen in Texas as they have been reported to do in India. However, the male-sterile plants do not set seed and incompatibility of stigmas and pollen has been thought to be the cause (Rao et al 1971).

Female Sterility

As mentioned previously, the identity of the strain New Mexico 13 is thought to be combination 16A (Tables 1 and 2). NM13 also produces female sterile, but male fertile, plants when crossed to CKP(B) NM13 has perfect flowers in "A" or neutral cytoplasm because it is recessive at all four sexual gene loci. But the interactions of the levels of female and male hormones are not yet understood because female steriles appear in all four presently known cytoplasms.

Summary

Plant hormones are assumed to be involved in controlling sexual expression in sorghum, and there is interaction between nuclear genes and genes carried by cytoplasmic inclusions. There appear to be two female inducing and two male inducing nuclear genes. Theoretically, there should be two female inducing, two male inducing, and one neutral cytoplasm. One male inducing cytoplasm has not yet been recognized but is being sought. The other four cytoplasms have been found and identified.

The assumption is that perfect flowers develop when female and male hormones are in perfect balance but that floral abnormalities develop when female and male hormones are out of balance. Any sexual genotype will have perfect flowers in one cytoplasm but will be male-sterile or otherwise abnormal in the other cytoplasms. Many of the genotypes expected to exist in four cytoplasms have been recognized and the basis of their identifications is presented. The genotypes that restore male fertiliity to hybrids in three cytoplasms are also presented.

References

APPADURAI, R., and PONNAIYA. B. W. X. 1967. Inheritance of fertility restoration in *Sorghum bicolor* (L) Moench. Madras Agricultural Journal 54:393-404.

CASADY, A. J., HEYNE, E. G., and WEIBEL, D. E. 1960. Inheritance of female sterility in sorghum. Journal of Heredity 51 :35-38.

ENDRIZZI, J. E., and MORGAN, D. T. 1955. Chromosome interchanges and evidence of duplication in haploid *Sorghum vulgare.* Journal of Heredity 46:201-208.

ERICHSEN, A. W., and Ross, J. G. 1963. Inheritance of colchicine-induced male-sterility in sorghum. Crop Science 3:335-338.

HESLOP-HARRISON, J. 1957. The experimental modification of sex expression in flowering plants. Biological Review. Cambridge Philosophical Society 32 : 38-90.

JOHNSON, J. W., ROSENOW, D T.. MILLER. F. R., and SCHERTZ, K. F. 1971. Sorghum breeding and improvement. P. R. 2942. *In* Grain sorghum research, consolidated P. R. 2938-2949, College Station. Texas, USA: Texas Agricultural Experiment Station.

MALM, N. R. 1967. Female-sterility in grain sorghum involving linked genes Crop Science 7: 548.

MAUNDER, A. B., and PICKETT. R C 1959 The genetic inheritance of cytoplasmic genetic male-sterility in grain sorghum. Agronomy Journal 51 :47-49

MURTY, B. R.. ARUNACHALAM, V, and SAXENA, M B. L. 1967. Classification and catalogue of world collection of Sorghum Indian Journal of Genetics and Plant Breeding Special Number 27 :1-394

MURTY, U R , and RAO. N G P. 1972 Apomixis in breeding grain sorghum *In* Sorghum in seventies, eds N G P Rao and L R. House New Delhi. India: Oxford and IBH Publishing Co 638pp

MURTY, U. R., RAO. N. G. P.. KIRTI, P. B., and BHARATHI. M. 1981. Apomixis and sorghum improvement Report of the Research Project, "Applicability of apomixis in grain sorghum breeding" Indian Agricultural Research Institute Regional Station, Hyderabad 500 030. A. P., India.

MURTY, U. R., SCHERTZ, K. F., and BASHAW, E. C. 1979. Apomictic and sexual reproduction in sorghum Indian Journal of Genetics and Plant Breeding 39: 271 -278.

OEHLKERS, F 1964 Cytoplasmic inheritance in genus *Streplocarpus* Lindley *In* Advances in genetics, eds Caspari and Thoday New York, USA: Academic Press.

QUINBY, J. R. 1980. Interaction of genes and cytoplasms in male sterility in sorghum. *In* Proceedings of the 35th Annual Corn and Sorghum Research Conference, Washington, DC. USA.

RAO, N. G. P., and NARAYANA, L. L. 1968. Apomixis in sorghums. Indian Journal of Genetics and Plant Breeding 28:121-127.

RAO, N. G. P., HARINARAYANA, G., MURTY, U. R.. TRIPATHI, D. P., and KOTAIAH, B. K. 1971. Self-incompatibility in grain sorghums. Indian Journal of Genetics and Plant Breeding 31 :153-155.

ROOD. S. B„ PHARIS, R. P., and MAJOR, D. J. 1980. Changes of endogenous gibberellin-like substances with sex-reversal of the apical inflorescence of corn. Plant Physiology 66:793-796.

SLADKY, Z. 1969. Role of growth regulators in differentiation processes of maize *(Zea mays* L.) organs. Biological Plantarum (Praha) 11 : 208-215.

SCHERTZ, K. F. 1977. Registration of A2 Tx2753 and B Tx2753 sorghum germplasm. Crop Science 17:983.

SCHERTZ, K. F„ and STEPHENS, J. C. 1966. Compilation of symbols, recommended revisions and summary of linkages for inherited characters of *Sorghum vulgare* Pers. Tech. Monograph 3. Texas Agricultural Experient Station. 42 pp.

SECURING, J F. and MILLER. F R 1978 Fertility restorers and sterility maintamers to the Milo-Kafir genetic cytoplasmic male sterility system in the world sorghum collection MP 1367 Texas Agricultural Experiment Station, College Station, Texas 77843, USA

STEPHENS, J C 1937 Male sterility in sorghum: its possible utilization in production of hybrid seed. Journal of the American Society of Agronomy 29 : 690-696.

STEPHENS, J. C, and HOLLAND, R. F. 1954. Cytoplasmic male-sterility for hybrid seed production. Agronomy Journal 46:20-23.

STEPHENS, J. C, KUYKENDALL, G. H.. and GEORGE, D. W. 1952 Experimental production of hybrid sorghum seed with a three-way cross. Agronomy Journal 44:369 -373

THIMANN, K. V. 1963. Plant growth substances: past, present, and future. Annual Review of Plant Physiology 14: 1-18.

TRIPATHI, D. P. 1979. Characterization of diverse cytoplasmic genetic male steriles in sorghum. Ph.D. Thesis. Division of Genetics, Indian Agricultural Research Institute, New Delhi, India.

Genetic and Environmental Response Characteristics of Sorghum

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Sorghum *bicolor* (L.) Moench is grown from sea level to elevations in excess of 3000 m in high rainfall areas and in semi-arid regions, and in different seasons of the year. Because of this wide range of adaptation there are naturally selected cultivars which resist an array of pests and diseases and possess high yielding capabilities. Sorghum grain was and continues to be a major food cereal across regions where other cereals are not so well adapted. Our responsibility is to develop even more stable and higher yielding cultivars from this wealth of diversity by making the appropriate collections from dissimilar climates and recombining into more widely adapted improved types useful to the world's people.

A plant breeder must know the climatic realm of the areas in which he is testing and the climatic range of adaptation of his improved or new materials. He also needs an appreciation of the original environment of the species he is working to improve. A system of climatic classification has many merits. This discussion will consist of comparisons between climates and the response of plants in their environment and how a crop breeder can take advantage of similarities or dissimilarities. Sorghum as a life form has evolved and is favored by certain types of climatic conditions. Its capability for survival and multiplication are limited and exist where the environment is most favorable for its growth.

As a species, sorghum has permeated those climatic regions of easy adaptation or transplantation. From Ethiopia it has moved or has been moved to the USA, Argentina, Venezuela, Central America, Australia, and into India and several unique areas of Africa. This area of adaptation of sorghum parallels the "Tropical Grassland" and "Grassland with Trees" (Fig. 1). These areas exist in abundance between the Tropics of Capricorn and Cancer; i.e., between 23'/2° N and S Latitudes. Specifically, there are major areas in Central and South Africa, India, Australia, South America, Central America and into South Texas where sorghum production abounds. Most of the crop's improvement has dealt with adaptation and yield characteristics in this median environment where the crop was easily adapted.

Perhaps the most important point with sorghum and other cereals is the need to adapt these critical food supplying crops to adjacent climatic areas, to which they are not easily transplantable, in order that potential areas of production are exploited. One example is to look at the "Temperate Grasslands," or "Extra-tropical Grasslands," which border the aforementioned (Fig. 2). The major differences here are patterns of rainfall, daylength, and temperature. There are vast areas in Southern Russia, northern China, South America, and smaller areas in South Africa and Australia where potential for expansion exists. In the United States we have moved sorghum far north into the "Temperate Grasslands." By utilization of existing germplasm, we could move the crop into many presently submarginal areas.

The main variation of both wild and cultivated sorghums is in the northeast quadrant of Africa, and all the evidence points to that area as the center of origin. Doggett (1970) and others have concluded that the great diversity in *S. bicolor* was created through disruptive selection and by isolation and recombination in the extreme varied ecological habitats of northeast Africa and the movement of peoples carrying the species through that continent. Sorghum has been taxonomically classified into some 70 groups (Murty et al. 1967). The present world collection embodies more than 17 500 items.

Sorghum varieties respond differently to varying photoperiods and temperature regimes.

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International Crops Research Institute lor the Semi-Arid Tropics 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum. 2-7 Nov 81, Patancheru, A.P., India Patancheru, A.P India: ICRISAT.

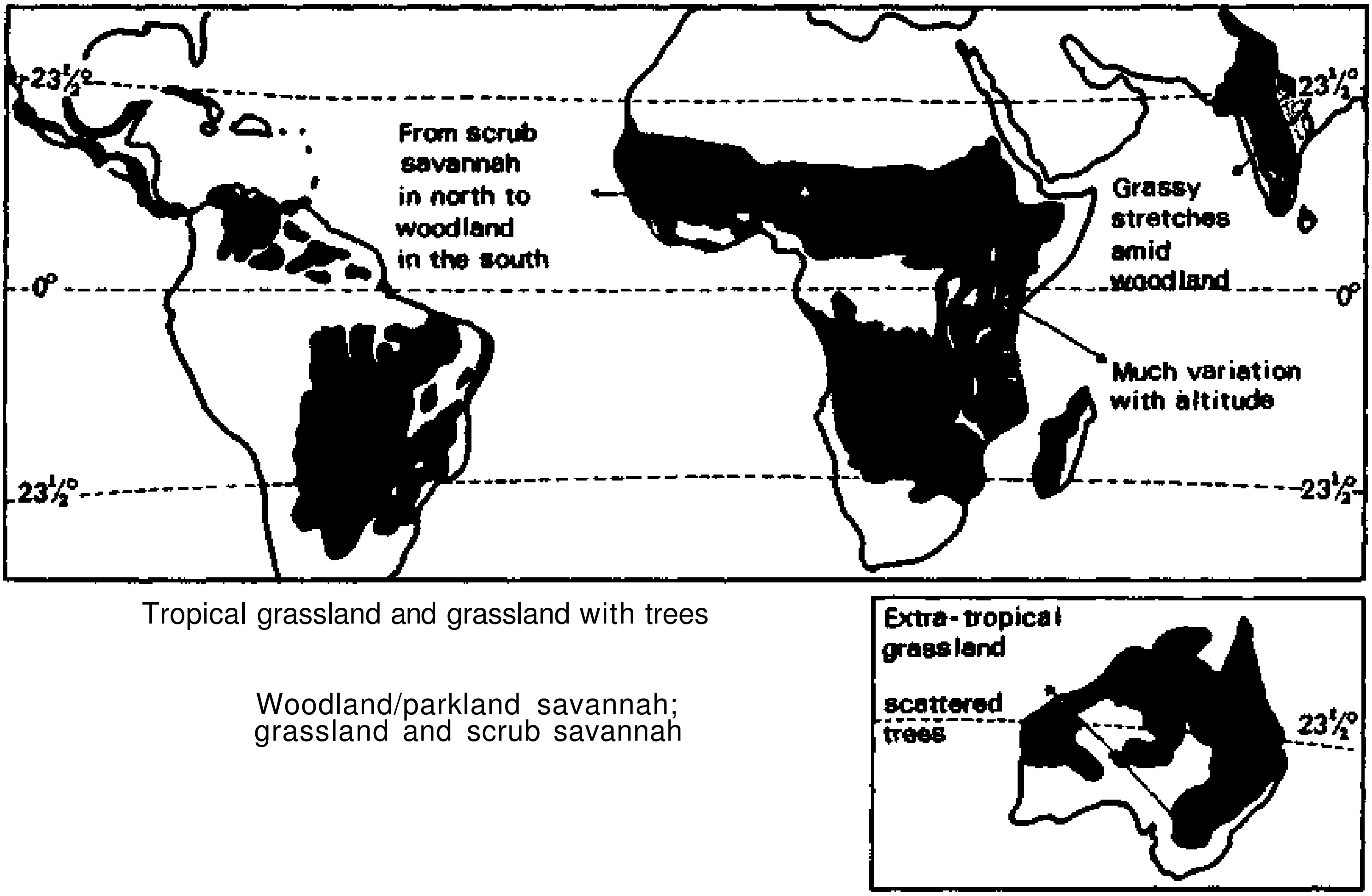

Figure 1. Tropical grassland and grassland with trees—typical production areas of major sorghum production. (Climatic classifications are based on similarities in temperature, rainfall, and natural vegetation.)

The species is classified as a short-day type. Looking back at the area of origin which is just north of the equator, we are confronted with the evolutionary question of 'how did it develop? Miller et al. (1968) established that sorghum has a critical photoperiod of 12 hr. However, they were able to classify some cultivars into groups that had higher critical photoperiods; even a class which does not respond or is photoperiod insensitive. They identified varieties with different photoperiod requirements and established that the response to differences in daylength may be as little as several minutes. If we look at selected areas in Africa where sorghum predominates and their daylength and rainfall patterns, we see that during the longest days when the photoperiod is above 12 hr in length, rainfall is in excess of 100 mm per month (Fig. 3). As the sun moves northward the area receiving an excess of 100 mm rainfall also moves. THE RAINS ARE FOLLOWING THE SUN I When daylengths become short (12 hr). the sorghum plant differentiates from vegetative to reproductive growth and the rains diminish. The crop then is free to mature in the dry season that follows. As daylengths increase again the rains start, planting takes place and the crop grows vegetatively during the long photoperiods that follow when rains of 100 mm per month are likely. The sequence allows for the survival of the greatest number of individuals to propagate the species.

Quinby et al. (1973) have shown that duration of growth and floral initiation, which is controlled by four loci, is greatly affected by photoperiod and temperature and their interaction. Quinby (1974) attributed the variation of maturity in sorghum to both dominant and recessive alleles at the four maturity loci (Table 1). Most tropical varieties are dominant at all four loci and a recessive at *Ma,*will cause them to be much less photoperiod sensitive and apparently less responsive to temperature variations. The identification and use of these genes allows the adaptation of specific types to regions where similar conditions exist. Because we know the response of these types and their genetics, we are able to predict ranges of adapta-

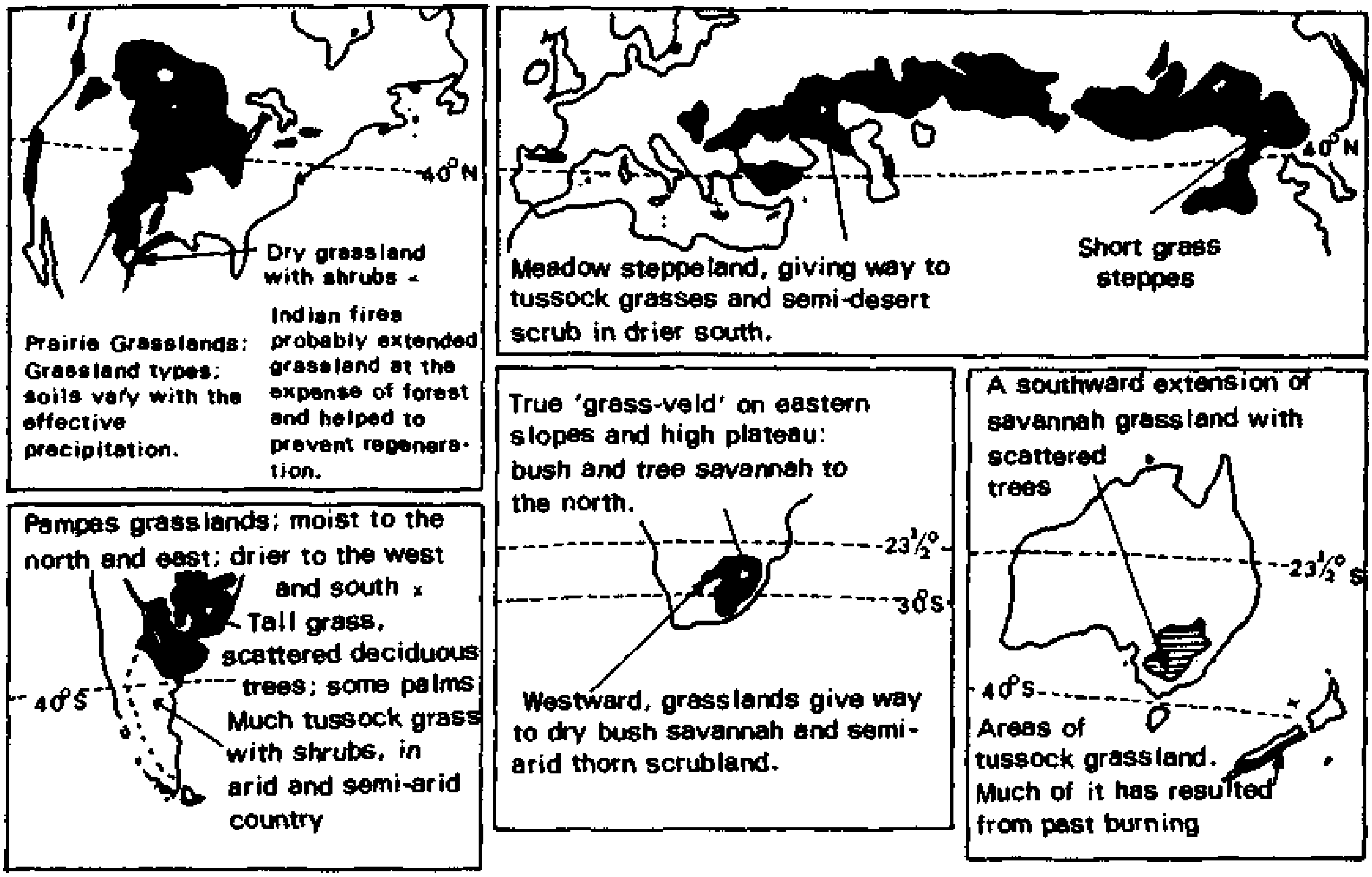

Figure 2. Extra-tropical grasslands—areas where major sorghum expansion could easily be made using selection pressure for adaptation at the extremities of the present biological range.

tion with reasonable certainty.

In most areas of the world taller plants are preferred, but in those areas where mechanical harvesting is practiced, shorter stature is required. Quinby and Karper (1954) have shown height to be controlled by four recessive, nonlinked, brachytic dwarfing genes. A single recessive gene may reduce height by 50 cm or more (Table 2). Most breeders recognize the positive correlation between height and yield and develop sorghums which are as tall as possible to withstand the hazards of production. Maximum productivity is generally obtained at about 1.5 to 1.75 m height.

Utilization of these two gene systems that so strongly affect adaptation has given birth to one of the truly classical plant breeding/climate utilization accomplishments of crop improvement—the Sorghum Conversion Program (Stephens et al. 1967).

The cornerstone to much of the present crop improvement in sorghum is the Sorghum Conversion Project. This Joint Texas Agricultural Experiment Station (TAES)-USDA project changes tall, late or nonflowering sorghums from the tropics into short, early forms which can be used in all areas of the world, but especially in the temperate zones. This is done by substituting up to eight genes which control height and maturity to obtain the desired genotypes. The procedure is outlined in Figure 4.

Because sorghum originated near the equator in northeastern Africa, it is sensitive to the length of day. Knowing the genetics of height and maturity and the response to daylength, it was possible to use the facilities of the USDA's tropical research station at Mayaguez. Puerto Rico and a temperate selection site at Chillicothe. Texas, to make vast amounts of germplasm available for further plant improvement. Selections were made from the World Collection which were judged to offer the greatest diversity and eliteness. Because of limited manpower and resources, it was possible to convert only those with outstanding characteristics. At present, there are 1279 items in the program. The original cross and four backcrosses with selection in each generation have allowed the recovery of over 98% of the germplasm in each entry. During the last backcross which is done by hand emasculation, the cross is made using the alien line as the

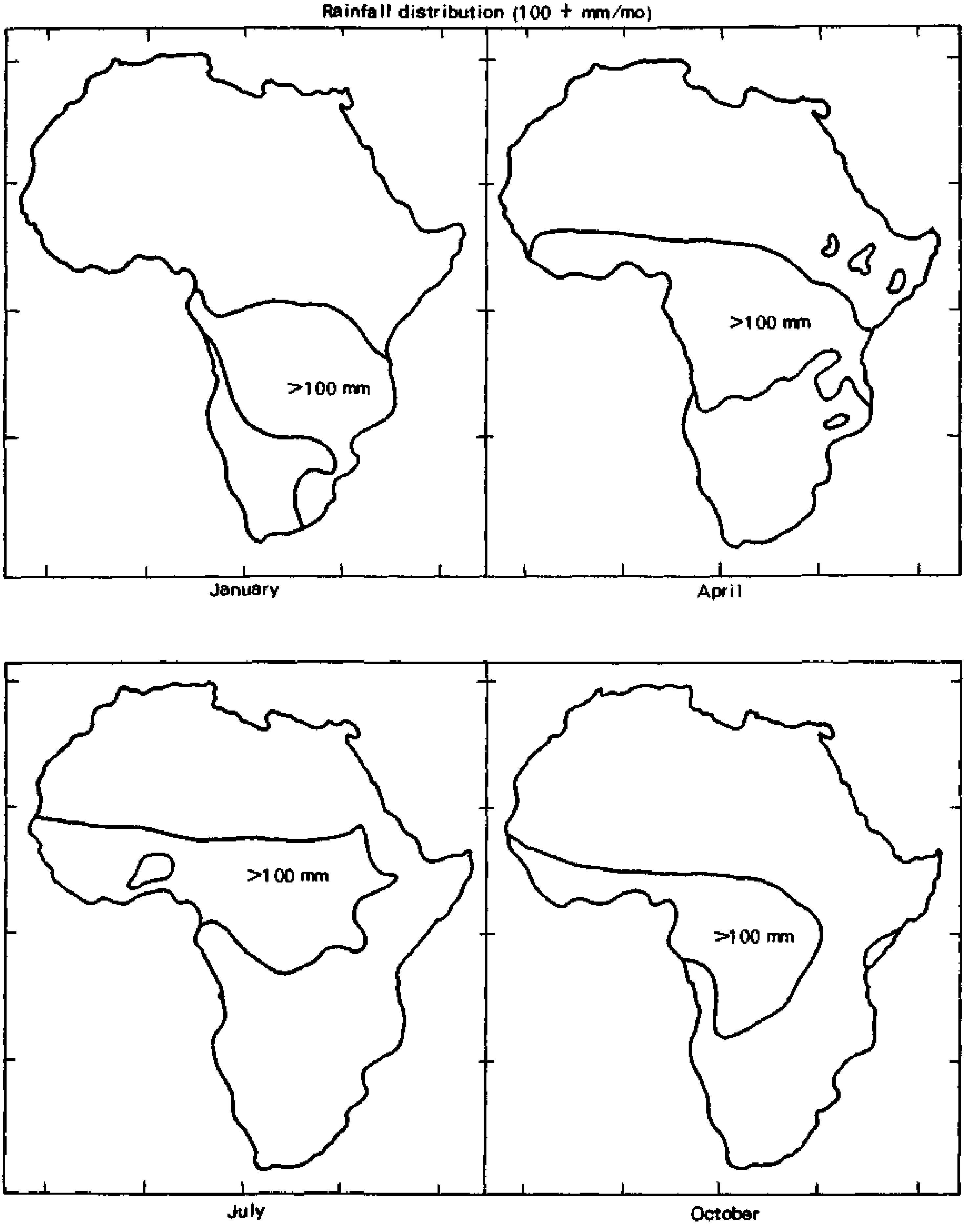

Figure 3. Rainfall distribution (100 mm+/mo) across Africa through the year, showing that the rains follow the sun. Sorghum has evolved a photoperiod-controlled reproductive system to insure survival under the monsoon rainfall pattern.

Table 1. Floral characteristics of eight maturity genotypes in *Sorghum bicolor* from a June planting at Plainvlew, Texas.

Designation	Genotype	Days to floral initiation	Days of panicle development	Days to anthesis	Panicle weight
100M	$Ma_1Ma_2Ma_3Ma_4$	61	30	90.5 ± 0.6	28.2 ± 0.6
90M	$Ma_1Ma_2ma_3Ma_4$	61	26	87.0 ± 0.6	40.3 ± 1.1
80M	$Ma_1ma_2Ma_3Ma_4$	40	29	69.0 + 0.2	30.8 ± 0.9
60M	$Ma_1ma_2ma_3Ma_4$	36	28	64.6 ± 0.4	34.3 ± 1.7
SM100	$ma_1Ma_2Ma_3Ma_4$	34	18	52.4±0.3	20.0+ 1.5
SM90	$ma_1Ma_2ma_3Ma_4$	34	20	54.2 ± 0.3	20.3 ± 0.6
SM80	$ma_1ma_2Ma_3Ma_4$	34	23	56.7 ± 0.4	19.3 ± 0.6
SM60	$ma_1ma_2ma_3Ma_4$	34	21	55.3 ± 0.2	23.2 ± 0.7

(From Quinby 1972)

Table 2. Height and days to anthesis for several genotypes of *Sorghum tricolor.*

Designation	Genotype	Days to anthesis	Height to flag leaf cm
	$Dw_1Dw_2Dw_3Dw_4$		
SA1170	$Dw_1Dw_2Dw_3Dw_4$	62	127
Dwf White Sooner Milo		61	94
D.Dwf White Sooner Milo	$dw_1dw_2Dw_3dw_4$	66	53
SA403	$Dw_1Dw_2dw_3dw_4$	65	43

(From Quinby 1974)

female. This allows the recovery of the cytoplasm of the converted line also.

Materials from this program are dramatically changing the sorghum industry. Some of the important economic characteristics obtained from this project are: (a) new sources of disease resistance—downy mildew, head smut, maize dwarf mosiac virus, foliar diseases, stalk rots, kernel rots and anthracnose; (b) insect resistance—sorghum midge, greenbug, corn leaf aphid, white flies, and Band's grassmites; (c) improved plant characteristics—drought, heat and salinity tolerance, stalk strength, twin-seed, easy threshing, erect leaves, lodging resistance, improved yield of grain, yield stability under diverse environments, greater root development, leaf area retention, increased grain filling rates, increased combining ability and new sources of cytoplasmic sterility; (d) outstanding kernel characteristics—thin pericarps, weathering resistance, reduced discoloration of the endosperm, increased protein content, superior balance of amino acids, improved flavor, expanded diversity for food product development and greater digestibility; (e) reduced genetic vulnerability—expanded diversity to widen the germplasm base.

As new sources of useful germplasm with unique properties are identified anywhere in the world, the material is entered into the program. By the same token, much of the material which is changing the complexion of hybrid sorghum in the USA is from the Conversion Program. Few research programs which are making significant contributions do not use materials released from this program. Because those items in the conversion program came from Africa and India, there are indications that materials being returned to these areas are useful in breeding projects there also. Perhaps the most use is made of elite lines that have part of their parentage from converted

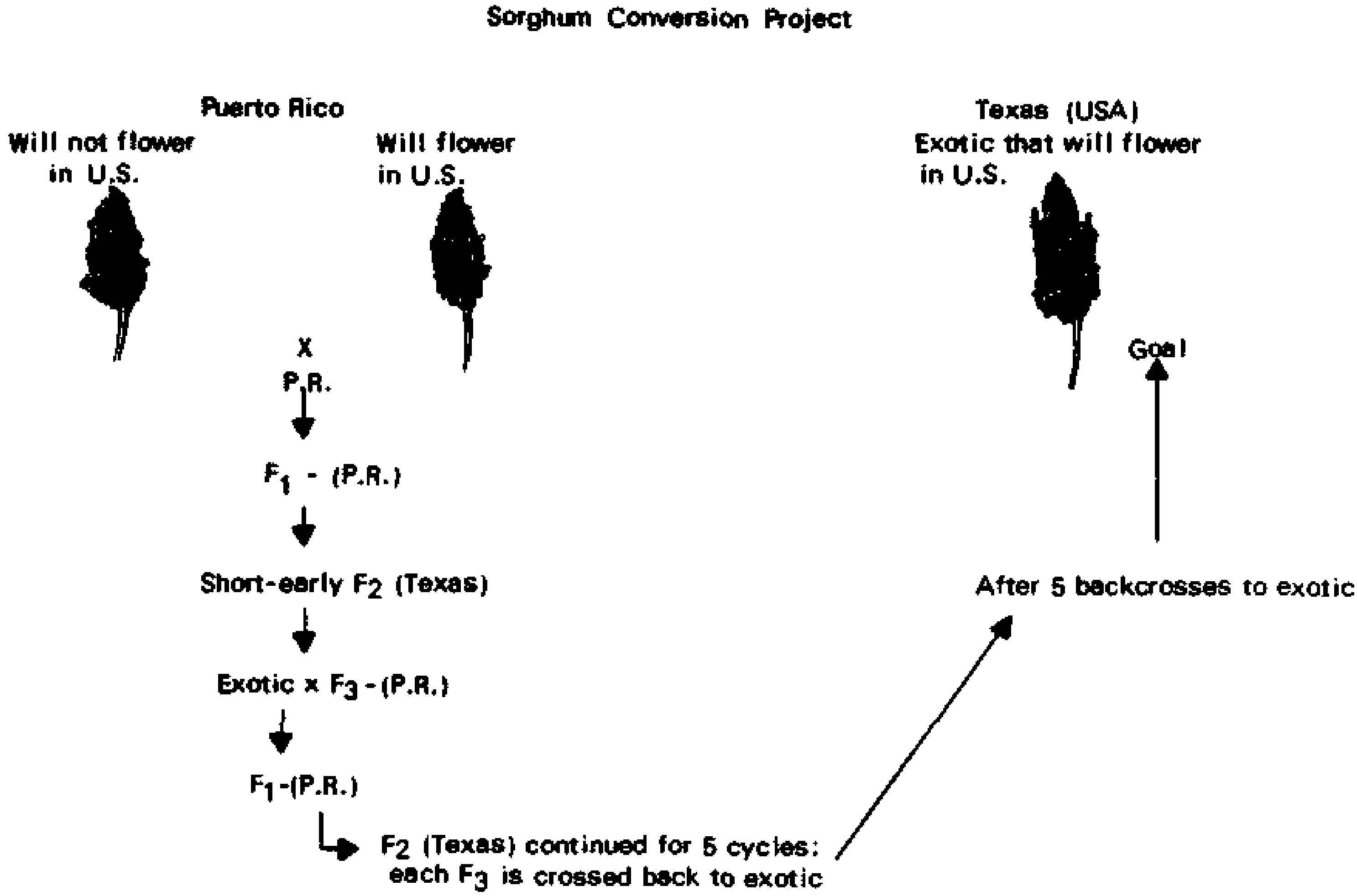

Figure 4. The Sorghum Conversion Project is a backcross breeding procedure that utilizes the knowledge of genetics of maturity and height to change tall, late photopehod-sensitive sorghums into short, early types which can be used throughout the world more easily.

lines and improved germplasm from existing breeding efforts. RTx 430, BTx 622, BTx 623. BTx 624, and RTAM428 are examples of such elite lines having part of their parentage derived from the Sorghum Conversion Program.

Physiological processes in cultivated crop plants are controlled and conditioned by a wide range of temperatures. It was not until recently that a great deal of work was done within various species to measure and finally select plants possessing major differences in temperature responses to their environments, i.e., temperature conditioned adaptation.

Nix and Angus (unpublished), Arnold (1959) and others have indicated that the base temperature for germination in *S. bicolor* is 10.5°C. These determinations were based on serial sowings in the field. However, Thomas and Miller (1979) using the procedure described by Gbur et al. (1979) have established that the base temperature is not constant within the species, but may vary from 4.6°C to 16.5°C. Associated work indicated that these differences among individual cultivars within the species may help explain major dissimilarities in adaptation. Leopold and Kriedemann (1975) indicated that it is the temperature extremes within the biological range that exerts an unremitting selective pressure and individuals within the species either succeed or perish on the basis of their capacity to either avoid or endure these temperature extremes. They further describe the importance of temperature by observing that environmental factors such as light, water and nutrients shape the community and determine its species composition, but that temperature can have regulatory influences which become translated into selective pressures.

Adaptation of a crop to a certain type of climate or environmental condition is genetically modulated and is affected by temperature and photoperiod.

Previous experience has consistently shown lower yields for high yielding sorghum hybrids which were developed in the temperate zone but grown in more tropical environments. However, there have been materials from the Sorghum Conversion Program which exhibited adaptation to much larger areas or which maintained high and stable yields when moved from temperate to tropical areas. It is suspected that this is an observed temperature response difference among these types. As a first step it was necessary to characterize the variation in base temperature. Base temperature is that temperature at which 50% of the seeds fail to germinate within a 10-day period. These points were estimated by using a segmented nonlinear regression technique (Gbur et al. 1979). The data from a thermogradient plate have demonstrated significant differences among base temperatures of the genotypes tested.

Thomas (1980) has further established that lines and hybrids designed as "tropically adapted" (TA) have lower base temperatures than the lines and hybrids designated as "temperately adapted" (TE). Hybrids have consistently exhibited lower base temperatures than their inbred parents. The F_1 hybrid between high and low base temperature parents is more likely to be lower or similar to the low parent (Table 3 and 4).

This differential response in base temperature may be the result of an evolutionary development related to the plant's survival suggested by Leopold and Kriedemann (1975). They indicated that it is temperature extremes within the biological range that exert the selective pressure on members of the species. In order for the tropically adapted types to have a selective advantage with a low base temperature, they must have come from an area which does not experience freezing temperatures. Those plants which developed in warm areas would not be subjected to frost early in the growth period and would not be removed from the plant community because they had the selective advantage of a low base temperature and were able to germinate at the onset of rain on any soil condition. This early establishment would give them advantages in both time and space. It could also force selection for pest resistance. On the other hand, those genotypes that developed at high elevations or areas where frost .was a definite probability early in the season, *only* survived if they did not germinate too early in the season when the probability of frost was high. Thus plants with high base temperatures become adapted to areas like the highlands of Ethiopia and USA Great Plains, (recall the temperate grasslands) while plants with lower base temperature were adapted to the warmer night-time environments like South Texas, Venezuela,the lowlands of Mexico, Australia, India, and the lowlands of Ethiopia and Africa (the tropical grasslands).

Table 3. Summary of base temperatures of tropically adapted and temperately adapted materials.

Designation	Parentages	Adaptability	Base temperature (℃)
RS671	Hybrid	Temperate (v)	1400
RTx2536	Male	Temperate	13.40
Top Hand	Hybrid	Temperate	12.00
NB505	Hybrid	Temperate	11.00
RS610	Hybrid	Temperate (s1)	996
RTx3430	Male	Tropical	900
BTx623	Female	Tropical	9.00
W-832R	Hybrid	Tropical	7.50
W-839DR	Hybrid	Tropical	7.50
WAC 715DR	Hybrid	Tropical	7.50
ATx623 x RTx430	Hybrid	Tropical (v)	7.50

Table 4. Array of base temperatures for several widely grown sorghums as determined by the thermogradient table method.

Varietal designation	Base temperature (℃)	SE
ATx399 x RTAM428	8.03	.102
ATx623 x RTx430	8.06	.107
ATx378 x RTx430	8.13	123
ATx623 x SLT-6	818	.083
ATx399 x RTx430	8.20	.050
BTx378	922	.341
RTx2752	9.71	.113
RS610	981	.128
BTx623	9.82	.132
RTx7000	9.90	.078
SC0599-11E	11.16	.243
RTx415	13.09	.051
RTx7078	13.09	.052

Crosses have been made between materials which have extremes in base temperature for germination. The F_2 segregations indicate that it is a complex phenomenon as would be expected.

but segregates can be isolated with a desired base temperature. Reciprocal differences are suspected since the cytoplasm is a site of many temperature responsive biochemical reactions and may also influence subsequent ranges in adaptation.

Using Sharpe and de Michele's (1977) basic enzyme model as a guide, a positive correlation may exist between the extremes of temperature tolerance that the different cultivar types possess. If a cultivar has a low base temperature it may not be able to in some ways tolerate high temperatures and vice versa. Preliminary data suggest that this may be the case. A line with a low base of 4.6℃ will cease to germinate at 37℃ while another line with a high base of 15.0℃ will continue to germinate adequately until 43℃.

Yield of harvested grain from two tropically adapted (TA) and two temperately adapted (TE) types are described in Table 5. Yield of the TE types. RS 610 and RS 671, increases slightly as one moves from 14° to 36° North latitude, while yield is highest at 14° and diminishes as one moves northward within the TA types. Differences between the means of the two types are a maximum at 14° and least at 36° N. Similar differences exist in Table 6, as the two TA types show stability or slight yield losses toward higher latitudes and the opposite exists for the two TE types. Using yields from four elevations in Guatemala at the same latitude (Table 7), when the contrast between TA and TE is made, the effect of temperature is still evident (Cuyuta, 48 m; Oasis, 190 m; Jutiapa, 906 m; and Barcena, 1260 m).

Sorghum has the major adaptation factors of height, duration of growth, response to photoperiod and reactions to temperature exposed to genetic manipulation. To develop the keys to a global sorghum program of improvement, an understanding of bioclimatology must also exist.

Table S. Yield in kg/ha for two temperately adapted and two tropically adapted sorghum hybrids grown at seven locations from 14 to 36° North Latitude.

		Temperately adapted		Tropically adapted		
Location	Climatic type	RS610	RS671	ATx623 x RTx430	ATx623 x 74CS5388	TA-TE
Guatemala, Coast	Tropical	4406	4610	5466	8327	+53%
Rio Bravo, Mexico	"	4400	4318	5000	5960	+26%
Weslaco, Texas	"	4122	4088	5090	5853	+ 33%
College Sta. Texas	*	4325	4333	6950	6350	+ 54%
Lubbock, Texas	Temperate	4363	3740	4420	4363	+ 8%
Halfway, Texas	"	5440	5156	5959	4647	0%
Kress, Texas		6063	5100	5326	5950	+ 1%
	x	4731	4478	5450	5921	
	xx	4605		5690		+24%

Table 6. Behavior of selected S. *bicolor* materials at different latitudes for yield (t/ha).

Hybrid	Climatic type	Cuyuta Guat.	Zacatapec Mexico	Weslaco Texas	Col. Sta. Texas	Lub. Texas	Halfway Texas	x
ATx623 x RTx430	TA	6.7	6.0	8.0	7.0	5.0	6.1	6.47
ATx623 x 77CS1	TA	7.8	5.8	7.0	7.0	6.1	7.8	6.95
ATx378 x RTx7000	TE	3.8	4.8	4.5	5.4	5.5	5.8	4.97
RS610	TE	4.6	4.0	4.6	4.3	5.1	5.4	4.67

What makes (Table 8) McAllen. Texas, and Bobo-Dioulasso, Upper Volta, similar from a sorghum production view as representatives of the Tropical Grasslands, or Dalhart, Texas, and Wepner, South Africa as representatives of the Extra Tropical or Temperate Grasslands? Temperature, photoperiod, rainfall, and the interactions of these climatic driving forces interact and within the biological range exert an unremitting selective pressure on members of the sorghum species to affect adaptation. By understanding these interacting forces we can move crops to adjacent bioclimatic classes and expand ranges of production and insure greater stability of food production.

Table 7. Behavior of selected *S. tricolor* materials at different elevations* at the same latitude for yield (t/ha), Guatemala.

		Yield (t/ha)				
Hybrid	type	Cuyuta	Oasis	Jutiapa	Barcena	x
BTx623	TA	5.8	50	52	4.5	5.1
ATx623 x CS3541	TA	100	90	9.7	9.2	9.5
ATx623 x 77CS1	TA	7.8	6.3	8.1	7.1	7.3
ATx623 x RTx430	TA	67	7.2	6.8	6.3	6.8
BTx3197	TE	4.6	4.7	4.9	5.1	4.8
ATx3197 :*X* RTx7078	TE	46	4.8	6.2	5.6	53
ATx399 x RTx2536	TE	4.1	50	59	3.8	47

a. Elevation: Cuyuta. 48 m. Oasis. 190 m. Jutiapa. 906 m. and Barcena, 1260 m.

Table 8. Daily average temperatures for four locations in North America and Africa.

	1		2		3		4	
Month*	Max	Mm	Max	Min	Max	Min	Max	Min
1	10	0.7	17	0.1	22	9	33	14
2	12	05	20	1	24	11	36	17
3	16	0.2	23	5	27	14	38	20
4	21	3	26	9	30	18	37	22
5	26	9	27	11	32	21	36	22
6	31	15	29	14	34	23	33	21
7	33	18	30	15	35	23	31	21
8	32	17	28	14	36	23	29	21
9	28	12	26	12	34	22	31	21
10	22	5	23	7	31	18	32	21
11	15	0.2	19	3	26	13	34	19
12	11	0.6	17	0.2	22	10	33	16

Station	Latitude	Longitude	Elevation
1. Dalhart. Texas	36°01 N	102°13W	1216m
2. Wepner, South Africa	29°44S	27°02 E	1440m
3. McAllen, Texas	26°12N	98°13W	37m
4. Bobo-Dioulasso, Upper Volta	11°10N	4°15W	435m

* Begins with January for northern hemisphere stations; July for stations in the southern hemisphere.

It is recognized that almost all crop plants which are grown under both tropical and temperate environments are more productive in the temperate region. Speculation is that increased night respiration or quantity of photosynthate causes the reduced growth and lower yields in tropical areas. Adaptation of a crop to a certain environment is genetically modulated and is affected by its response to temperature and photoperiod. Chemical reactions occurring in the plant have an optimum and suboptimum range and research has generally been specific to measure only the optimum and not the extremities of these ranges. This has led to the understanding that yield can be maximized at optima but overlooks that actual yield is the additive effort of the plant's capacities throughout its life cycle often made up of minima and maxima and a few optima. Temperature is the most critical selector and has a regulatory influence which becomes translated into selective pressures, often removing from the population unfit individuals as it is selecting superior individuals adapted to unique temperature extremes.

We do not expect all plants of a species to behave similarly for reactions to diseases, insects of other phenomena; therefore, they should not be expected to have similar temperature and photoperiod responses.

Sorghum originated in the tropics and is a warm season (C-4) short-day plant. Early research suggested that all individuals within the species had the same base temperature for germination and growth. It has now been established that major variation exists within *S. bicolor* for base temperature. These differences in response between plants suggest that by measuring the temperature characteristics, there may be more effective ways of predetermining areas of geographical adaptation—at least in a broad sense. This should allow the breeder to predict ranges of adaptation for a particular genotype with only "fine tuning" required for local adaptation.

References

ARNOLD, C. Y. 1959. The determination and significance of the base temperature in a linear heat system. Proceedings of American Horticultural Sciences 74: 430-455

DOGGED. H 1970 Sorghum London. UK: Longmans, Green and Co 403 pp

GBUR, E E., THOMAS, G L . and MILLER, F. R. 1979 Use of segmented regression in determination of the base temperature in heat accumulation models Agronomy Journal 71 : 949 953

LEOPOLD, A. C, and KRIEDEMANN, P. E. 1975. Pages 375-399 *in* Plant growth and development. New York: McGraw-Hill.

MILLER. F R . BARNES. D K , and CRUZADO. H J. 1968 Effect of tropical photopenods on the growth of *Sorghum bicolor* (LI Moench. when grown in 12 monthly plantings. Crop Science 8:499 502

MURIY, B. R , ARUNACHALAM. V , and SAXENA. M B L. 1967 Classification and catalogue of a world collection of sorghums. Indian Journal of Genetics and Plant Breeding 27 (Special Number): 1 312.

Nix, H. A. and ANGUS. J F. (Unpublished) A model of crop development Division of Land Use Research, CSIRO, Canberra, Australia

QUINBY, J. R. 1974. Sorghum improvement and the genetics of growth. College Station. Texas, USA: Texas, A&M Press

QUINBY, J. R , and KARPER, R. E 1954 Inheritance of height in sorghum Agronomy Journal 46:212-216.

QUINBY, J. R , and HESKETH. J. D.. and VOIGT. R. L. 1973 Influence of temperature and photoperiod on floral initiation and leaf number in sorghum Crop Science 13:243-246

SHARPE, P. J H., and DEMICHELE. D. W. 1977 Reaction kinetics of poikilotherm Journal of Theoretical Biology 64:649-670

STEPHENS, J. C, MILLER, F R , and ROSENOW, D T. 1967. Conversion of alien sorghums to early combine genotypes Ctop Science 7 : 396

THOMAS. G. L. 1980. Thermal and photothermal effects on the growth and development of diverse grain sorghum genotypes Ph.D. dissertation, Texas A&M University, College Station, Texas, USA

THOMAS, G. L., and MILLER, F. R. 1979. Base temperature for germination for temperate and tropically adapted sorghums. Presented at the Eleventh Biennial Grain Sorghum Research and Utilization Conference. 28 Feb -1 Mar, Wichita, Kansas, USA.

Selection in Temperate-Tronical Crosses of Sorghum

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While most tropical areas of the world are less developed, the utility of tropical germplasm for crop improvement is universal; this is particularly true of sorghum. Earlier attempts at exploiting "tropical-tropical" crosses in India and Africa having proved to be of limited utility and the "temperate-temperate" crosses in USA having led to plateauing of hybrid yields, "temperate-tropical" crosses have become an integral part of all sorghum breeding programs, the conversion approaches having received particular emphasis in the USA and the more conventional approaches in India. During the past decade we have been involved in analyzing the breeding behavior of "temperate-tropical" crosses to enable us to incorporate attributes of economic worth into genetic backgrounds of higher levels of yield and yield stability. This paper attempts to project the potentialities of such crosses for sorghum improvement.

"Temperate* and "Tropical" Sorghums

All sorghums are of tropical origin. Their introduction ahd adaptation to the long-day conditions of the western hemisphere, more particularly the USA, has led to the designation of this group as "temperate" sorghums.

According to Quinby (1968). the process of temperate adaptation essentially involved the mutation of the dominant *Ma, Ma_1* locus to its recessive *ma, ma,* so as to enable flowering under long-day conditions. In most "temperate-tropical" crosses, earliness is dominant when plants are grown under tropical conditions. For purposes of mechanical harvesting, U.S. workers selected the dwarf mutants. Consequently sorghums termed as "temperate"involve mutations for maturity and height and are generally characterized by earliness and dwarfness.

In this connection, it should be recognized that the mutations for height and maturity did take place in the tropics and are not consequent to their introduction in temperate regions. Dwarf (brachytic) and earlier versions of sorghums are encountered in farmer fields of Sudan, possibly Ethiopia, west and southern Africa, and other regions. Yellow endosperm *safra* and white or colored seeded *feterita* fields of different heights and maturities are common in Sudan even today. But at the same time, it has to be recognized that emphasis on selection, purification, improvement and perpetuation of dwarf and early forms was in the U.S. because of daylength and agronomic requirements. Thus, the so-called temperate sorghums are essentially mutations for height and maturity, which took place in the tropics. What is of greater consequence is the transference of attributes between the shorter and earlier versions and their taller and sometimes later maturing progenitors.

In one of our inconclusive studies on induced mutations in tropical sorghums (Rao et al. 1970). we postulated that a rare mutational event in tropical sorghums with partially exposed internodes altered them to forms with enclosed internodes and that such a change possibly disrupted the entire genotype leading to changes in growth rhythms, heights, panicle morphology.

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum. 2-7 Nov 81. Patancheru, A.P.. India. Patancheru. A.P. India: ICRISAT.

nsect reaction, etc. We also felt that the genetics of height and maturity, as elegantly analyzed by Quinby, apply to forms that have undergone such an a priori change, and that the allelism of height and maturity genes between forms with exposed and enclosed intemodes needs further analysis.

From the point of view of adaptation, while some of the late tropical forms do not flower under long-day conditions, all "temperate" sorghums do flower and yield in the tropics although they may understandably be different for insect and disease reaction, yield levels, etc. Thus, the so-called temperate sorghums, which are of tropical origin, differ from their tropical progenitors because of a complexity of physiological and genetical changes associated with internodal elongation and maturity. It is these associated changes that differentiate the two groups of cultivated sorghums *[Sorghum bicolor* [L.J Moench) that are significant in gene transfer. Our efforts (Rao and Rana 1978) to characterize "tropical and temperate" sorghums and their utilization established that the two groups exhibit considerable divergence both physiologically and genetically and that recombination of attributes from the two groups is difficult but accomplishable. It is felt that the two groups need a distinct varietal or subspecific status and a better terminology to which taxonomists should give consideration. These associated changes, their breeding behavior and their consequences for sorghum improvement are discussed below.

Physiological and Genetical Differentiation: The Optimum Phenotype

Traditional tropical sorghums are generally tall and late and are characterized by higher biological yields and low economic yields. Compared with the early maturing dwarfs, the total dry matter produced per plant in the tropical sorghums is much higher and its distribution is 70:30 between stalk and ear. This is consequent to a single peak for the rates of growth coinciding with flowering whereas the more productive sorghums have two peaks for rates of growth and a 50 : 50 dry matter distribution (Goldsworthy 1970; Rao and Venkateswarlu 1971; Anantharaman et al. 1978). Such tropical sorghums are generally photosensitive, usually flowering after the cessation of rains. They are highly localized in their adaptation.

The pattern of internodal elongation, to some extent, reflects the pattern of growth. Our analysis of the patterns of internodal elongation in different groups of sorghums (Balarami Reddy et al. 1981b) revealed that several "temperate" types and hybrids were generally characterized by a linear pattern, whereas a third degree polynomial curve was required for some of the cross derivatives and relatively shorter tropical forms (Fig. 1).

The two groups of sorghums also exhibit differences with respect to tissue concentration of nitrogen, phosphous and potash, their uptake patterns (Rao and Venkateswarlu 1971) and response to fertility and population levels (Rao 1979).

The agricultural consequences of such physiological characteristics of tropical sorghums are

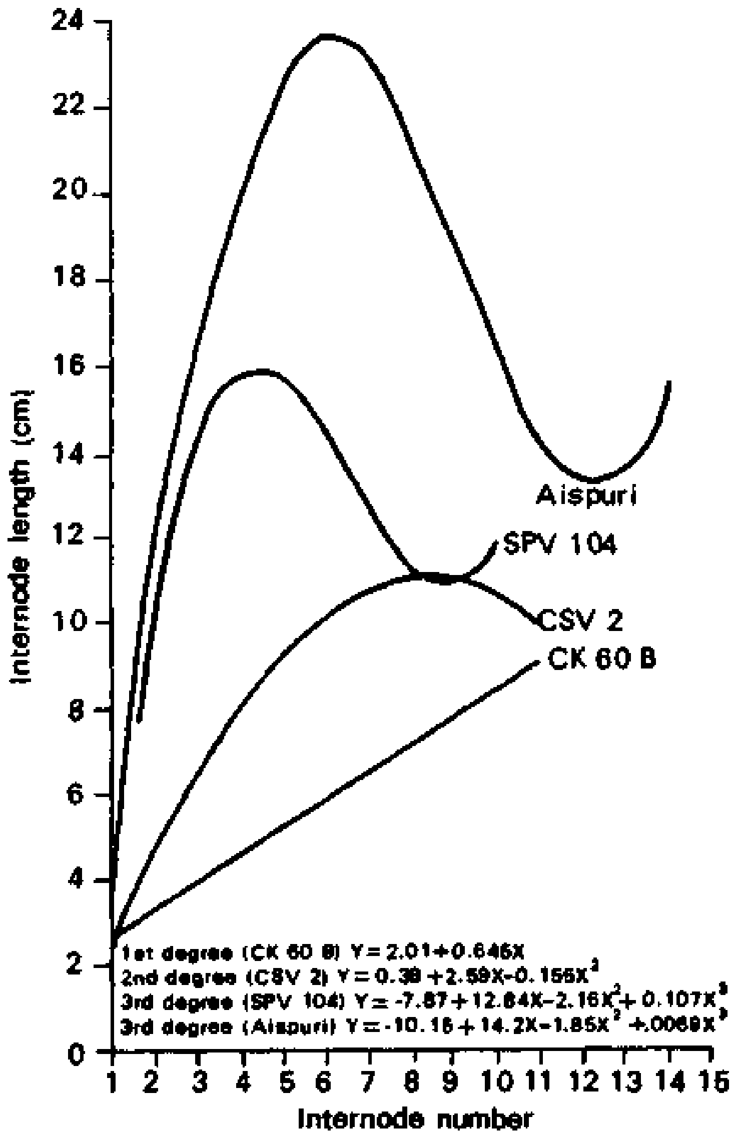

Figure 1. Expected internodal patterns in sorghums of diverse origin.

restricted adaptation, their vulnerability to rainfall fluctuations (Rao et al. 1975), adaptability to low populations, and lower rates of response to fertilizer use and low *economic* yields which together constitute subsistence agriculture (Rao 1981b.)

Genetically, the distribution of dominant and recessive alleles for grain yield, plant height and flowering is asymmetric and in opposite directions in the two groups; the "tropical" group with dominant alleles for yield and plant height and the "temperate" group with dominant alleles for earliness (Rao 1970b; Rao and Rana 1978). Consequently the associations between yield, plant height and maturity are strong, rendering recombination difficult (Harinarayana et al. 1971; Subba Reddy and Rao 1971). Gene distribution for resistance attributes (Table 1) such as shoot fly (Rana et al. 1975; Balakotaiah et al. 1975), and quality characters such as protein and lysine (Kang 1969) also exhibit group differences and present problems for gene transfer.

Attempts have been made at incorporation of the attributes of economic worth across groups. While the converted sorghums of the USA may be considered more "temperate", the derived sorghums reflected varying levels of recombination. Selections which represented productive peaks were at heights and maturities intermediate between the two groups (Rao et al. 1973) and recovery of such productive intermediates was limited and could be accomplished through emphasis on between-family selection (Tripathi et al. 1976). A majority of crosses between groups failed to yield balanced recombinants of economic worth and it was only an occasional cross where there was satisfactory recovery. Such productive crosses represent unique combinations and there is yet no predictable method of detecting them except by actual trial. Conventional estimates of combining ability do not generally lead to predictable results.

Based on some of the more productive derivatives and their parents across a range of heights and maturities, we have recently undertaken a computer exercise to determine the most productive lines in relation to height and maturity. We arrived at the conclusion that productive progenies, were obtained at heights of 175-180 cm, flowering at 68-70 days and with reduced leaf numbers. Such intermediate progenies derived from crosses between the two groups of sorghums, satisfied the needs of food and fodder and insect and disease resistance. They also combined the individual superiority of the tails and the community performance of the dwarfs besides conferring wide adaptability. Thus, the phenotypic optimum is an 'intermediate optimum' (Fig. 2). Although the recovery of such optimal types is low from direct "temperate-tropical" crosses, there are indications that a second cycle of crosses involving desirable derivatives would furnish greater opportunities since the height and maturity effects will then be minimal. Such intermediate types with optimal dry matter production and distribution, the critical stages of growth coinciding with periods of favorable weather, a linear pattern of internodal elongation and exhibiting resistance or tolerance to the prevalent pests and diseases would represent the optimum phenotype to strive for, and the vehicle is the "temperate-tropical" crosses to begin with

Table 1. Shoot fly damage In temperate and tropical sorghums and their derivatives.

Group	No. of lines	Percent damage (transformed values)	
		Mean	Range
Temperate (exotics)	3*	54.3	35.3-70.5
	19	61.9	49.3-69.7
Tropical (Indian)	3*	283	265-31.1
	20	35.1	25.0-43.2
Temperate x Tropical	5*	34.8	30.1-45.8
(derivatives)	64	52 1	36.3-68.4
SE		4.57	

* Average number of plants ranged from 1198 to 1266; SE = 4.13

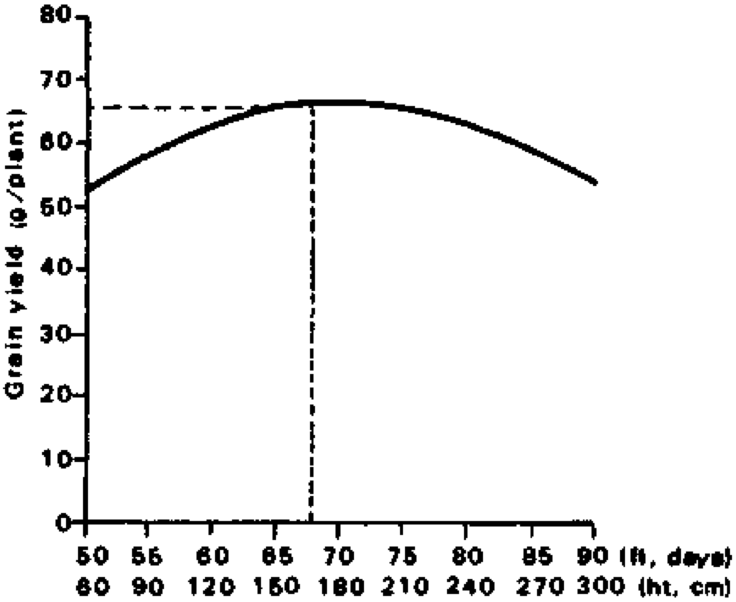

Figure 2. Optimum phenotype as related to plant height and flowering time.

and crosses among derived lines at a later stage. Such genotype alterations reflecting changes in dry matter production and distribution and growth rhythms result in efficient water use and form the very basis of improving dryland sorghums for yield and stability (Rao et al. 1979).

Hybrid Improvement: Selection of Parents

The potentialities of "temperate-tropical"crosses in hybrid breeding can be seen from Table 2.

The first commercial sorghum hybrids developed in India based on male-sterile Combine Kafir (msCK 60) did not have Indian varieties as male parents as was generally expected; they were exotic x exotic combinations. In the case of the msCK 60 x Indian variety combinations, apart from differences for height and flowering, accumulation of dry matter in the stem after flowering did not result in heterotic advantage for grain yield. The behavior of msCK 60 x Indian combinations and temperate x Indian crosses in general has been analyzed in detail (Rao 1970b, c; Rao and Venkateswarlu 1971; Rao 1972a). It should also be noted that the first sorghum hybrids, CSH-1 and CSH-2, did have some tropical parentage in that the male parents selected were from yellow endosperm *feterita* (IS 84) and yellow endosperm *begari* (IS 3691) respectively.

Subsequently the females developed in India like 2077A and 2219A, which furnished female parents for CSH-5 and CSH-6 respectively are also largely "temperate". Male improvement through selection in "temperate-tropical" crosses resulted in the development of CS 3541, 148/168, and PD3-1-11 which furnished male parents for commercial hybrids. CS 3541 has been derived from a cross between IS 3541 (African Zera Zera) x IS 3675 and furnished the male parent for the commercial hybrids CSH-5, CSH-6 and CSH-9. CS 3541 is relatively short and less photosensitive compared with its tall and sensitive progenitor IS 3541. Similarly, the male parent of the *rabi* (winter) hybrid CSH-7R was 148/168, derived from the cross IS 3687 x *Aispurian* Indian variety; PD3-1-11, the male parent of CSH-8R, was derived from the cross IS 84 x BP 53.

Amongst female parents that entered commercial hybrid combinations, 36A, derived from CK60B x PJ36K, and 296A, from IS 3922 x *karad* local, are also based on "temperate-tropical" combinations. While male improvement contributed substantially for most hybrids, it was female improvement that was responsible for the consistent superiority of CSH-9 (Rao et al. 1982).

While the first commercial hybrids of India were

Table 2. Mean performance (X) and heterosis % (H) in temperate x <temperate. tropical x: tropical, and temperate x tropical crosses.

Cross	No of Crosses	Grain yield/ plant(g)		Days to flower		Plant height	
		X	H	X	H	X	H
Temperate x Temperate	6	85 6	87.2	74.4	464	148	33.5
Tropical x Tropical	3	103.4	20.2	104.3	-2.80	287	11.4
Temperate x Tropical	12	112.8	773	87.0	-0.20	242	370
SE		2.31		0.14		2.12	

largely "temperate", parents of recent hybrids are the result of selection in "temperate-tropical" crosses. Thus, in recent years, greater attention has been bestowed on diversification of germplasm resources, as in the conversion program of the USA. and "temperate-tropical" crosses in India for deriving parents for commercial hybrids. But the actual identification of the parents that entered into commercial hybrid combination has largely been through actual evaluation of experimental hybrids in yield trials. In spite of several attempts at formulating a quantitative theory of selection for heterosis most of the information available is based on trial and error.

Most studies on heterotic responses point to the importance of seed number. Earlier studies based on crosses with msCK60 revealed that heterosis was maximum for panicle components evolved in the same direction and that considerable recombination breeding would be necessary before the compact-panicle types with reduced length of primary axis could be combined with elongated-panicle types like the *kafirs* (Rao 1970 b,c). Further studies on character associations in hybrids indicated that as long as seed numbers are not adversely affected, seed weight is important and that late maturity is not necessary to attain high yields. In fact, highest yields may be possible in hybrids flowering in 65-70 days. Heterosis for root activity also revealed distinct patterns. While heterosis up to knee-high stage and seedling vigor are common, there are cases like CSH-2 where heterosis for root activity persisted up to flowering and may be worthwhile to exploit (Damodar et al. 1978b).

Based on heterosis and combining ability studies, Rao et al. (1968) suggested using high yielding derived lines from "temperate-tropical" crosses as parental material, and this has been discussed. A subsequent study (Rana et al. 1974) furnished proof that selected derivatives used as males yielded hybrids of superior grain yields and seed weight compared with those resulting from the use of IS 84, the male parent of CSH-1.

Evaluation of male per se performance and its relation to test cross yields indicated that line performance could be used to screen potential parents (Fig. 3) and that subsequent evaluation may be based on test crosses (Singhania and Rao 1975). A parental yield trial was therefore made part of the coordinated trial program to obtain data on parental yields and flowering behavior.

The use of early testing as a method of

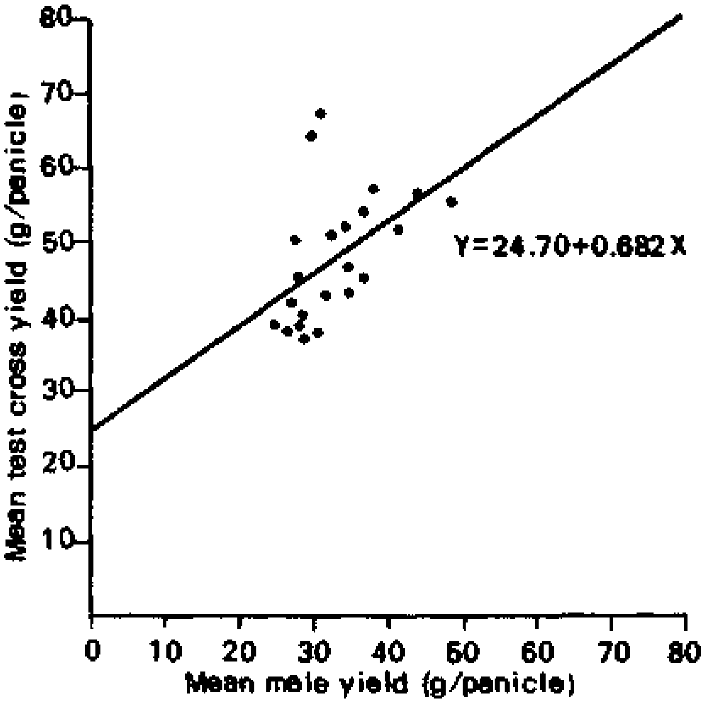

Figure 3. Regression of test cross performance on male performance.

identifying superior males (Mishra and Rao 1980a) revealed that test crosses based on F2 enable identification of crosses that could yield superior parents, and that using this information together with F3 test crosses, one could limit the number of progenies to be tested for isolating lines that could yield superior hybrids (Tables 3 and 4). While early test cross procedures also capitalized largely on additive genetic variance, there was an indication of greater use of *sca* compared with conventional methods (Mishra and Rao 1980b). Some male parents selected on the basis of their performance under favorable conditions at a single location resulted in hybrids of wider adaptability (Singhania and Rao 1975; Mishra and Rao 1980b).

It has now become a practice to develop populations among B and R lines respectively for selection of future parents. Studies involving BxB. BxR and RxR cross combinations revealed that BxR and RxR crosses could be preferred over BxB crosses due to their higher diversity for yield components, insect resistance (Table 5), and better grain quality ensuring higher germination (Rana et al. 1978). Hence, even for female improvement, BxR crosses with superimposition of early test cross procedures to identify maintainors could be a useful procedure (Jaya Mohan Rao et al. 1982).

Although allelic and nonallelic interactions may be the major source of heterosis, several

Table 3. Test cross performance in early generation testing in some crosses.

Cross	Mean grain yield/plant (g)					
	F_2 test cross		F_3 test cross		F., progenies	
	N*	X⁶	N	X	N	X
R24 x CSV-7R	58	79.S	29	92.9	28	75.7
IS 3922 x M35-1	55	74.8	12	72.8	34	58.2
CSV-7R x 512	64	64.6	38	70.3	34	73.8
CSV-6 x 512	31	626	8	780	20	50.7
SE		2.9		49		42

a *H* = No. of progenies
b X = Mean.

Table 4. Estimate of general (g) and specific (s) combining ability variance for grain yield.

Estimate		Env. interaction		Stability
$\hat{\sigma}^2 g_f$	= 68.3**	$\hat{\sigma}^2 g_f$	x e = 36 3**	Low
$\hat{\sigma}^2 g_m$	= 2.9	$\hat{\sigma} g_m$	x e = 6.7	High
$\hat{\sigma}^2 g$	= 52.9**	$\hat{\sigma} g$	x e = 29 3**	Low
$\hat{\sigma}^2 s$	= 24.2**	$\hat{\sigma} s$	x e = 7.9	High
$\hat{\sigma}^2 g/\sigma^2 s$	= 2.2:1			

•• Significant at 1%; • Significant at 5%

Table 5. RxR, BxR and BxB hybrids.

Hybrid	No of crosses	Days to 50% flowering	Plant height (cm)	Grain yield/plant (g)	% Stem borer tunnelling (angles)
			Group means		
RxR	10	77	176	62	28
BxR	20	76	205	65	27
BxB	6	74	179	59	31
		Average heterosis (% over midparent)			
RxR	10	0.6	13.3	84.4	- 10.1
BxR	20	- 1.5	17.5	127.2	- 7.5
BxB	6	- 0.2	32.8	116.3	- 16.9
Between group mss (2)		42.5**	10 369*•	331	136**
Error (88)		5.6	321	209	39

•* Significant at 1%.
Numbers in parentheses indicate degrees of freedom

reports indicate that the nature of gene action in yield heterosis involved predominantly *gca.* There are indications that the nature of gene action in different hybrids could be different (Rao and Murthy 1970). But the basic question is about the methodology to capitalize on *sca.* While selection based on morphological criteria seems largely to use additive genetic variance, the nature of gene action involved for enzymatic criteria like nitrate reductase and amylase activities seems to involve predominantly *sea* (Mishra and Rao 1981 a,b). If the value of such criteria leading to metabolic efficiency is conclusively established, they might then furnish the means to utilize *sea.*

All commercial hybrids developed todate are based on *milo* cytoplasm. Alternate sources of cytoplasmic-genetic male sterility have now been identified (Table 6) and characterized genetically, biochemically and through electron microscope studies (Rao 1962; Schertz 1977; Tripathi 1979; Tripathi et al. 1981 a,b,c,d,). It is hoped that their utility will be established in the near future.

Breeding Superior Varieties: Selection for Yield Improvement

The potentialities and limitations of "temperate-tropical" crosses for yield improvement have been considered earlier (Rao and Harinarayana 1968; Rao 1972 b). While such crosses do furnish opportunities for handling adequate genetic variability, strong character associations tend to restrict recombination. Estimates of combining ability do not provide reliable predictions of selection gains. Only certain "unique cross-combinations" yield recombinants of economic worth. A satisfactory basis for selection has yet to emerge.

Conventional pedigree, bulk and backcross methods have been extensively employed, but their limitations on exploitation of a limited gene pool, low genetic recombination and quick fixation of linkage blocks due to continuous inbreeding have often been spelt out. Population breeding procedures have been suggested to force recombination among large number of varieties. Though intermating is effective to break initial linkage blocks, its utility in self-pollinating species has been questioned since the extent to which it disintegrates the natural adaptive gene complexes, characteristic of self-pollinating species, is not known precisely (Bos 1977). Besides, crosses involving several parents also pose problems of population size, particularly when selection is aimed at improving quantitative characters like yield (Sneep 1977). These problems are very relevant to handling such diverse crosses involving the "temperate-tropical" sorghums. The breeding system in cultivated sorghum is unique in that it ranges from complete self-pollination to total outcrossing by virtue of its floral biology and known mechanisms of cleistogamy, genetic and cytoplasmic-genetic male sterility, self-incompatibility and apomixis which would permit use of diverse breeding systems (Rao and Narayana 1968; Rao 1972b; Murthy et al. 1980).

Prediction of the unique combinations where selection would yield fruitful results is no doubt difficult, yet the initial choice of parents has to be between the tropical and temperate groups. Presence of desired genes, diversity among genotypes, parental performance per se and the nature of combining ability are still the best criteria. In spite of the fact that most of the tropical cultivars are excessively tall, late, and low in productivity due to excessive dry matter production and inefficient translocation, the dominant genes for yield are present in tropical cultivars. "Temperate" sorghums present different gene constellations and furnish genes for dwarfing, earliness and population performance. Hybridization between the two groups, therefore, forms

Table 6. Cytoplasmic-genetic Interaction for seed sat in F1.

	B-li nes						Restorers		
ms lines	CK60B	NAG-B	MAL-B	M31-2B	VZM2B	G1B	GM1-5	K-Local	Nandyal
CK60A	S	S	F	F	F	F	F	F	F
Nagpur-A	s	S	F	F	F	F	F	F	F
Maldandi-A	s	S	S	S	S	S*	F	F	F
M31-2A	s	S	S	S	S	F	F	F	F
VZM2A	S	S	S	S	S	S	S	S	S
G1A	S	S	S	S	S	S	S	S	s

* Fertile in summer. S = sterile; F = fertile.

the basis of yield improvement in both tropical and temperate regions. There is evidence that selection of crosses for higher F1 and F2 mean performance results in a large number of promising progenies in further generations. At least one of the parent in such crosses is always a good general combiner (Seshagiri Rao 1979).

While the generally positive relationship of yield with maturity and height has been established, continued selection for short stature, earlier maturity and high yields resulted in the dissipation of such effects; optimal yields are obtained at intermediate heights and maturities (Rao et al. 1973). Our studies (Tripathi et al. 1976) indicated that with choice of suitable parents and emphasis on selection between families, directional selection using pedigree method could result in isolation of desirable homozygotes in spite of the strong character associations. Subsequent use of such derivatives in cross combinations would result in rapid progress since the height and maturity effects will be minimal.

The recombination patterns in single, backcross, three-way and double crosses involving "tropical and temperate" parents and their crosses derivatives have been investigated by Seshagiri Rao (1979). The probability of obtaining high yielding plants was high in dwarf (D) x tall (T) and DxD combinations; in the (DxT) D three-way crosses, the choice of the third parent was critical. The use of a tall parent in the grandparentage was useful and gains from DxT crosses could be improved if the effects of height genes were rapidly minimized by an extra dose of dwarfing genes. Backcrosses and three-way crosses in specific combinations resulted in isolation of high-yielding dwarfs and mid-tails in greater probabilities. Reciprocals of good backcrosses. random three-way crosses, and double crosses failed to accomplish this goal. These studies on mating systems (Table 7, Fig. 4 and 5) are thus indicative that gene frequencies could be shifted in the desired direction only under controlled and specific cross combinations. The results did not favor the breaking up of adaptive gene complexes indiscriminately in diverse crosses. It strengthens the view of adaption of specific cross combinations. Yet. there is some evidence from the USA that population approaches could result in selection gains. The base populations used in the USA did not provide the variability for height and maturity encountered in "temperate-tropical" crosses. After correction for height and maturity, and obtaining high yielding derivatives, limited intermating between such derivatives may be useful.

The criteria for selection in yield improvement need some consideration. Selection based on phenotypic criteria such as yield components and index approaches have been considered, but they are of limited utility (Subba Reddy and Rao 1971). Hence selection based on yield per se providing for proper accounting of environmental variability has been more frequently employed. Yet, selection criteria unrelated to height and maturity could be useful. Genotype differences for tissue concentration and response patterns of major nutrients have been demonstrated (Rao and Venkateswarlu 1971; Ramachandran and Rao 1973). The tissue concentration of nitrogen seems to be positively correlated with yield and could furnish a useful criterion (Fig. 6). Genotypic differences for root activity have also been demonstrated and might be useful (Damodar et al. 1978a). Nitrate

Table 7. Cumulativa probabilrtias (%) of selection for grain yield in single, back, thraa way, and double croaaaa in sorghum.

Yield/Plantt (g)	SC		BC		TWC			DC	
	DxD	DxT	(DxD)xD	(DxT)xD	(DxD)xD	(DxD)xT	(DxT)xD	(DxD)x(DxT)	(Dx:D)x(DxD)
> 60	9.1	5.2	3.6	9.9	4.7	3.3	16.7	1.9	1.8
> 70	2.4	1.6	0.7	4.1	1.0	0.7	7.7	0.3	0.3
> 80	0.2	0.4	0.5	1.6	0.1	0.1	3.1	—	
> 90	—	0.1	—	0.5		—	1.0	—	
>100	—	—	—	0.1		—	0.3	—	

SC * single cross; BC = backcross; TWC = three-way cross; DC - double cross. D = Dwarf, T = Tall.

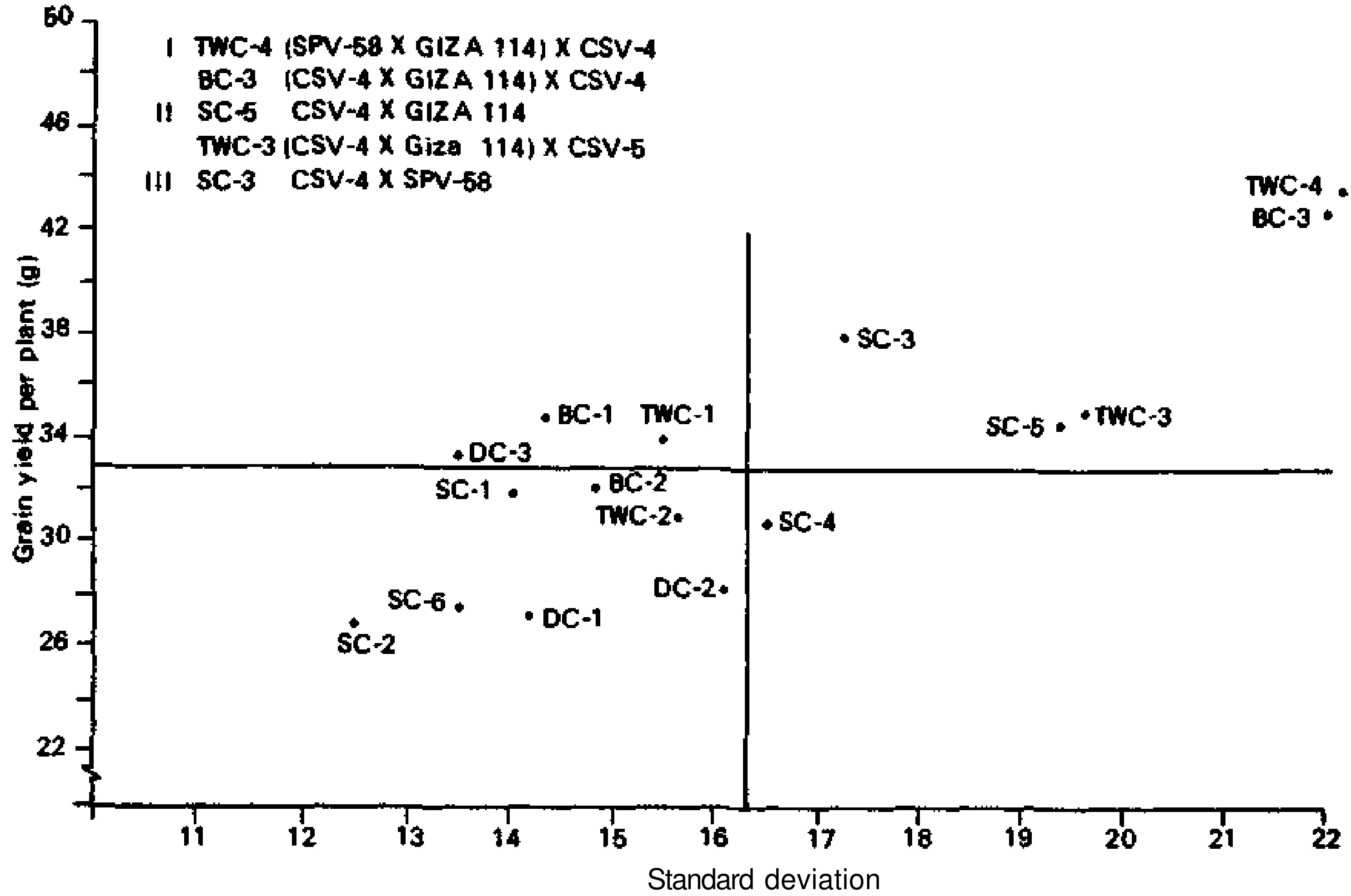

Figure 4. Mean and variability in F2 generation under different mating systems.

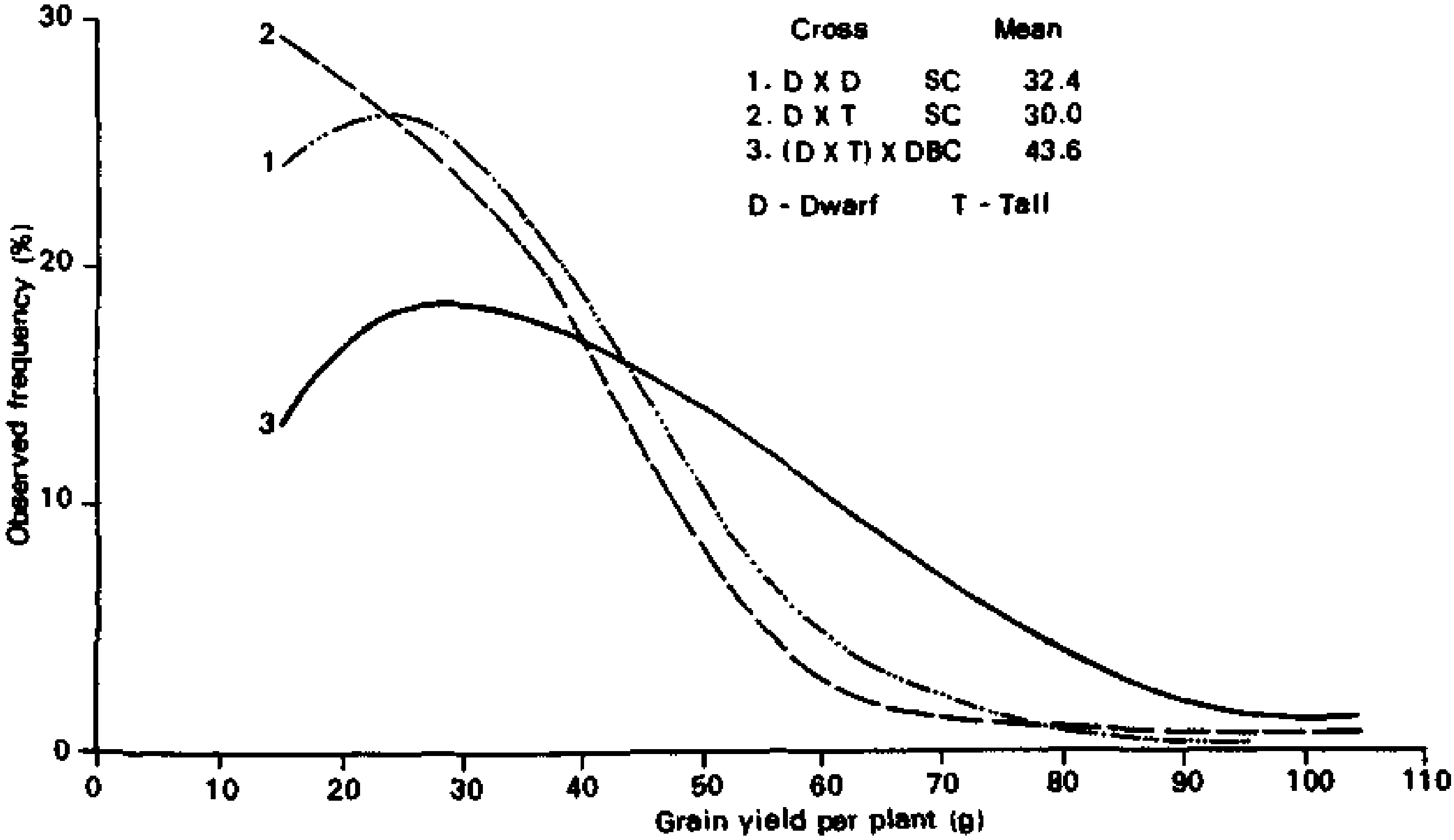

Figure 5. Average yield performance in different mating systems in F2.

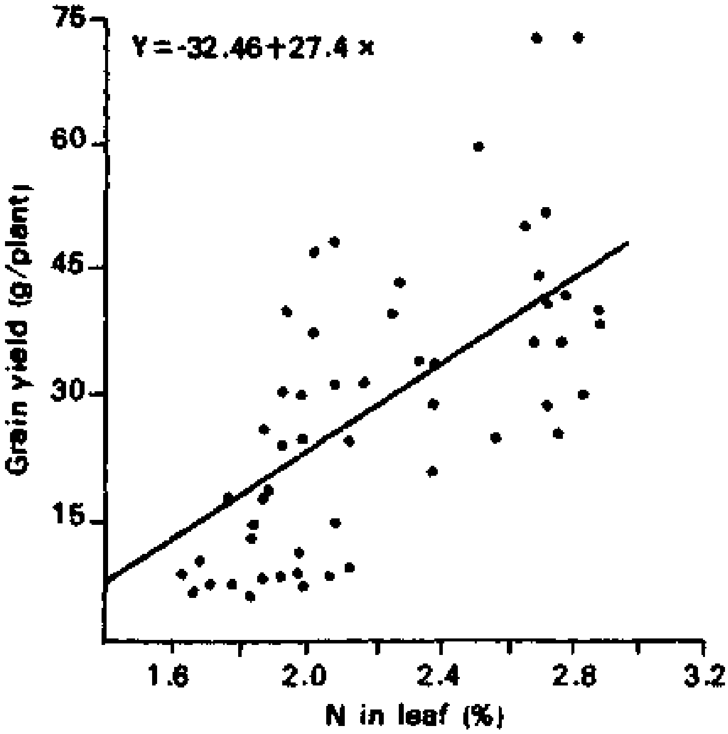

Figure 6. Relation between grain yield and leaf nitrogen (%).

Table 8. Estimates of H, H and E(Δ y) under high and low input management environment (total locations = 20).

Parameter	High management (H)	Low management (L)	H/L(%)
H	0.84	0.77	109.1
VH	092	0.88	104.4
E(A y) kg/ha	759	569	133.4

VH—Logical measure of joint effect of d^2e and d^2g on the value of the test environments
E(A v)—Expected genetic gain

reductase activity at the vegetative stage appears to be phenotypically correlated (r = 0.68*) with yield and might yet be another physiological criterion (Mishra et al. 1981a). Nutritional considerations in selection, particularly the incorporation of the high lysine trait, have been a subject of discussion (Nanda and Rao 1975). Our efforts (Jaya Mohan Rao 1980) to transfer high lysine to agronomically desirable grain types of acceptable yield levels indicate possibilities of dissipating the generally known negative relationship between protein and lysine and that the incorporation of this trait is not an impossible task. Efforts in this direction should continue.

It has been frequently stated that the performance of high yielding hybrids and varieties is satisfactory only under optimal input and management, but with sorghum being a crop of tropical drylands, selection should be practiced under suboptimal conditions. Consequently, it was not uncommon to select and test under two different sets of growing conditions. Our studies (Vidyasagar Rao et *al* 1981) have established that selection under optimal conditions is advantageous (Table 8). Yield based rankings and rankings based on risk aversion criteria did not differ markedly, indicating the validity of our selection under optimal conditions in combining yield with stability under varying management and climatological conditions (Barah et al. 1981).

To date, nine high yielding varieties (CSV-1 to 9) have been released and more are under prerelease multiplication. The relative Derformance of hybrids and varieties established hybrid superiority, but the derived varieties are superior to locals (Rao et al. 1981). Improved varieties like SPV 221 and SPV 245 and several others are superior to CSH-1, the first hybrid, in yield levels. We are presently in the process of approaching CSH-5 in yields at the varietal level. Varietal improvement is a continuous process which will contribute both directly and as parental material for hybrid improvement. There is a case for superior varieties of approximately similar maturity as the hybrids. Since hybrid seed production is a repetitive process and might not cover the entire production area, varietal supplementation will minimize the losses due to the vulnerability of late locals to drought and midge. It is necessary to reestablish the maturity equilibrium of sorghum to match the duration of the rainy season.

The shifts in flowering, height, and yield accomplished with "temperate x tropical" crosses are depicted in Figure 7.

Selection and Adaptation

Hybridization of "temperate and tropical" *sources* of germplasm provides for opportunities as well as problems related to adaptation and adaptability. One of the major consequences of genotype alteration is changed adaptation.

Since traditional cultivars are known to be highly local in their adaptation, past breeding efforts have been oriented towards the needs of several

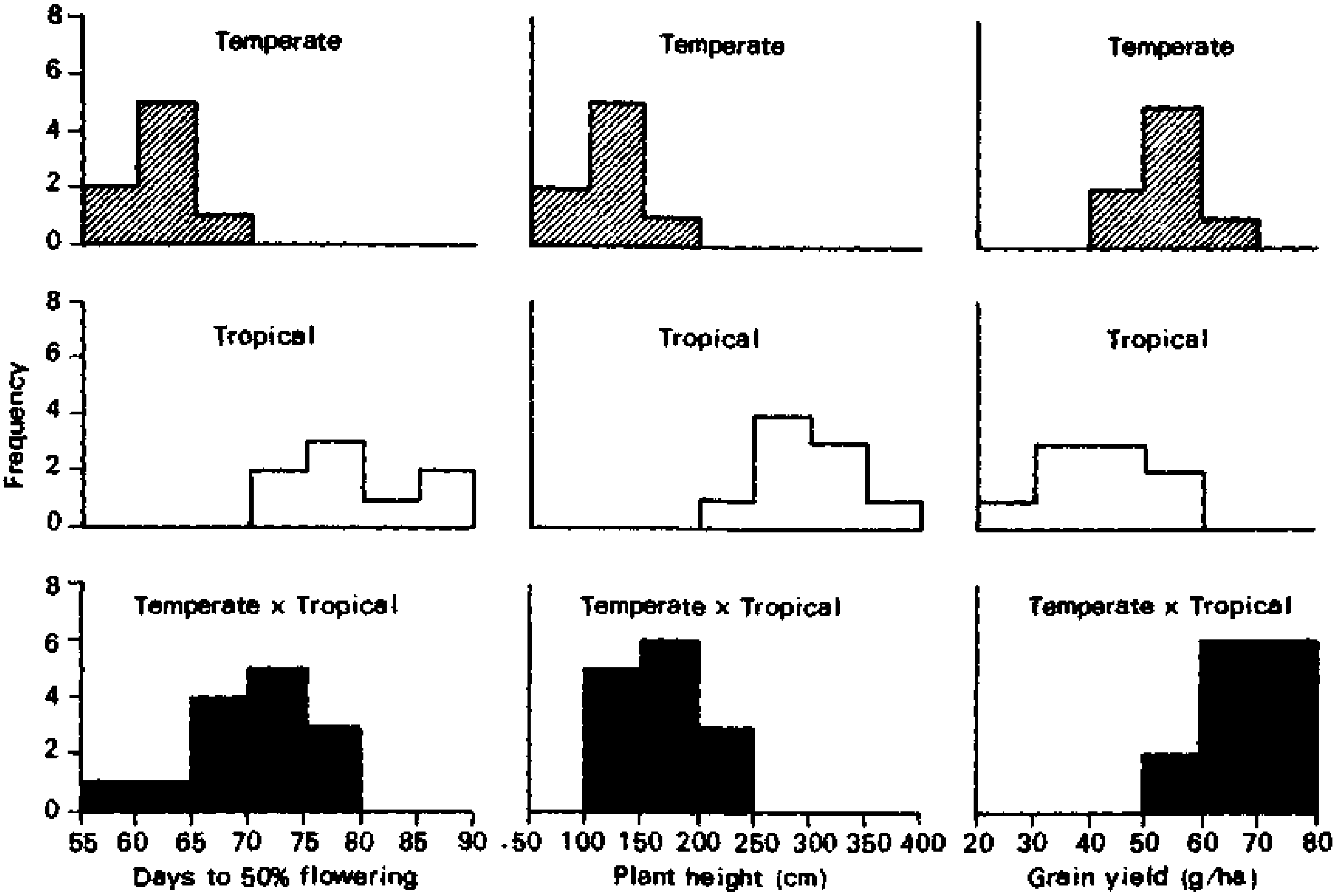

Figure 7. Days to flower, plant height, and grain yield characteristics of temperate, tropical, and temperate x tropical derivatives.

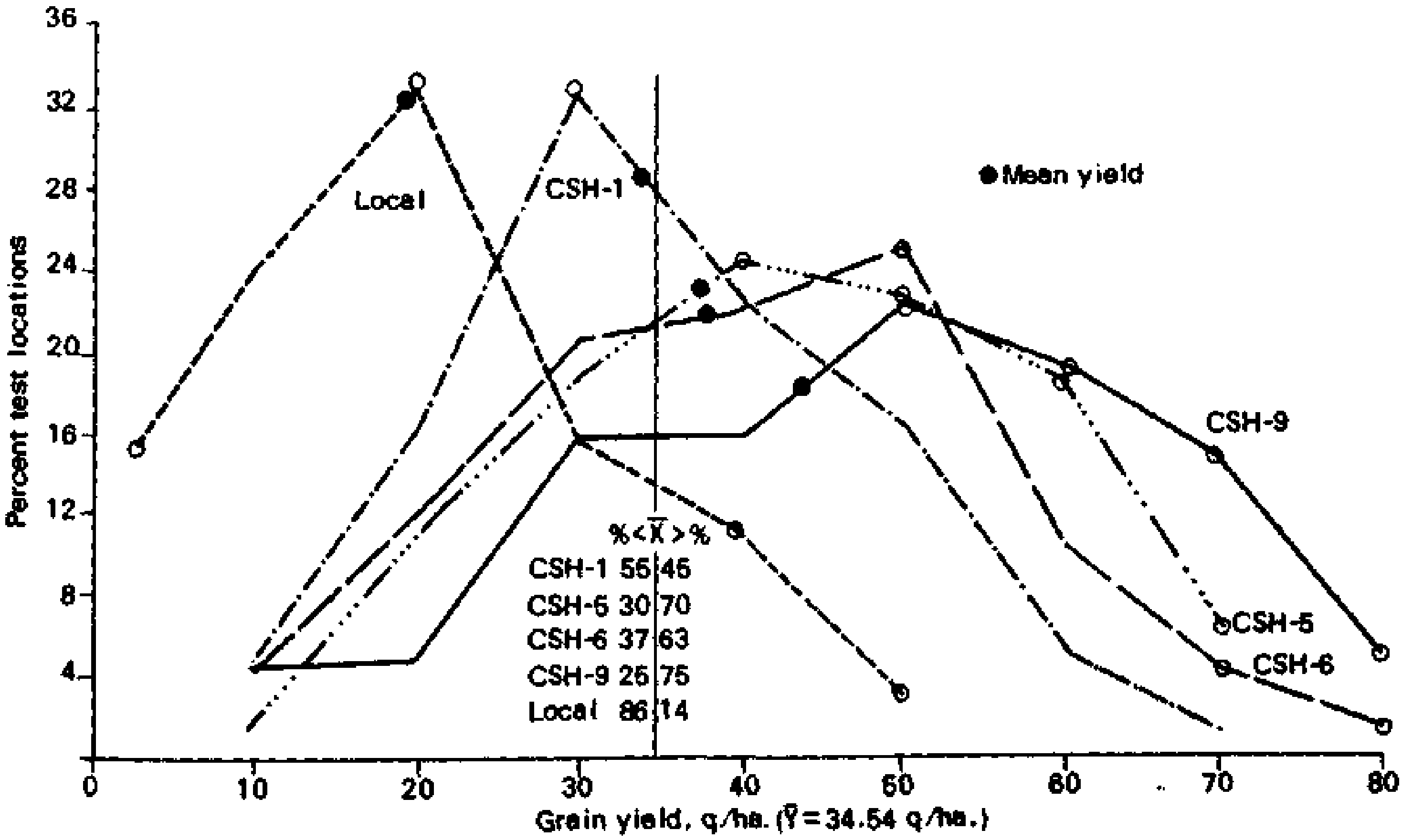

Figure 8. Yield performance of hybrids over 63 to 100 locations (Kharif 1978-1980).

pockets limited by eco-geographical and agroclimatic considerations. The development and release of new hybrids and varieties of sorghum, less sensitive to photoperiod. have resulted in cutting across traditional barriers (Rana et al. 1971). Their adaptability over vast areas covering almost the entire *kharif* (monsoon) sorghum tract of the country (Fig. 8) covering low and high rainfall areas, has been established (Rao 1970a; Rao et al. 1975; Rao et al. 1981). They have performed well in several other countries as well. The genotype x year interaction is low and with the multilocational testing mechanism spread all over the country, the superiority of a genotype could now be established in a single year's testing. All India releases which could not be conceived earlier are today fait accompli. While the homeostatic advantages of hybrids are more pronounced (Rao and Harinarayana 1968; Singhania and Rao 1976a. b; Rao et al. 1981). efforts to bridge this gap between hybrids and varieties are currently in progress (Balarami Reddy and Rao 1981). A more detailed consideration of adaptation of sorghums in relation to soil and climatic considerations has been discussed in the paper "Transforming Traditional Sorghums in India" (Rao 1982), in this symposium.

Consequent to the changes in the genetic background, adaptational problems in relation to pest and disease occurrence need particular consideration in selecting new genotypes.

"Temperate" sorghums, when introduced into tropics, tend to exhibit greater susceptibility than "tropical" types to shoot fly *(Atherigona varia soccata* Rond.) and stem borers, while midge incidence is generally similar in the two groups. A comprehensive account of insect resistance in sorghum covering sources and mechanisms of resistance and breeding aspects has been presented by us earlier (Rao et al. 1977). Sources of resistance to shoot fly and stalk borers *(Chilo partellus, Busseola fusca* and *Sesamia inferens) are* mostly of tropical origin (Rao and Rana 1978). Several of the sources also exhibit resistance to both shoot fly and stem borer, and it has been possible to combine tolerance to both pests in some of the derivatives from "temperate-tropical" crosses. Nonpreference is the primary mechanism of resistance to shoot fly, stem borer and midge although some evidence of antibiosis is available. The genetic basis of nonpreference, particularly, with shoot fly has been analyzed in detail and a breeding methodology outlined (Rao

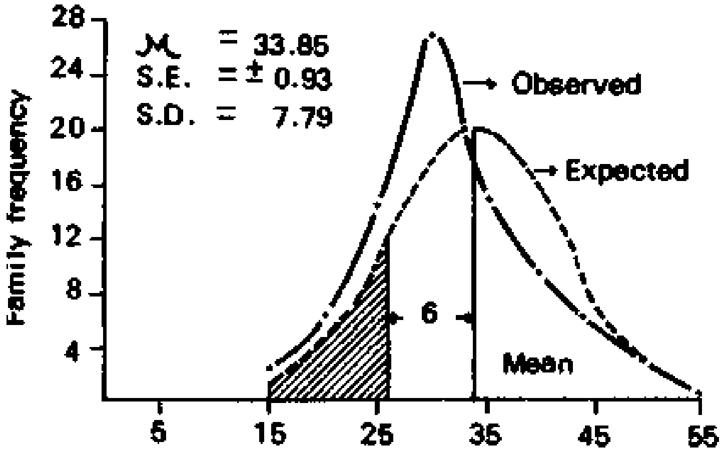

Figure 9. *Frequency distribution of F3 families for shoot fly damage, shaded portion indicating the area where selection for shoot fly resistance is effective.*

et al. 1974; Balakotaiah et al. 1975; Rana et al. 1975; Sharma et al. 1977; Singh et al. 1978). Inheritance of shoot fly resistance is quantitative (Fig. 9) and recent selections are intermediate in their reaction to shoot fly. Efforts are in progress to incorporate higher levels of resistance. Recent selections also exhibit higher levels of resistance to stem borers compared with their temperate progenitors. Resistance to midge is available from both tropical and temperate sources and some of the midge resistant lines like IS 12660C and IS 2508C reported from USA are from the conversion program. Earhead bugs are common in several parts of Africa and India, and there is some evidence that resistance to midge and head bugs could be incorporated simultaneously. Present emphasis is on incorporating resistance to several of the common pests of tropical sorghums in potential lines of agronomic worth being derived from the "temperate-tropical" crosses.

Compared with insect resistance, incorporation of resistance to major sorghum diseases has resulted in greater success (Rao et al. 1978). Consequent to the development of early maturing cultivars, the probability of such sorghums being caught in late October rains during some years does exist and breeding for resistance to grain deterioration in early maturing types assumes importance. The total process of grain deterioration, including the physical and fungal aspects, received our attention (Rana et al. 1777; 1978). Sources of resistance have been identified, the genetic basis of resistance and selection criteria have been established and agronomically desirable hybrids and varieties with satisfactory levels of resistance to grain deterioration have been released. The hybrids CSH-5, CSH-6 and CSH-9, and CSV4, CSV5, SPV126 and SPV245 among varieties are some such examples. Several male steriles like 2219A, 2077A, 323A, and male parents like CSV4(CS 3541), CSV 5(148/168) and several of the released hybrids and varieties have high levels of resistance to downy mildew.

The genetic basis of downy mildew resistance has been established (Rana et al. 1982). Several released hybrids and varieties also combine resistance to leaf spots and rust (Rana et al. 1976). Resistance to charcoai rot is presently receiving increased attention. Current emphasis is on incorporation of multiple resistance in agronomically desirable backgrounds and commercial varieties and hybrids (Rao et al. 1978).

There has been progress in identifying sources of resistance to the Asiatic and African species of *Striga.* The cultivar N13 of Nandyal in Andhra Pradesh, in particular, exhibited resistance to both *S. asiatica* and S. *hermonthica. Striga* resistance also seems to come from tropical sources and several progenies derived from crosses between groups are presently under evaluation.

From the point of view of adaptation to insect pests and diseases in the tropics, shoot fly, stem borer, midge and head bugs among insect pests, grain deterioration, downy mildew, grey leaf spot *(Cercospora sorghi)* and sooty stripe *{Ramulispora sorght)* among diseases, and the two species of *Striga* need particular attention in selecting altered genotypes of sorghum with wide adaptation. On present evidence, it is not difficult to incorporate satisfactory levels of resistance to these pests and diseases in cultivars of commercial value.

Food habits and various food preparations of sorghum across the tropics at first sight seem to impose limitations on acceptability of new genotypes. Recent studies from ICRISAT reveal that hybrids like CSH-5 and the M35-1 variety satisfy the culinary requirements of a range of food preparations in Asia and Africa. As such, food preferences need not present adaptability barriers in developing newer genotypes of wide adaptability.

Thus, selection for adaptation involves the agricultural system in its entirety. In our efforts to transform the traditional subsistence system to a more productive and stable alternative, genotype alterations through "tropical-temperate" crosses have played a major role and furnished the very basis of such a change (Rao 1981a). Adaptation,

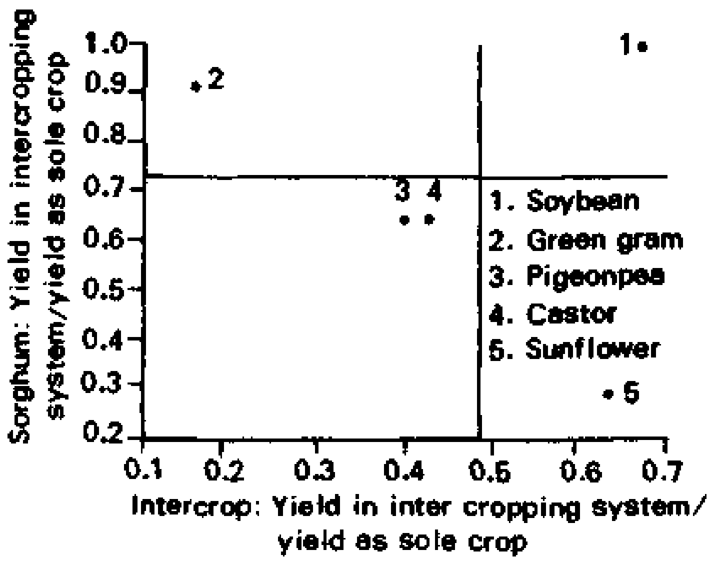

Figure 10. Species competition in sorghum-based intercropping systems.

therefore, involves not only higher levels of yield and stability accomplished through genotypic changes for dry matter production and distribution, duration, growth rhythms, insect and disease resistance, food preference, etc., but also adaptation to a new agricultural system involving changes in agronomic practices and cropping systems (Fig. 10). Response to improved populations, fertilizer use, suitability to sole-, inter-, and multiple-cropping systems (Table 9) and ratoonability—all formed part of the selection process. Its success in enhancing stability, productivity and profitability in sole-, inter- and multiple-cropping systems have been illustrated (Tarhalkar and Rao 1974; Rao and Rana 1980; Raoetal. 1979). While plant breeding in the past was oriented towards changing agronomy, it is the altered genotypes that ushered in changes in agronomic practices and cropping systems in recent years.

Outlook

"Temperate-tropical" crosses of sorghum provided the major means of genotype alteration in the seventies. Their contribution towards the movement from the climate-vulnerable subsistence farming of narrow adaptation to a more stable and productive alternative of wider adaptation, particularly in the Indian subcontinent, is a significant event. It involved a significant conceptual change. In depth research of a basic nature during the eighties should open up new vistas in sorghum improvement. Manipulation of diverse

Table 9. StabilKy parameters for total yield (kg/ha) in intarcropping systams.

	Sorghum				Groundnut		
IS	X	b_i	σ^2_{d}	IS	X	b_i	σ^2_{d}
S + P	5685	092	NS	G + S	3877	2.11**	
S + C	3957	1.00	NS	G + P	2315	0.89	NS
S + G	5053	0.99	NS	G + C	1654	0.51**	*
S + SB	5553	1.03	NS	G + SB	1734	0.49**	ft*
Mean	5358				2395		
S.E.	61.9				31.1	0.11	

* Significant at 5%; ** Significant at 1%; NS = Not significant
S = Sorghum, P = pigeonpea, C = castor, G = groundnut, SB = soybean
IS = Intercropping system.

cytoplasmic sources, apomixis, nutritional quality, metabolic efficiency, multiple resistance to insect pests, diseases and *Striga* should reinforce the foundations laid during the seventies. *Rabi* sorghum improvement in India, for which better guidelines are presently available, will be a priority item during the eighties.

While genotype alteration will continue to provide the focus, genotype adaptation to African agricultural systems might provide for a conceptual change and transformation of traditional African sorghums. Unique performance and wide adaptability are not uncorrected; they are in fact closely correlated. Improvements based on "temperate-tropical" crosses already accomplished will have value for countries in Africa. Traditional African agricultural systems with inherent relay plantings, wide spacings and late cultivars offer unlimited opportunities for system manipulation towards better utilization of the natural resources. Only altered genotypes could open up new opportunities (Rao 1981a). Together with local breeding efforts, adaptation of altered genotypes to African agricultural systems should furnish the major event for sorghums in Africa during the eighties.

The fascinating breeding system in sorghum ranging all the way from complete self-pollination to total outcrossing with known mechanisms of cliestogamy, genetic and cytoplasmic-genetic male sterility, self-incompatibility, cross sterility, apomixis, etc., has several secrets that are yet to be unraveled.

References

ANANTHARAMAN, P. V., ACHUTA RAO, K., KANDILIKAR, S. S., and RAO, N. G. P. 1978. Genetic analysis of some exotic x Indian crosses in sorghum, xix: Patterns of dry matter accumulation. Indian Journal of Genetics and Plant Breeding 38:333-338.

BALAKOTAIAH, K., RANA, B. S., TRIPATHI, D. P., and RAO, N. G. P. 1975. Genetic analysis of some exotic x Indian crosses in sorghum, x: Inheritance of resistance to sorghum shoot fly. Indian Journal of Genetics and Plant Breeding 35:344-349

BALARAMI REDDI, B., and RAO, N. G. P. 1982. Genetic analysis of some exotic x Indian crosses in sorghum, xxvii: Bridging the gap between hybrid and varietal performance. Indian Journal of Genetics and Plant Breeding 42:64-69.

BALARAMI REDOY, B., VASUDEVA RAO, M. J., RANA, B. S., JAYA MOHAN RAO, V., and RAO, N. G. P. 1981. Genetic analysis of some exotic x Indian crosses in sorghum, xxiv: Internodal patterns and their significance in sorghum breeding. Indian Journal of Genetics and Plant Breeding 41 :409-413.

BARAH, B. C. BINSWANGER, H. P., RANA, B. S., and RAO, N. G. P. 1981. The use of risk aversion in plant breeding: Concept and application. Euphytica 30:451-458.

Bos, I. 1977 More arguments against intermating F2 plants of self pollinating crops. Euphytica 26:33-46.

DAMODAR, R„ SUBBA RAO, I. V., and RAO, N. G. *P.* 1978a. Genetic analysis of some exotic x Indian crosses in sorghum, xx: Genotypic differences for root activity. Indian Journal of Genetics and Plant Breeding 38:421 -430.

DAMODAR, R., SUBBA RAO, I. V.. and RAO, N. G. P. 1978b. Heterosis for root activity in grain sorghum. Indian Journal of Genetics and Plant Breeding 38:431-436.

GOLDSWORTHY, P. R. 1970. The growth and yield of tall and short sorghums in Nigeria. Journal of Agricultural Science. Cambridge 75:109-122.

HARINARAYANA, G., RAO, N. G. P., and VENKATRAMAN, R. 1971. Genetic analysis of some exotic x Indian crosses in sorghum, iv: Chi-square analysis of association between yield, maturity and plant height in F2 generation. Indian Journal of Genetics and Plant Breeding 31 :442-450.

JAYA MOHAN RAO, V. 1980. Genetic analysis of nutritional quality in grain sorghum. Ph. D. Thesis, Osmania University. Hyderabad, India.

JAYA MOHAN RAO, V., BALARAMI REDDY, R., EKLADIAUS, K. G., RANA, B. S., and RAO, N. G. P. 1982. Genetic analysis of some exotic x Indian crosses in sorghum, xxiv: Basis for further improvement of parental lines. Indian Journal of Genetics and Plant Breeding 42 : 60 -63.

KANG, G. S. 1969. M. Sc. Thesis, IARI, New Delhi.

MISHRA, S. P., and RAO, N G. P. 1980a Genetic analysis of some exotic x Indian crosses in sorghum, xxi: Early test cross procedures for selection of superior parents. Indian Journal of Genetics and Plant Breeding. 40:

MISHRA, S. P., and RAO, N. G. P. 1980b. Implications of parental selection procedures on hybrid performance and adaptability. Indian Journal of Genetics and Plant Breeding 40.414-422.

MISHRA, S. P., SINHA, S. K., and RAO, N. G. P. 1981 a. Genetic analysis of nitrate reductase activity in relation to yield heterosis in sorghum. Zeitichrift fur Pflanzenzuchtung.

MISHRA, S. P., SINHA, S. K., and RAO, N. G. P. 1981b. Heterosis and combining ability for amylase activity in germinating seeds of sorghum. Zeitichrift fur pflanzengucht ung.

MURTY, U. R., RAO, N. G. P., KIRTI, P. B., and BHARATHI, M. 1980. The present status of apomixis knowledge in grain sorghum. Sorghum Newsletter 23:108-109.

NANDA, G. S., and RAO, N. G. P. 1975. Genetic analysis of some exotic x Indian crosses in sorghum, ix: Nutritional quality and its association with yield. Indian Journal of Genetics and Plant Breeding 35:131-135.

QUINBY, J R. 1968. Opportunities for sorghum improvement. *In* Proceedings, 23rd Corn and Sorghum Improvement Conference, Chicago, USA.

RAMACHANDRAN. M.. and RAO, N. G. P. 1973. Varietal differences and nutrient response in sorghum. Indian Journal of Genetics and Plant Breeding 34A:1016 -1024.

RANA, B. S., BALAKOTAIAH, K.. TRIPATHI, D. P., and RAO. N. G. P. 1971. Adaptability of grain sorghum hybrids and varieties in India. Pages 528-535 *in* Sorghum in seventies, eds. N G. P. Rao and L. R. House. New Delhi, India: Oxfosd and IBH Poblishing Co.

RANA, B. S., TRIPATHI, D. P. BALAKOTAIAH, K., and RAO, N. G. P. 1974. Genetic analysis of some exotic x Indian crosses in sorghum, vii: Evaluation of derived lines as male parents. Indian Journal of Genetics and Plant Breeding 34:128-132.

RANA, B. S., TRIPATHI, D. P., BALAKOTAIAH, K., DAMODAR. R.. and RAO. N G. P. 1975. Genetic analysis of some exotic x Indian crosses in sorghum, xi: Selection for shoot fly resistance. Indian Journal of Genetics and Plant Breeding 35:350-355

RANA, B. S., TRIPATHI, D. P.. and RAO, N. G. P. 1976. Genetic analysis of some exotic x Indian crosses in sorghum, xv: Inheritance of resistance to sorghum rust. Indian Journal of Genetics and Plant Breeding 36:244-249

RANA, B. S., JAYA MOHAN RAO. V., TRIPATHI. D. P., and RAO, N G. P. 1977 Genetic analysis of some exotic x Indian crosses in sorghum xvii: Selection criterion for resistance to grain deterioration. Indian Journal of Genetics and Plant Breeding 37:480-487.

RANA, B. S JAYA MOHAN RAO, V., and RAO, N. G. P. 1978. Genetic analysis of some exotic x Indian crosses in sorghum, xviii: Breeding for resistance to grain deterioration. Indian Journal of Genetics and Plant Breeding 38:322-332.

RANA, B. S.. ANAHOSUR.K. H., VASUDEVARAO, M. J.. JAYA MOHAN RAO, V., PARAMESWARAPPA, B., and RAO, N. G. P. 1982. Genetic analysis of some exotic x Indian crosses in sorghum, xxviii: Inheritance of field resistance to sorghum downy mildew. Indian Journal of Genetics and Plant Breeding 42: 70-74.

RAO, N. G. P. 1962. Occurrence of cytoplasmic-genetic male sterility in some Indian sorghums. Indian Journal of Genetics and Plant Breeding 22:257-259.

RAO, N. G. P. 1970a. Genotype x environment interactions in grain sorghum hybrids. Indian Journal of Genetics and Plant Breeding 30.75-80

RAO, N. G. P. 1970b. Genetic analysis of some exotic x Indian crosses in sorghum. I. Heterosis and its interaction with seasons. Indian Journal of Genetics and Plant Breeding 30:347-361.

RAO, N. G. P. 1970c. Genetic analysis of some exotic x Indian crosses in sorghum. II. Combining ability and components of genetic variation. Indian Journal of Genetics and Plant Breeding 30:362-376.

RAO, N. G. P. 1972a. Five years of sorghum breeding. Journal of Scientific and Industrial Research 31 :498 -509.

RAO. N. G. P. 1972b. Sorghum breeding in India: Recent developments. Pages 101-142 in Sorghum in seventies, eds. N. G. P. Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co.

RAO, N. G. P. 1979. Technological basis and components of sorghum production programmes. Indian Farming 29:19-21.

RAO, N. G. P. 1980. New technology for higher sorghum production. Indian Farming 30:31-35.

RAO. N. G. P. 1981a. West African agricultural systems and sorghum improvement. ICRISAT/OAU/JP31 SAFGRAD Report.

RAO, N. G. P. 1981b. Genotype alteration: The basis for agricultural transformation in tropical dry lands. Presidential address, Indian Society of Genetics and Plant Breeding, IARI, New Delhi.

RAO, N. G. P. 1982. Transforming traditional sorghums in India. These Proceedings: ICRISAT.

RAO. N. G. P., and HARINARAYANA, G. 1968. Phenotypic stability of hybrids and varieties in grain sorghum. Current Science 38:97-98.

RAO. N. G. P., and MURTHY, B. R. 1970. Components of heterosis in two sorghum hybrids. Indian Journal of Genetics and Plant Breeding 30:230-236.

RAO, N. G. P., and NARAYANA. L. L. 1968. Apomixis in grain sorghums. Indian Journal of Genetics and Plant Breeding 28:121-127.

RAO. N. G. P., and RANA. B. S. 1978. Characterization of tropical and temperate sorghums and their utilization. *In* Proceedings. National Symposium on Plant and Animal Genetic Resources. Indian Agricultural Research Institute, New Delhi.

RAO. N. G. P., and RANA. B. S. 1980. Sorghum based cropping systems to meet shortages of pulses and oil seeds in India. Current Science 49:622-626.

RAO, N. G. P., and VENKATESWARLU, J. 1971. Genetic analysis of some exotic x Indian crosses in sorghum. III: Heterosis in relation to dry matter production and nutrient uptake. Indian Journal of Genetics and Plant Breeding 31 :156-176.

RAO, N. G. P., HARINARAYANA, G., ARUNACHALAM, V., TRIPATHI, D. P., and BALAKOTAIAH. K. 1973. Genetic analysis of some exotic x Indian crosses in sorghum. VI: Character associations under selection. Indian Journal of Genetics and Plant Breeding 33:1 -6.

RAO, N. G. P., RANA, B. S., BALAKOTAIAH, K., TRIPATHI, D. P., and FAYED, M. F. S. 1974. Genetic analysis of some exotic x Indian crosses in sorghum, viii: F1 analysis of ovipositional nonpreference underlying resistance to sorghum shoot fly. Indian Journal of Genetics and Plant Breeding 34:122-127.

RAO, N. G. P., RANA, B. S.. and JOTWANI, M. G. 1977. Host plant resistance to major insect pests of sorghum. Pages 63-79 *in* Proceedings, FAO-IAEA (International Atomic Energy Agency) Advisory Group Meeting, Dakar, Senegal.

RAO, N. G. P., RANA, B. S., and TARHALKAR, P. P. 1979. Stability, productivity and profitability of some inter cropping systems in dry land agriculture. Pages 292 -298 *in* Proceedings, International Intercropping Workshop, ICRISAT, 10-13 Jan, Hyderabad, India. Patancheru, A.P., India: ICRISAT.

RAO, N. G. P.. RANA, B. S., JAYA MOHAN RAO. V., and BALARAMI REDDY, B. 1982. Genetic analysis of some exotic x Indian crosses in sorghum, xxv: Development of new hybrids and varieties and their performance. Indian Journal of Genetics and Plant Breeding 42 :213 -219.

RAO, N. G. P., RANA, V. K. S.. and TRIPATHI, D. P. 1968. Line x tester analysis of combining ability in sorghum. Indian Journal of Genetics and Plant Breeding 28:231 -238.

RAO. N. G. P., SUBBA RAO, S., and VIDYASAGAR RAO, K. 1975. Rainfall fluctuations and crop yields. Current Science 44:694-697.

RAO, N. G. P.. TRIPATHI. D. P., and RANA. V. K. S. 1970. Induced mutations in sorghum. Sorghum Newsletter 13:46-48.

RAO. N. G. P., VASUOEVARAO, M. J., RANA, B. S., and JAVA MOHAN RAO, V. 1979. Response to water availability and modifications for water use efficiency in tropical dry land sorghums. *In* Proceedings. Symposium on Responses to Water Availability, Water Technology Centre, Indian Agricultural Research Institute, New Delhi.

RAO, N. G. P., VIDYABHUSHANAM, R. V., RANA, B. S„ and JAYA MOHAN RAO, V. 1978. Breeding sorghums for disease resistance in India. Pages 430-433 *in* Proceedings, International Workshop on Sorghum Diseases. ICRISAT, 11-15 Dec, ICRISAT, Hyderabad, India. Patancheru, A.P., India: ICRISAT.

SCHERTZ, K.F. 1977. Registration of A2 Tx 2753 and BTx 2753 sorghum germplasm. Crop Science 17:983.

SESHAGIRI RAO, A. 1979. Evaluation of different mating systems in *Sorghum bicolor* L. Moench. M. Sc. Thesis, A. P. Agricultural University, Hyderabad, India.

SHARMA, G. C, JOTWANI, M. G., RANA, B. S., and RAO, N. G. P. 1977. Resistance to the sorghum shoot fly and its analysis. Journal of Entomological Research 1:1-8.

SINGH, S. P., JOTWANI, M. G., RANA, B. S., and RAO. N. G. P. 1978. Stability of host plant resistance to sorghum shoot fly. Indian Journal of Entomology 40:370-383.

SINGHANIA, D. L. and RAO, N. G. P. 1975. Genetic analysis of some exotic x Indian crosses in sorghum, xii: Line performance in relation to heterosis. Indian Journal of Genetics and Plant Breeding 35:387-90.

SINGHANIA, D. L, and RAO, N. G. P. 1976a. Genetic analysis of some exotic x Indian crosses in sorghum, xiii: Environmental components of variability for grain yield for hybrids and their parents. Indian Journal of Genetics and Plant Breeding 36:111-117.

SINGHANIA, D. L. and RAO, N. G. P. 1976b. Genetic analysis of some exotic x Indian crosses in sorghum xiv: Stability of hybrids and their parents. Indian Journal of Genetics and Plant Breeding 36:118-124.

SNEEP, J. 1977. Selection for yield in early generation of self fertilizing crops. Euphytica 26:27-30.

SUBBA REDDY, B. V., and RAO, N. G. P. 1971. Genetic analysis of some exotic Indian crosses in sorghum, v. Character association and response to selection in advanced generation progenies. Indian Journal of Genetics and Plant Breeding 31 :510-520.

TARHALKAR. P. P.. and RAO. N. G. P. 1974. Changing concepts and practices of cropping systems. Indian Farming 25:3-7. and 15.

TRIPATHI, D. P. 1979. Characterization of diverse cytoplasmic-genetic male steriles in sorghum. Ph.D. Thesis, Indian Agricultural Research Institute, New Delhi.

TRIPATHI, D. P., MEHTA, S. L. and RAO, N. G. P. 1981a. Aminoacids in anthers of milo and Indian origin cytoplasmic-genetic male sterile sorghums. Theoretical and Applied Genetics 59:113-116.

TRIPATHI, D. P., MEHTA. S. L. and RAO, N. G. P. 1981b. Soluble protein and isoenzymes from anthers of diverse male steriles in sorghum. Indian Journal of Genetics and Plant Breeding 41 :170-177.

TRIPATHI, D. P., DONGRE. A. B., MEHTA, S. L. and RAO, N. G. P. 1981c. Soluble protein and esterase isoenzyme pattern on iso-electric focussing from seeds and anthers of diverse cytoplasmic genetic male sterile sorghums. Zeitischrigt pflanzenzuchtung.

TRIPATHI, D. P., MEHTA. S. L. NAM-PRAKASH. and RAO. N. G. P. 1981d. Characterization of diverse male sterile pollen grains by scanning electron microscopy. Indian Journal of Genetics and Plant Breeding 41 :75-81.

TRIPATHI. D. P., RANA, B. S., BALAKOTAIAH, K.. and RAO, N. G. P. 1976. Genetic analysis of some exotic x Indian crosses in sorghum, xvi: Effects of directional selection on yield and component characters. Indian Journal of Genetics and Plant Breeding 36:250-258.

VIDYASAGAR RAO, K., SUBBA RAO, S., and RAO, N. G. P. 1981. Genotype x input management inter-actions in sorghum. Indian Journal of Genetics and Plant Breeding 41 :54-58.

Population Breeding Techniques in Sorghum

Bhola Nath*

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

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

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

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

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

Development of Random-Mating Populations

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

Selection of Component Parents

Selection of suitable parents for the development

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru, A.P., India. Patancheru, A.P. India: ICRISAT.

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

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

Incorporation of Male-Sterility Genes

Because sorghum is largely a self-pollinated crop it is desirable to incorporate male-sterility genes to facilitate outcrossing. Two male-sterility genes, ms_3ms_3 and ms,ms_7, are suitable. The selected parents are individually crossed to a male-sterile stock; a suitable population segregating for male sterility is a better donor than an inbred line. The crossing could be accomplished either by hand emasculating the parental lines or by using them as males in making crosses with male-sterile plants in the segregating male-sterile stock. The F_2 generation of these crosses segregates for male-sterile plants. It is preferable to backcross the parents once or twice, depending on the agronomic superiority of the male-sterility donor stock, before intermating to develop the population. Using the parents once as females during the backcrossing is desirable to introduce cytoplasmic in addition to genetic variability.

Intercrossing and Random Mating

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

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

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

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

Improvement of Populations

The following selection methods are available to improve populations:

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

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

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

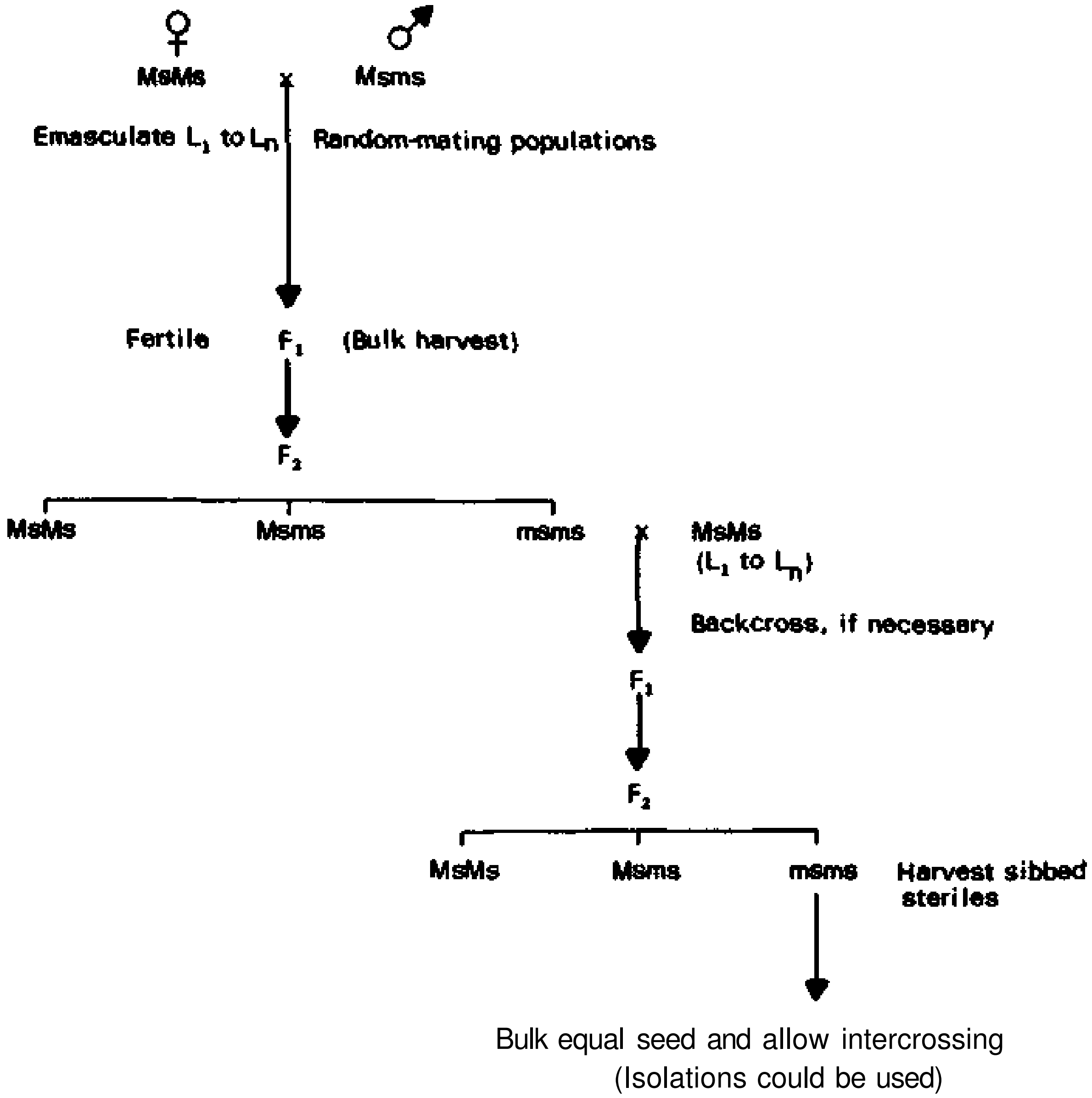


Figure 1. Incorporation of male-sterility gene and intercrossing.

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

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

Mass Selection

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

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

Half-Sib Family Selection

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

S, Family Selection

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

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

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

S_2 Progeny Selection

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

Population Improvement at ICRISAT

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

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

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

Progress from Selection

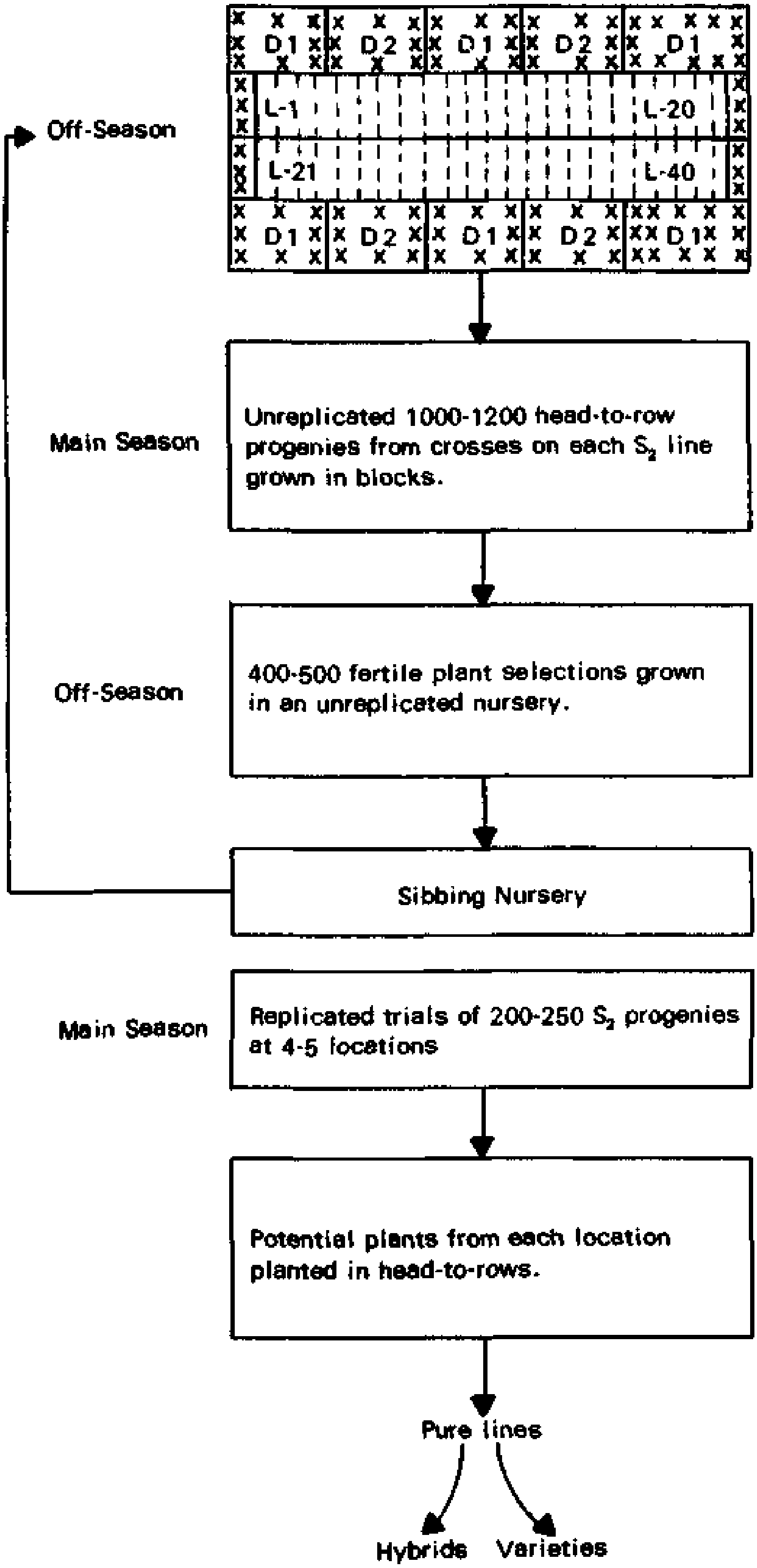
Observations show that good progress has been made towards improving the populations for agronomic desirability, grain yield, grain quality, resistance to various leaf diseases and grain molds, and to some degree for resistance to shoot fly and charcoal rot, although the progress for all characters has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

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

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

Table 1. Populations under recurrent selection at ICRISAT.

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



RECOMBINATION GENERATION

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

HALF-SIB PROGENY SELECTION

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

S_1 PROGENY SELECTION

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

S_2 PROGENY TESTING

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

Where:

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

S_2 progeny bulk

Individual S_2 lines.

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

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

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

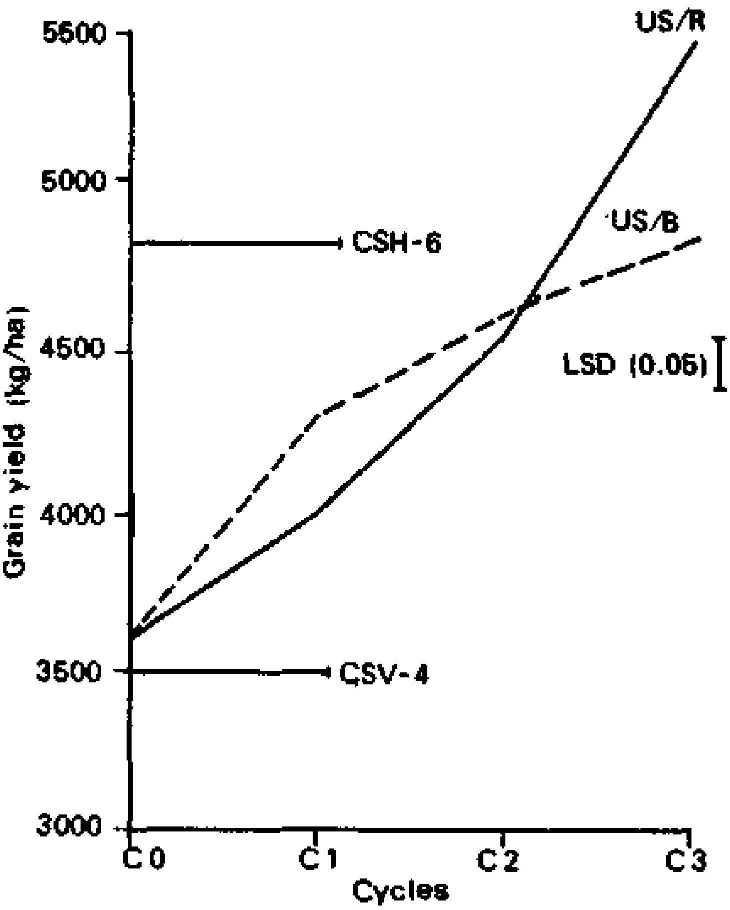


Figure 3. Grain yield performance of different cycles in the two populations (US/R and US/B). a released hybrid (CSH-6). and variety (CSV-4).

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

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

Simultaneous Selection

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

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

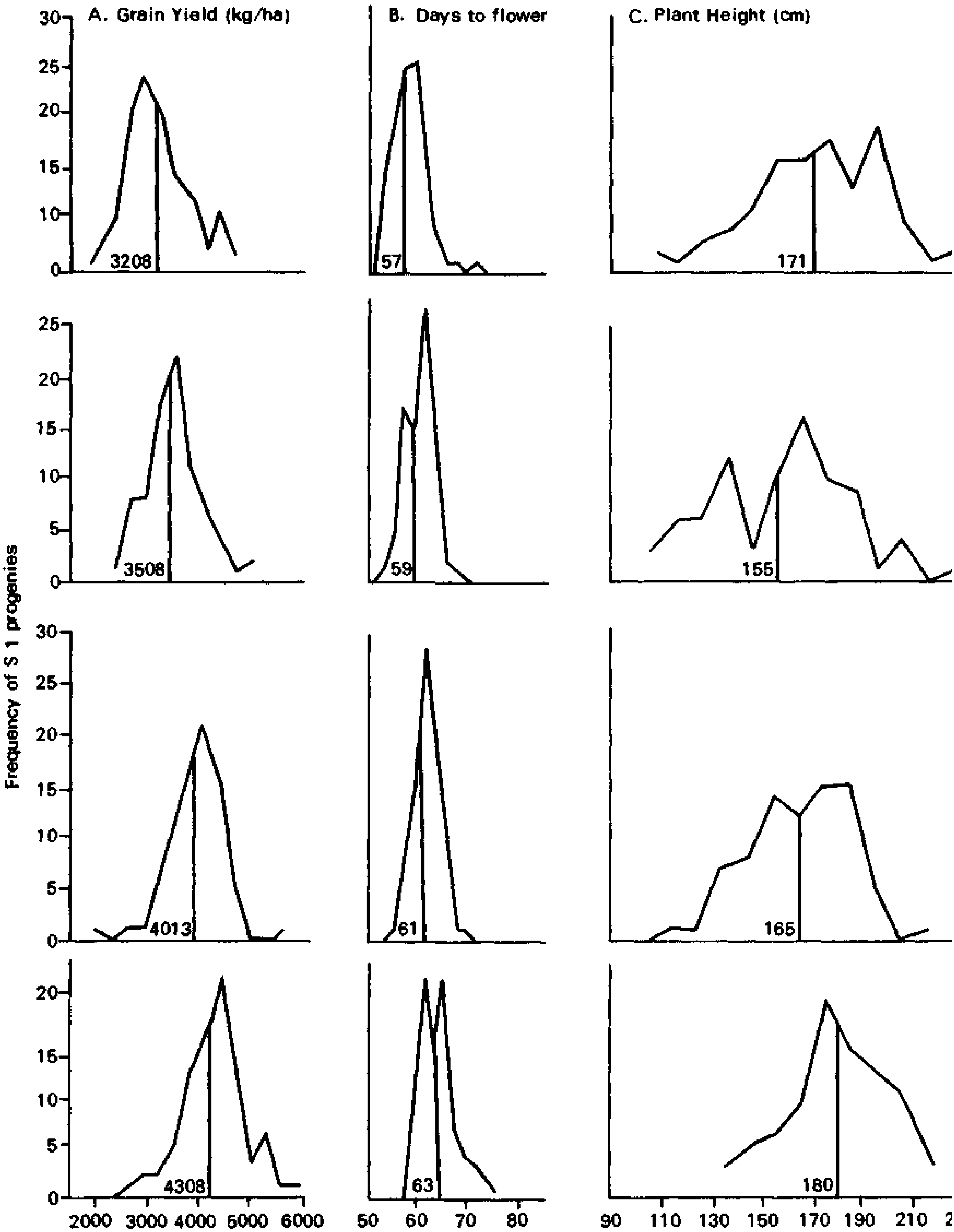


Figure 4. Frequency distribution of S, progenies in different cycles of the US/B population for three agronomic traits.

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

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

Extraction of Superior Lines from Populations and Their Utilization

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

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

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

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

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

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

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

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

Incorporation of Additional Traits into Populations

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

An alternate system used for the incorporation of additional germplasm in populations at ICRISAT is presented in Figure 5. The crossing is accomplished at two levels: (1) crossing new germplasm to promising derivatives from populations and (2) crossing them to populations during recombination. Population-derived lines may be used as female parents to make use of possible male-sterile plants. On the other hand, populations are most conveniently used as male parents using bulk pollen. The F_2s from both types of crosses are screened for the trait(s) of concern and confirmed in F_3 progenies. The F_1 families can simultaneously be evaluated along with S_2 lines of the population for agronomic traits. Depending upon the performance of lines, a decision is taken to incorporate the F_3 progenies during the next recombination cycle of the population or to backcross with the population and repeat the process. The system takes advantage of the male sterility in population derivatives and provides opportunities to correct their defects as with traditional methods of breeding. It provides a way of introducing useful variability into populations without the risk of reducing their superiority and enhances the opportunity of recombination among useful traits. Since new variability is continuously cycled in the populations, one would expect continuing progress. It is because of this hope that we discontinued maintaining separate backup populations in the ICRISAT program.

Population vs Conventional Breeding Systems

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

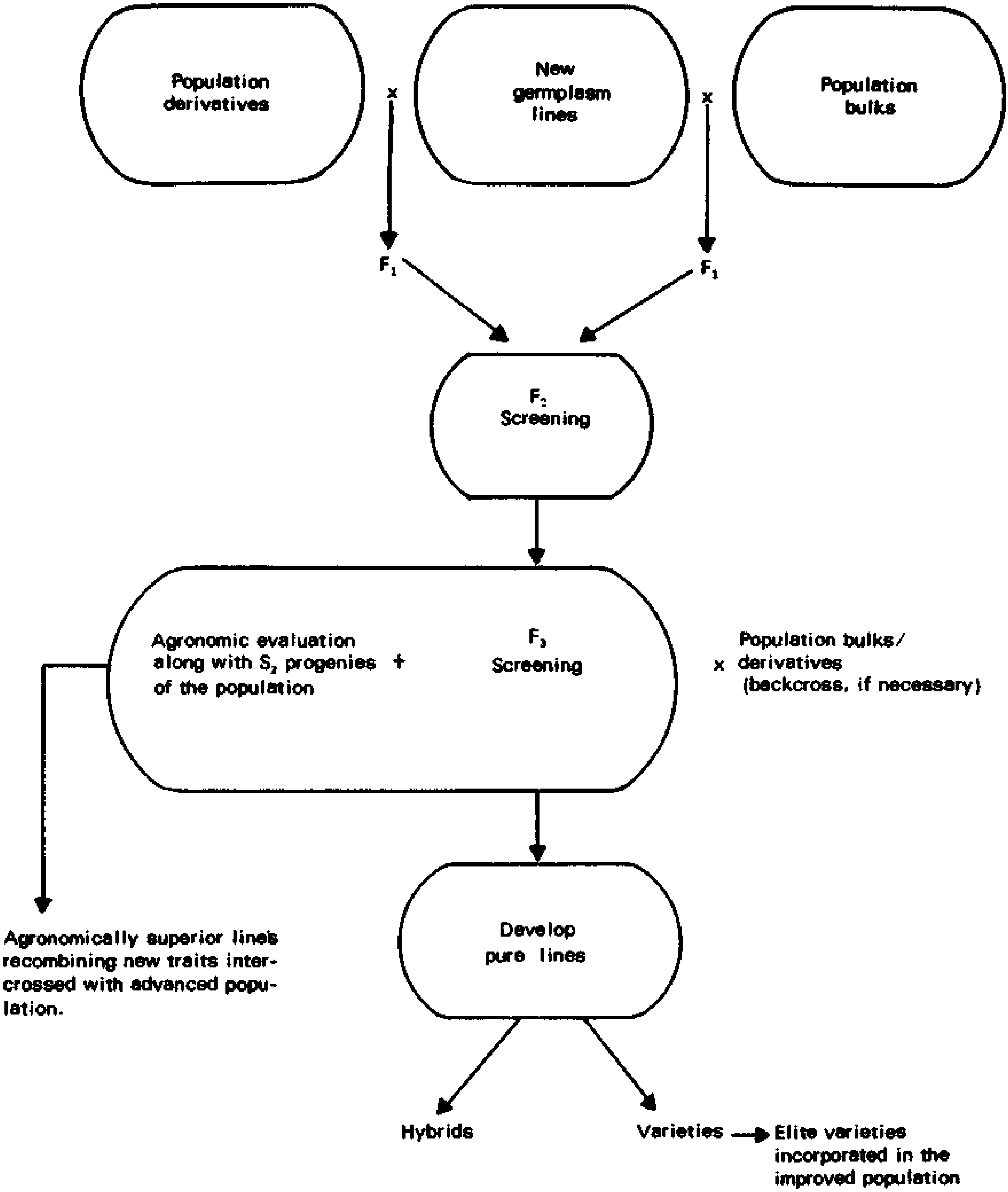


Figure 5. Incorporation of additional germplasm.

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

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

Table 4. **Comparison of population and conventional breading systems.**

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

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

Future Projections

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

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

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

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

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

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

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

References

AICSIP (All India Coordinated Sorghum Improvement Project) 1980/81 Progress Report: SB43-54.

ANDREWS, D. J., BHOLA NATH, and HARE. B W 1977 Methods of population improvement in pearl millet and sorghum. Presented at the Second FAO/SIDA Seminar on Field Crops in Africa and Near East, 18 Sept.-5 Oct, Lahore. Pakistan

ARAN PATANOTHAI. 1981. KKU-IDRC Semi Arid Crops Project Summary Report. Khon Kaen University, Thailand.

BHOLA NATH. 1977 Population breeding in sorghum. Presented at the International Sorghum Workshop, 6-12 Mar, ICRISAT. Hyderabad, India

BHOLA NATH. 1980. Relevance of population breeding to national programs in sorghum. Presented at the Annual Workshop of the All India Coordinated Sorghum Improvement Project, 11-14 May, Coimbatore, India

BHOLA NATH, and LAWRENCE. P. K. 1975. The improvement of advanced populations. Presented at the Cereals Consultants Meeting. April 1975. ICRISAT, Hyderabad, India.

DOGGETT, H. 1968. Mass selection systems for sorghum. Crop Science 8:391-392.

DOGGETT, H. 1972. The improvement of sorghum in East Africa *In* Sorghum in seventies, eds N G P. Rao and L. R. House New Delhi, India: Oxford and IBH Publishing Co.

EBERHART, S A. 1972 Techniques and methods of more efficient population improvement in sorghum. *In* Sorghum in seventies, eds. N G. P. Rao and L R. House New Delhi, India: Oxford and IBH Publishing Co.

GARDNER. C. O 1972 Development of superior populations of sorghum and their role in breeding programs. *In* Sorghum in seventies, eds. N. G. P Rao and L. R. House. New Delhi, India: Oxford and IBH Publishing Co.

HALLAUER, A. P. 1981. Selection and breeding methods. Pages 3-55 *in* Plant breeding II. ed K.J Frey Ames. Iowa, USA: Iowa State University Press.

ICRISAT. 1974. Annual Report 1973/74 Patancheru. A.P.. India: ICRISAT

ICRISAT 1978 Annual Report 1977/78. Patancheru, A.P., India: ICRISAT.

ICRISAT. 1980. Annual Report 1978/79. Patancheru, A.P.. India: ICRISAT.

ICRISAT. 1981 Annual Report 1979/1980. Patancheru, A.P.. India: ICRISAT.

JINDA JAN ORN, GARDNER, C O., and Ross. W. M. 1976. Quantitative genetic studies of the NP3R random mating grain sorghum population. Crop Science 16: 489-496.

OBILANA, A. T. 1982. Population improvement in sorghum in Nigeria. These Proceedings (Short Communications): ICRISAT.

OBILANA, A. T.. and ELROUBY, M. M. 1980. Recurrent mass selection for yield in two random mating populations of sorghum [*Sorghum bicolor* (L.) Moench]. Maydica 25:127-133.

PRASIT. JAISIL. 1981. Effect of recurrent selection in two sorghum populations. M. Sc. thesis, APAU, Rajendranagar, Hyderabad, A.P., India.

Ross. W. M. 1976. Quantitative characters of five *Sorghum bicolor* (L.) Moench random mating populations. Maydica 21 :177-186.

Ross, W. *M..* GARDNER. C. O.. and NORDQUIST, P. T. 1971. Population breeding in sorghum. Pages 93-98 *in* Proceedings. Grain Sorghum Research and Utilization Conference, Lubbock. Texas, USA.

Ross. W. M., and NORDQUIST, R. T. (In press). Yield and yield stability of seven sorghum random mating populations. Sorghum Newsletter 23.

Breeding for Pest Resistance in Sorghum

B. L. Agrawal and L. R. House*

In view of potential economic and environmental constraints of insecticide use, breeding of crop varieties with resistance to harmful insects is a promising method of insect control. Such sorghum varieties offer the most effective way of controlling pests, particularly in areas where technological knowhow and resources are limited.

Major Insect Pests of Sorghum

Although nearly 100 insect species have been recorded as pests of sorghum in the semi-arid tropics, stem borer, midge, shoot fly and earhead bugs are the most widespread and devastating (Table 1). Sorghum shoot fly *{Atherigona varia soccata)* is prevalent in South and South East Asia, the Middle East, Mediterranean Europe and Africa. Among the stem borers, *Chilo partellus* and *Sesamia inferans* are distributed in the Indian Subcontinent, South East Asia, and East and West Africa; *Sesamia critica* in East, North East and Mediterranean Europe except France and the Iberian Peninsula; *Busseola fusca.Eldana saccharina, Acigna ignefusalis* and *S. calamistis* in the African continent and *Diatreae saccharalis* and *D. grandeosella* in the Americas (Seshu Reddy, personal communication). Sorghum midge *{Contarinia sorghicola* Coq.) is almost a universally distributed pest. Among earhead bugs, *Calocoris angustatus* is a serious pest in South India and *Agnoscalis* species in the Sudan; several other species of bugs and earhead caterpillars have been reported from various parts of India and Africa. The nymphs and adults of the sucking chinch bug *(Blissus leucopterus)* are widely distributed in the U.S., Canada, Mexico, and Latin America and attack sorghum during all stages of growth (Rao et al. 1977).

These major insect pests will be used in this paper to illustrate concepts of breeding for resistance. It is recognized that these priorities might change with time.

Table 1. Distribution of different insect species.

Shoot Fly	
Atherigona varia soccata	South and South-East Asia; Middle East; Mediterranean Europe; and Africa
Stem Borers	
Chilo partellus, and Sesamia inferans	Indian Subcontinent; S E Asia; East and West Africa
S critica	East. North-East and Mediterranean Europe, except France and Iberian Peninsula.
Busseola fusca. Eldana saccharma. Acigna ignefusalis and S. *calamistis*	African Continent
Diatreae saccharalis and *D grandeosella*	Americas
Midge	
Contarinia sorghicola	Almost universal
Earhead Bugs	
Calocoris angustatus	S. India
Agnoscalis species	Sudan
Chinch Bug *(Blissus leucopterus)*	USA, Canada, Mexico, and Latin America.

* Plant Breeder; and Principal Plant Breeder and Leader, respectively; sorghum Program, ICRISAT.

International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru, A.P., India. Patancheru, A.P India: ICRISAT

Breeding for Insect Resistance

Breeding is a process of changing a characteristic of a population over a number of generations by applying selection pressure on the population. The rate of success in a resistance breeding program is associated with several factors.

1. The availability of a broad germplasm base from which good, stable and diverse sources of resistance can be selected.
2. The availability of effective, efficient and reliable screening techniques. For this it is essential to have a good knowledge of the biology of the insect, the insect-host plant relationship and the insect-environment relationship.
3. If possible, knowledge of the mechanism of resistance; whether it is tolerance, preference or antibiosis.
4. Knowledge of the mode of inheritance.
5. Selection of the right breeding procedures.

In order to accomplish these goals efficiently a good interdisciplinary team approach between breeder and entomologist is essential.

Shoot Fly

The shoot fly can be a severe pest attacking sorghum in the seedling stage. Eggs are laid singly on the. lower surface of leaves. The emerging maggot migrates to the growing point, kills it (causing a deadheart), and feeds on the decaying tissue. Once plants are 30 to 40 cm tall they become resistant to this pest.

Source Material

A systematic search for over 20 years for sources of resistance, primarily by field screening of the world sorghum germplasm collection, was undertaken by the All India Coordinated Sorghum Improvement Project (AICSIP) and recently by ICRISAT. Over 10 000 germplasm lines have been screened for this pest, and 213 lines have been selected as low susceptibles. Among selected lines IS-923, IS-2195 and IS-2312 have performed well in AICSIP trials. These selected low susceptible lines belong to different taxonomic and geographic regions. Earlier, most of the shoot fly resistant sources identified were from the South India winter sorghums belonging to either Durra or Dagadi groups. Now several new sources have been identified that represent several other regions and taxonomic groups. Absolute resistance to this pest has not been found. The degree of tolerance/resistance of the source varieties varies with season, year and particularly with fly pressure. Most shoot fly resistant sources have the *glossy* expression during the seedling stage. Some of the sources have gone through mutilocation testing in countries where shoot fly is a problem and some have been found to be stable. Singh et aid978) conducted a stability study on 15 lines in six environments and noticed that most of them were consistent in their fly reaction; IS-1054, IS-5469 and IS-5490 were found to be the most stable.

The main culms of plants attacked by the fly are killed and tillers that develop subsequently may also be killed. However, some varieties produce synchronous fast-growing agronomically productive tillers that produce good yields. Such "recovery resistant" types are quite often detected in the field and are useful in overcoming field loss.

de Wet et al. (1976) indicated the possibility of transferring shoot fly resistance through introgression from *Saccharum* to *Sorghum.* Initial efforts have not been rewarding.

Screening Technique

In sorghum, though the Starks' interlards and fish meal technique was very effective in creating uniform and desired levels of shoot fly infestation, very little progress was made over the last two decades. One important reason could be that selection was made at the time of harvest when there was no effective way to identify plants with real resistance. At maturity, a large proportion of the shoot fly damaged plants recovered and looked similar to undamaged plants. At ICRISAT this practice was followed until the 1977 postrainy season and resulted in hardly any progress.

It was found necessary to score all seedlings soon after the stage of damage is over and to maintain identity until maturity. There was concern about escapes, i.e., plants that were missed by the egg-laying adult. The proportion of such plants varies with the level of infestation (Table 2). It could be assumed that the plants having no eggs are escapes, but this would eliminate oviposition nonpreference reported by Maiti and Bidinger in 1979. They found that trichomes on the abaxial surface of the leaf contribute to less egg laying. This information assisted in categorizing different mechanisms of resistance that could

Table 2. Some criteria for selecting mechanisms of resistance to shoot fly.

Egg laying	Trichomes	Resistance mechanism	No of selections made	
			77R	78K
No	No	Escapes	201 (398%)	73 (6.7%)
Yes	No	Antibiosis	123	515
No	Yes	Ovipositional nonpreference	100	106
Yes	Yes	Mechanical	79	400
Approximate proportion of nontnchomed : trichomed			40:60	50:50

be identified at the seedling stage (Table 2). Oviposition nonpreference could be identified by the lack of eggs on trichomed plants. Antibiosis occurs when eggs are laid in the absence of trichomes but no deadhearts occur. Recovery resistance refers to a situation in which the main plant is killed and the crop develops from tillers. Escapes are suspected when there are no eggs and no trichomes.

This system of identification of resistant plants in the seedling stage with selection for better agronomic types at maturity was tried first in the postrainy season of 1977. The gains using this system for the last 3 years have been quite rapid and very encouraging. Good progress has been made in evolving several diverse breeding lines with levels of shoot fly resistance exceeding that of the original source material and in fairly good agronomic backgrounds.

Mechanism of Resistance

Nonpreference is an important mechanism of resistance. Sometimes it is operative even in the absence of a preferred host(s) (Wongtong and Patanakam Jom 1975; Jotwani et al. 1974). One deterrent to oviposition in sorghum is the presence of trichomes (microscopic hairs) on the abaxial surface of leaves of resistant genotypes (Maiti and Bidinger 1979). Their presence on the abaxial surface is highly associated with oviposition nonpreference (r=-0.8) and is also a highly heritable trait ($h^2$0.9) (Omori, unpublished). Varying trichome intensity does not influence oviposition nonpreference. It is controlled by a single recessive gene (Gibson and Maiti. unpublished). The possibility of other deterring factors is not ruled out. Sometimes, trichomes also offer mechanical resistance by interfering with the migration of the maggot towards the growing point (Reddy and Abraham, unpublished). In a preliminary analysis, the trichomes and unknown antibiotic factors seem to contribute equally towards shoot fly resistance (Table 2).

ICRISAT physiologists noticed that most shoot fly resistant varieties have a *glossy* (pale green, smooth, shining leaves) expression in the seedling stage. It was then observed that most of ICRISAT's advanced shoot fly resistant breeding material was unconsciously selected for this glossy trait. Tarumoto (1980) indicates that glossy is controlled by a single recessive gene. The level of resistance has been found to be greatest when both the glossy and trichome traits occur together (about 80% of the time) (Fig 1). The resistance of glossy genotypes differ with the intensity of glossiness.

A component analysis was done on Omori's unpublished observations to assess the complexity of shoot fly resistance and to quantify the contribution of major factors to shoot fly resistance. Four traits—trichome density, glossy intensity, eggs/plant, and percent deadhearts—were considered. Correlations were obtained both at the genotypic and phenotypic levels and the results are presented in Table 3. Highly significant correlations were found among all four traits. Shoot fly incidence was found to be highly and negatively associated with the glossy and trichome traits. The high correlation noticed between glossy and number of eggs/plant is evidence of contribution to oviposition nonpreference.

These correlations were partitioned into direct

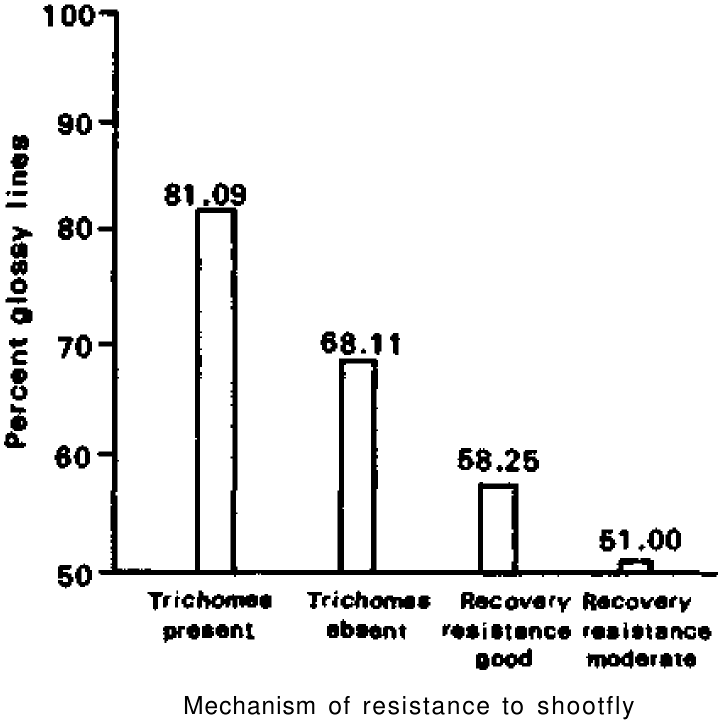


Figure 1. Percent glossy shoot fly breeding fines with and without trichomes and with recovery resistance.

and indirect effects using a standardized partial regression coefficient technique. Although glossy is highly associated with shoot fly resistance it has very little direct effect on shoot fly resistance (i.e., r_g = -0.935 and p_g= -0.166). This indicates that the high correlation which was observed is the result of other traits and hence the glossy appearance may be an indicator trait for some other trait that contributes to resistance (Fig 2).

The presence of glossy trait has been found to be negatively correlated with yield (r = -0.453). The reason for this requires further investigation. There are fairly good indications that glossy contributes to reduced infestation by the flea beetle and also the shoot bug *(Perigrinus maidis)* (Woodhead. personal communication). Recent observations at ICRISAT suggest that it also contributes to seedling drought resistance (Maiti, personal communication). It appears that the glossy expression could play an important role in the simultaneous incorporation of resistance to several traits.

Genetics

Genetic studies conducted to date indicate that the nonpreference mechanism is the predominant one and it is quantitatively inherited with a predominance of additive gene action (Rao et al.

Table 3. Genotypic and phenotypic correlation coefficients between factors contributing resistance to shoot fly.

Factors		Trichome intensity	Glossy intensity	No. of eggs/ plant	Deadhearts
Trichome intensity	rg	1.0000	0 8330**	-0.6973**	-0.8174**
	rp	1,0000	0.8289**	-0.4946**	-0.7190**
	h^2	0.995/			
Glossy intensity	rg		1 0000	-0.8255**	-0.9351**
	rp		1.0000	-0.5848**	-0.8177**
	h^2		0.9890		
No. of eggs/plant	rg			1.0000	0.9971**
	rp			1.0000	0.7334**
	h^2			0.5008	
% Deadheads	rg				1 0000
	rp				1.0000
	h^2				0.7752

rg = Genotypic correlation coefficients
rp = Phenotypic correlation coefficients
h^2 = Heritability
** = Significant at 1% probability level

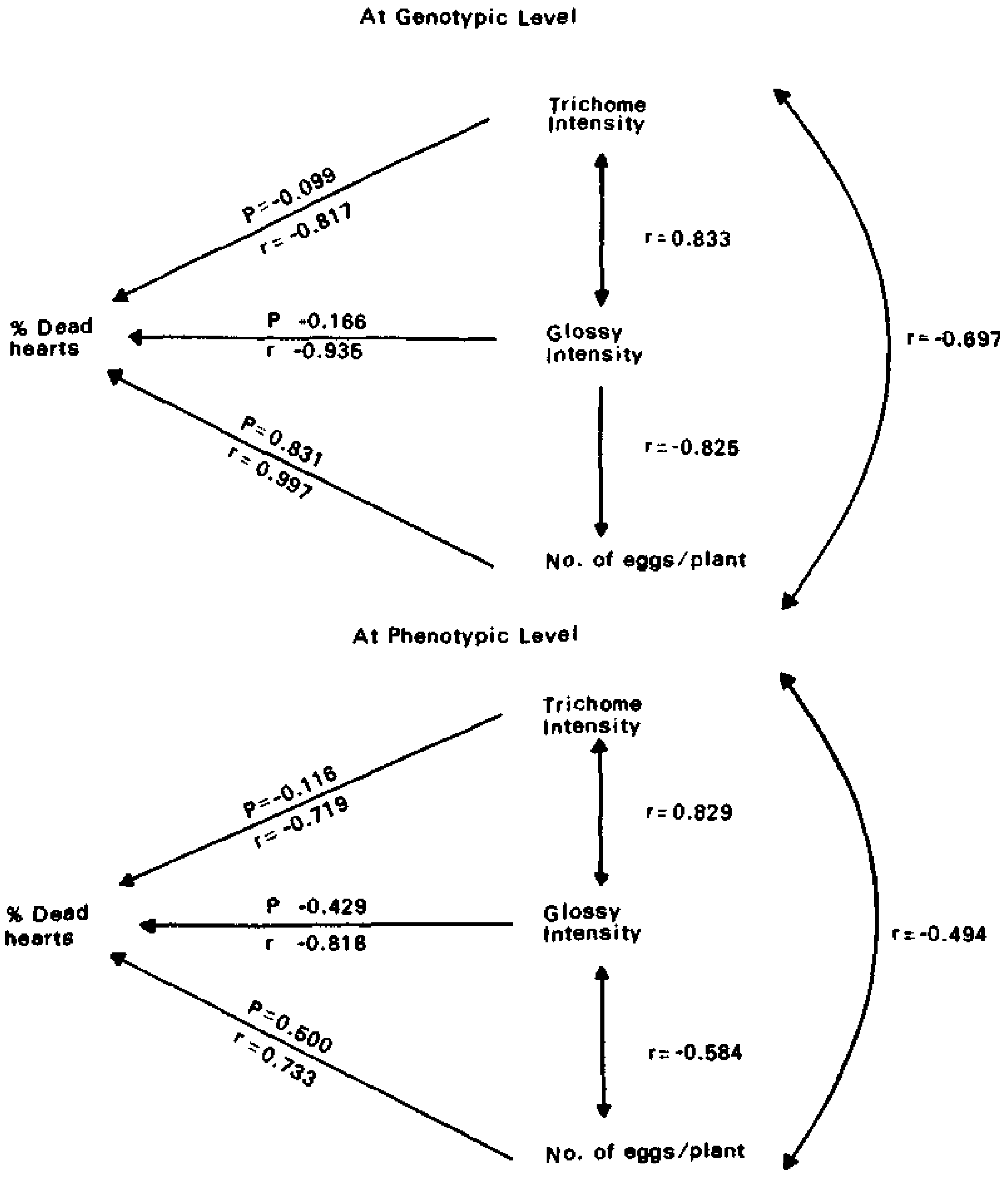


Figure 2. Path analysis of factors contributing resistance to shoot flies.

1974; Sharma et al. 1977). Rao et al. (1974) found that hybrids are generally superior to parents. Further studies of Balakotaiah et al. (1975) conducted on large F_2 populations revealed that the frequency distribution of different mortality classes closely fits the normal curve and the inheritance of shoot fly resistance is predominantly additive. Based on backcrosses, F_3s. and advanced generation progenies, Rana et al. (1975) found the heritability of shoot fly resistance to be around 25%. Rana et al. (1980) reported that the F_1 is almost intermediate between the two parents. Resistance was found to be partially dominant under low to moderate shoot fly pressures but not under heavy infestation conditions. In this study resistance was also found to be polygenic in nature and governed by genes with predominantly additive effects.

The analysis of the genetics of resistance to shoot fly done by Borikar and Chopde (unpublished) indicated that both additive and nonadditive components of gene action are important for shoot fly deadhearts under low pressures. However, the deadhead percentage is predominantly controlled by additive gene action under moderate to high shoot fly pressures. Heritability ranged from 15 to 25% depending on shoot fly pressure. In general, oviposition preference is controlled by additive genetic factors. The heritability studies also revealed that the genetics of deadhearts and eggs/plant is influenced by the level of shoot fly population. It therefore appears that genetic studies and breeding for shoot fly resistance must be associated with population pressure. Selection for shoot fly resistance preferably should be made in conditions of high infestation.

Stem Borer

The stem borer attacks all stages of the crop from about 4 weeks after germination, and it attacks all parts of the plant except the roots. In the early stage, the larvae feed on the leaves in the whorl of the plant and often cause deadhearts. Late attack results in stem tunneling and boring of the peduncle which may result in breakage of chaffy heads.

Source Material

During the 70s, Jotwani and his colleagues systematically field screened the sorghum germplasm collection for *Chilo* resistance, and tested the first 10 000 accessions at several locations in India. They confirmed the resistance of promising lines by inoculation. Twenty-six lines were found relatively less susceptible to *Chilo.* Most of them were of Indian origin with the exception of IS-3096 from the USA., IS-7273 from Nigeria, and IS-9136 from Kenya.

ICRISAT breeding stocks and the germplasm accessions not tested by Jotwani and his colleagues, were tested at ICRISAT in 1980 at several locations in India using natural or artificial infestation. Of the 10 744 germplasm lines screened, 289 lines have shown less susceptibility to *Chilo* and are being tested further. Some lines have been found to have low suceptibility to both shoot fly and stem borer. IS-4660, IS-18427, and IS-18479 are tolerant to both *Chilo* and *Busseola* (Seshu Reddy, personal communication).

Stem Borer Screening

Varying degrees of success in terms of screening for resistance to borer have been observed. A high natural *Chilo* infestation is found at several research stations in India. At the ICRISAT site, due to lack of uniformity, natural infestation has been discarded. Instead ICRISAT entomologists have developed an artificial diet giving recovery of 74% adults. A technique for releasing these larvae over the whole nursery through a dispenser makes it possible to screen three hectares of material each season. Testing by inoculation during the postrainy season, where the growth of the plants is slower because of low temperatures, is more effective than in the rainy season. Shoot fly becomes a problem in the early seedling stage and reduces the plant stand. It is not possible to use chemical protection against shoot fly because of residual effects on young *Chilo* borers. It has been necessary to remove shoot fly eggs manually from seedlings every alternate day during the shoot fly susceptible stage—a cumbersome, laborious, and costly process.

Hissar in North India has been identified as a good hot spot for *Chilo* during the rainy season and has proved to be a good location for testing purposes. Sowings made in the first week of July receive uniform and massive attack of *Chilo.* Pantnagar and Bhavanisagar are other good locations where there is a moderate incidence of *Chilo* during the rainy (late July sowing) and late summer (March sowing) seasons, respectively. Effective screening with varying levels of *Chilo* from natural and inoculated situations is now possible.

Mechanism of Resistance

Information on factors contributing to stem borer resistance is limited. Jotwani (1976) observed that tolerance and antibiosis are operating in resistant cultivars. Evidence for antibiosis was furnished by Kalode and Pant (1967). Jotwani (1978) reported that the development of *Chilo parteltus* was retarded on three selected resistant cultivars, i.e., IS-1151, IS-4764, and IS-4776. On these three lines there was higher mortality in the early larval stage, the larval period was increased, and the percent pupation was less on resistant cultivars compared with the susceptible hybrid CSH-1. Phenols and cyanides have been found not to play a significant role in resistance while waxes may play a role by way of obstructing larval migration (Sue Woodhead and Chapman, personal communication). More biochemical studies on borer resistance are under way at ICRISAT. If some simple, easily detectable mechanisms are identified, it will help in selecting resistant genotypes more effectively and efficiently.

Genetics

Rana and Murty (1971) reported that resistance to stem borer is polygenically inherited. The F_1 hybrids were intermediate for primary damage (leaf feeding) but better than the mid-parent for secondary damage (stem tunneling). Resistance to primary damage was found to be governed by additive and additive x additive type of gene action while additive and nonadditive type gene actions were important for secondary damage. The inheritance patterns of primary and secondary damage were different.

Midge and Head Bugs

Midge is a small, bright, orange-red, rapidly mutiplying fly that lays eggs inside the floret during flowering. The maggot feeds on the developing seed and prevents seed set. Earhead bug is severe at the milk and dough stages of seed development. The nymphs suck the seed, and grain yield and quality are drastically affected. Its damage varies from slight to extreme reduction of seed size.

Source Material

Systematic testing for resistance to midge was initiated by Wiseman and his colleagues in 1968 in Texas. Johnson et al. (1973) reported good levels of resistance to midge in Ethiopian converted materials (Zera-zera type). To date, nearly 125 midge resistant lines have been identified, and they are well documented in the literature. These midge resistant lines belong to different countries (Sudan, Ethiopia, Uganda. India, and Pakistan) and taxonomic groups (Zera-zeras, Caudatum Nigericans. Caffrorum Darso, Durra, and Durra Nigericans). Faris et al. (1979) evaluated Ethiopian converted lines and AF-28 in Northeast Brazil for stability of midge resistance. AF-28 was found to be the most stable across sowing dates. Lines IS-2508C and IS-2757C showed moderate stability. Converted Ethiopian Zera-zera cultivars have shown promise on a global basis for resistance to midge. Other important lines used in the breeding program include S-Girl-MR-1, DJ-6514, and TAM-2566

Relatively little progress has been made for the systematic identification of sources resistant to earhead bugs. Over 90 germplasm lines have been identified as promising against *Calocoris* at ICRISAT, but their resistance still needs to be confirmed. Several advanced breeding lines have been identified with reasonable levels of resistance. Most of them are derivatives of IS-12573C, a midge resistant line.

Screening Techniques

The problem of managing the high levels of midge and head bug populations in the field for screening purposes remains unsolved. In the field, populations vary considerably Under such a situation, the test entries that differ in days to flowering may not be equally infested It is therefore necessary to separate test material into groups of similar flowering times. A susceptible check with the same time of flowering as the test group should be included. Because of these problems, several seasons of testing are required to confirm resistance.

Early planting of susceptible sorghums with a range of days to flowering helps in increasing and to some extent in maintaining constant midge and head bug populations in the test material. This approach is useful for the initial testing of a large amount of material. Later, the resistance of promising lines/genotypes can be confirmed by using a cage technique. Using this technique, Rosetto et al. (1975) found AF-28 to be resistant to midge whereas Sart was found to be susceptible. Page (1979) reported that converted lines IS-12608C and IS-12664C expressed significantly higher levels of resistance against midge than KS-19 and Alpha. Line Q-13828, which showed resistance to midge under field conditions, was susceptible under caged conditions. Several other workers have found the technique quite effective and useful for confirming resistance. Large-scale testing using this technique is not possible unless we learn how to rear the midge and the head bug.

Mechanism of Resistance

Nonpreference and antibiosis are the major mechanisms operating in most sources of midge resistance. AF-28, a strong and stable source of midge resistance has been found to have fewer numbers of eggs than a susceptible cultivar indicating an oviposition nonpreference mechanism (Rosetto et al. 1975). Its tight glumes make oviposition difficult. Also, the closed tight glumes of 1S-2260 and IS-2263 enable the lines to resist midge (Berquist et al. 1974). The level of attack on a cultivar may also be a function of the number of midge flies attracted to the head (Wiseman and McMillan 1968: AICSIP 1973).

An antibiosis mechanism has been noticed in several midge resistant varieties like AF-117, SC-239-14, SC-175-9. and SC-175-14 and SC-574-6 (Rosetto 1977). Gowda and Thontadarya (1978), Jotwani (1978) and Page (1979) also found antibiosis to be a mechanism of resistance to sorghum midge. Significant differences were noticed in the number of flies that emerge from the earheads of resistant genotypes compared with susceptible ones. Varying contents of tannin in the grain are a probable biochemical factor imparting resistance. A relatively high correlation was noticed between tannin content in the grain and midge incidence by Santos and Carmo (1973) and Santos et al. (1974).

According to earlier workers, short tight glumes and cleistogamy contribute to midge resistance. On the other hand, several recent studies have indicated the presence of resistance in non-cleistogamous sorghum lines also. Murty and Subramaniam (1978) found no relationship between length of glumes, presence of awns and rachis length with resistance. Instead, they found compactness of earheads associated with midge resistance.

Genetics

Very little information is available on the genetics of midge resistance, and there is none on head bugs. Widstrom et al. (1972) studied the gene effects conditioning resistance to midge. Most of the crosses expressed highly additive gene effects. An exception was the S-Girl-MR-1 x 130 cross in which dominance conditioned susceptibility to midge injury. Epistatic effects were also noticed. More genetic studies are required to have a clear idea of the nature of inheritance and the type of gene action before designing an effective breeding procedure,

Breeding For Shoot Fly, Borer, Midge, and Head Bug Resistance

The quantitative nature of inheritance of resistance to shoot fly, stem borers, and midge makes the breeding problem difficult. This problem is made even more difficult because yield is also a quantitatively controlled trait. The complexity of the problem further increases when breeding simultaneously for resistance to more than one trait.

The success achieved in maize at CIMMYT in transferring resistance to corn borer and the work of Hanson et al. (1972) in developing alfalfa varieties possessing multiple resistance by using recurrent selection suggest that this approach is valuable. The use of broad-based, random-mating, pest-resistant populations should be an appropriate long-term approach for breeding sorghums resistant to several major insects. Pedigree breeding methods, on the other hand, are useful for short-term gains and for transferring resistance for a single pest.

Based on the stage at which damage occurs and the type of damage caused, the four pests discussed in this paper have been placed into two groups: (1) shoot pests (shoot fly and stem borers! and (2) earhead insects (midge and head bugs).

Two pest-resistant populations, one for shoot pests and the other for head pests, are in the process of development using ms_3 and ms_7 male-sterility genes. After their development, they will be tested for the first few years using a low to moderate insect pressure and then be subsequently advanced, using mass selection. Once the populations are improved for characters like height, maturity, grain quality, and resistance, S_2 testing will be used as outlined in Figure 3. Major selection pressure is placed on resistance to the shoot pests so that only undamaged plants are advanced to the next generation.

Affected plants cannot be discarded before flowering in the head pest populations as they can be in the shoot pest populations, since the damage occurs only after that period. The recurrent selection system will involve S_2 testing; selection in both S, and S_2 families will be under insect pressure. The half-sibs will be tested under

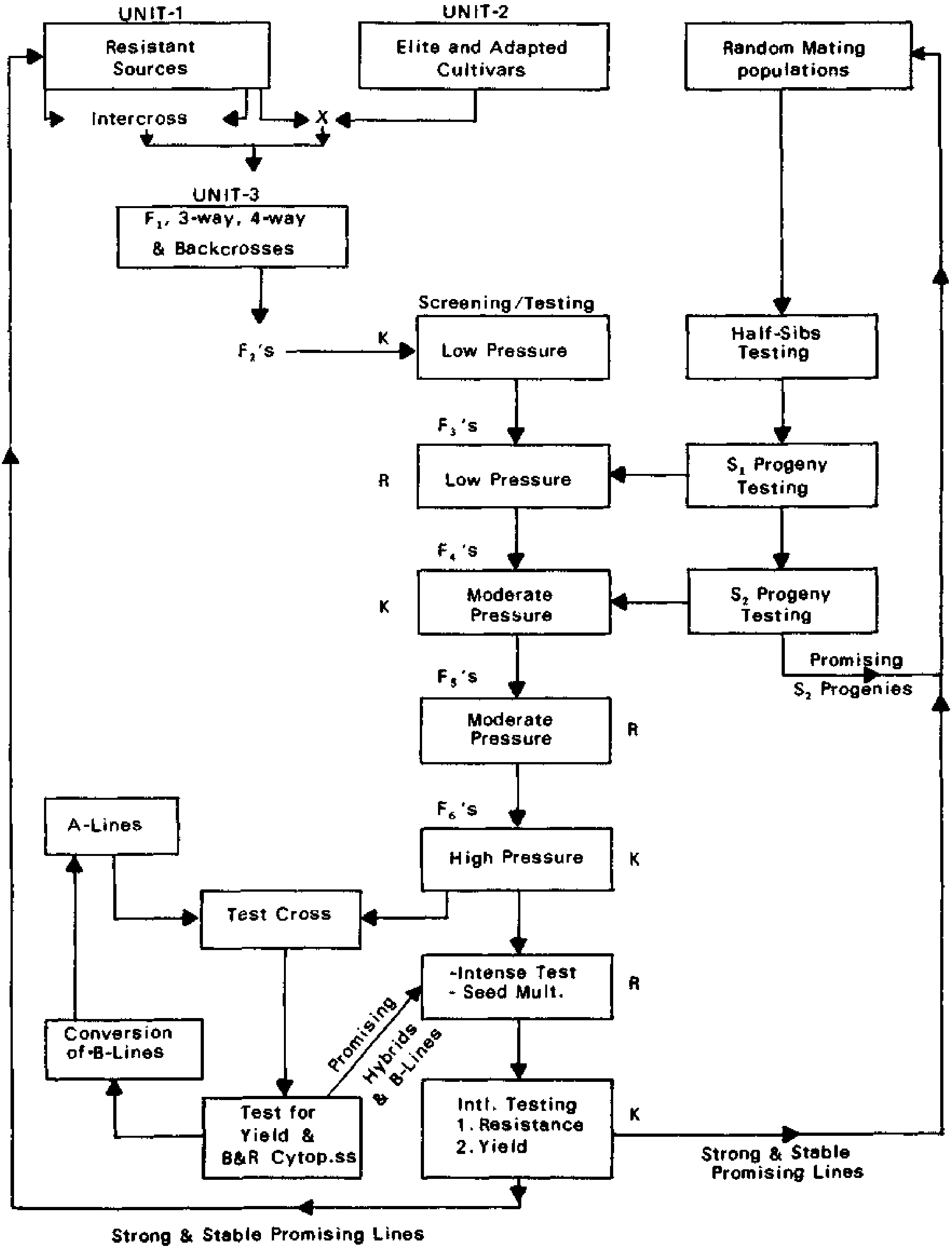


Figure 3. Proposed scheme for pest resistance breeding in sorghum.

protection and normal management during the main crop season, and selections will be made for height, maturity, and grain quality. While testing S_1 progenies during the postrainy season, simultaneous selections for grain size and charcoal rot can be made. S_2 progenies will be tested in the main rainy season using moderate insect pressure.

During recombination, new promising derivatives with confirmed resistance can be incorporated into the populations to increase the frequency of genes for resistance and agronomic eliteness. New sources of resistance which are agronomically poor should not be directly included in the population so that the agronomic features of the populations are not adversely affected. The source material for other traits, preferably with B cytoplasm, may also be fed into these populations so as to increase the variability and opportunities for simultaneous incorporation of other traits.

Promising S_2 progenies may be advanced and purified under continuous insect pressures. Later their B and R cytoplasmic reaction, combining ability, and performance for both yield and resistance can be tested. The best derivatives may be used as improved sources, as resistant cultivars, or as hybrid parents, and then some can be fed back into the populations. Lines showing B reaction, and having appropriate height, flowering time, and good combining ability may be converted into resistant female stocks for the production of resistant hybrids.

In due course, when the gene frequency for resistance and agronomic traits improves, the populations can be pooled to bring together resistance for all four pests.

Besides population breeding, pedigree breeding is also currently being used as a short-term approach to quickly breed for resistance to individual pests and to meet immediate requirements. The procedures for handling donor parents, making the crosses, growing and screening for resistance, agronomic traits, and grain quality are outlined in Figure 3. There are three basic units to this approach. Unit 1 involves the strengthening of source material, Unit 2 the development of agronomically elite lines, and Unit 3 the crossing of material in units 1 and 2. Unit 3 segregating material is advanced with continuous testing using lower insect pressures in early generations and increasing insect pressures as gene frequencies for insect resistance increase. Advanced promising entries with resistance should be tested internationally if the parents are reasonably well adapted.

In the last few years, good progress has been made in developing breeding material with reasonably good agronomic backgrounds and resistance to shoot fly. midge, and earhead bugs. The development of such materials for stem borer will take more time.

Many shoot fly resistant breeding lines are available with good levels of resistance. Some show better resistance than the best source materials (Table 4). Following the identification of trichome and glossy traits and the modification of the field screening technique, the exploitation of variability for shoot fly resistance in many genetic backgrounds has become possible. Several shoot fly resistant lines/progenies have been extracted directly from ICRISAT's advanced populations.

An array of promising midge resistant derivatives from crosses with AF-28, IS-12573C, DJ-6514, and S-Girl-MR-1 has been evolved. Some lines have up to 90-95% seed set as compared with a maximum of 5% on the susceptible checks.

Several advanced lines with resistance to earhead bugs have been identified directly from midge resistant breeding material. IS-12573C is a frequent parent in most of these derivatives. Some have common resistance to both midge and earhead bugs. PHB-156 has good resistance and yields well. It is currently being used in Africa.

Future Plans

In the future, our priority will be to breed for resistance first to stem borers, then midge, followed by shoot fly, and finally earhead bugs. It may be necessary to initiate a program for resistance to the armyworm *Mythimna.*

Development of A-lines and hybrids with resistance will be important objectives.

Screening procedures, particularly for midge and earhead bugs, require development before it is possible to effectively undertake large-scale screening activities. The identification of more "hot spots" for each major insect is essential.

More information on mechanisms and the genetics of traits contributing to resistance needs to be generated. A concentrated effort will be made on the identification of easily recognized, highly heritable, and simply inherited traits like glossy and trichomes.

Table 4. **Promising shoot fly rasistant sorghum Unas identifiad at ICRISAT Center in 1979/80 through scraaning and usa of tha glossy and trichomad traits.**

Pedigree	% Deadhearts
(IS-5622 x 2KX6I-2 1-1-1-1 4	54 1
(IS-5622 x WABC-1121 x CS 35411 -16-1-2-1-1-1	598
(IS-1034 x IS-3691) *-2-3-2-1-1-1*	598
(IS-5622 x CS-3541) 11 1 1-11	50 7
(GG x 370 x EN-3363) 8 1 1 1 1	59 7
(IS-5622 x WABC-1121 x PHYRI -7-1-1-1-1	579
(IS-84 x IS-1082)-3-1 1 1	580
(IS-1054 x CS-36871-1-1-1-1	588
(0222 x CS-3541 -10 x IS 3962) -3-1-1-1	529
(UChV$_2$ x IS-1054)-1- 1-1-1	50.7
<UCHV$_2$ x IS-10541-2-1 -1-1	586
(UCHV, x IS-3962M-1-1-1	53 9
(UCHV$_2$ x IS-3962)-6-1-1-1	31.7
(UCHV$_2$ x IS-39621-8-1-1-1	52.7
(Rs/R-S$_7$-188 x IS-2312) -1-1-1-3	56.0
(Rs/R~S$_7$-188 x IS-23121-1-1-1-5	500
(CSV-3 x IS-56221-3-1-1	55.9
(SPV-29 x IS-39621-1-2-1	46.0
(IS-1082 x SC-108-4-8) x SC-108 x SC-108-4-81-1-1-1	55.4
(ESGPC x IS-12573CI-3-1-1-3	42.7
(ESGPC x IS-125730-3-2-3-1	453
(ESGPC x IS-12573CI-4-1-1-1	545
(IS-2816C x 5D x Bulk)-2-1 -1 -1	42.3
(IS-2816C x 5D x Bulk)-2-2-1-1	27.7
(IS-2816C x 5D x Bulk)-2-1-1-1	60.0
IS-1054 (M35-1)	85.3
IS-5604	85.5
IS-2312	90.7
IS-1082	89.3
CSH-1	100

A number of sources of resistance for each insect from different geographic origins and taxonomic groups have been identified but no information is available on their variability for genes conferring resistance. Once this information is available it will help us generate stronger source material. In the absence of such information, we will be forced to use a large number of source lines which can be difficult to handle.

A search will continue to be made for varieties with resistance to more than one trait in order to hasten the development of elite varieties with multiple resistance.

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References

AICSIP (All India Coordinated Sorghum Improvement Project) 1973 AICSIP 1970/73 ICAR and associated agencies

BALAKOTAIAH, K , RANA, B S.. TRIPATHI. D P.. and RAO. N. G P. 1975 Genetic analysis of some exotic and Indian crosses in sorghum X. Inheritance of resistance to sorghum shoot fly Indian Journal of Genetics and Plant Breeding 35:344 349

BERQUIST, R. R.. ROTAR. P.. and MITCHELLA. W. C.1974. Midge and anthracnose head blight resistance in sorghum. Tropical agriculture (Trinidad) 51 : 431 -435.

BORIKAR. S. T., and CHOPDE. P. R. (Unpublished). Inheritance of shoot fly resistance under three levels of infestation in sorghum.

DE WET, J. M. J., GUPTA, S. C, HARLAN, J. R., and GRASSL. C. 0.1976. Cytogenetics of introgression from *Saccharum* into *Sorghum.* Crop Science 16:568-574.

FARIS. M. A., LIRA. M DE A., and VEIGA, A. F. DE S L. 1979 Stability of sorghum midge resistance. Crop Science 19:577-580.

GOWDA, B. L. V., and THONTADARYA, T. S. 1975. Varietal response of sorghum to the midge, *Contarinia sorghicola* (Coquillet) (Diptera: Cecidomyiidae). Current Research 4:177-179.

HANSON, C. H.. BUSBICE, T. R„ HILL, R. R.. HUNT. O. J., and OAKES. A. J. 1972. Directed mass selection for developing multiple pest resistance and conserving germplasm in alfalfa. Journal of Environmental Quality 1:106-111.

JOHNSON, J. W„ ROSENOW. D. T., and TEETES, G. L.1973. Resistance to the sorghum midge in converted exotic sorghum cultivars. Crop Science 13:754-755.

JOTWANI. M G 1976. Host plant resistance with special reference to sorghum. Proceedings of the National Academy of Science (India) 46B: 42 48.

JOTWANI, M. G. 1978. Investigations on insect pests of sorghum and millet with special reference to host plant resistance. Technical Research Bulletin. Division of Entomology. IARI, New Delhi. India 114 pp.

JOTWANI, M. G.. SHARMA, G. C. and SRIVASTAVA, K. P. 1974. Utility of non-preference for oviposition in developing sorghum lines resistant to shoot fly. Entomologists' Newsletter 47:3-4.

KALODE, M. B., and PANI. N. C. 1967 Effects of host plants on survival, development and behavior of *Chilo zonellus* (Swinhoe) under laboratory conditions. Indian Journal of Entomology 29:48-57.

MAITI, R. K., and BIDINGER, F. R.1979. A simple approach to the identification of shoot fly tolerance in sorghum. Indian Journal of Plant Protection 7:135-140.

MURTY, A. D. and SUBRAMANIAM. T. R. 1978. Varietal susceptibility of sorghum to the midge *(Contarinia sorghicola* Coq.). Madras Agricutural Journal 65: 180 -182.

PAGE, F. D.1979. Resistance to sorghum midge (*Contarinia sorghicola* Coq.) in grain sorghum. Australian Journal of Experimental Agriculture and Animal Husbandry 19:98-101.

RANA, B. S., and MURTY, B. R. 1971. Genetic analysis of resistance to stem borer in sorghum. Indian Journal of Genetics and Plant Breeding 31 :521-529.

RANA, B. S.. TRIPATHI, D. P., BALAKOTAIAH, K., DAMODAR. R., and RAO, N. G. P. 1975. Genetic analysis of some exotic x Indian crosses in sorghum. XI. Selection for shoot fly resistance. Indian Journal of Genetics and Plant Breeding 35:350-355.

RANA, B. S., JOTWANI, M. G., and RAO, N. G. P.1980. Inheritance of host plant resistance to sorghum shoot fry. *In* Insect science and its application, ICIPE, 4-8 May, 1980, Nairobi, Kenya.

RAO, N. G. P., RANA, B. S., BALAKOTAIAH, K„ TRIPATHI, D. P., and FAYED, MPS. 1974. Genetic analysis of some exotic x Indian crosses in sorghum. VIII. F, analysis of ovipositional non-preference underlying resistance to sorghum shoot fly. Indian Journal of Genetics and Plant Breeding 34:122-127.

RAO, N. G. P.. RANA, B. S., and JOTWANI, M. G. 1977. Host plant resistance to major insect pests of sorghum. *In* Use of induced mutations for resistance of crop plants to insects. Proceedings, FAO/IAEA Advisory Group, 1977. Dakar. Senegal.

ROSETTO, C. J.1977. Types of resistance of sorghum to *Contarinia sorghicola.* Sorghum Newsletter 20: 5.

ROSETTO, C. J.. BANZATTO, N. V., LIRA, J. F. M., and OVERMAN. J. L. 1975 AF-28, A *Sorghum bicolor* variety resistant to sorghum midge, *Contarinia sorghicola.* Sorghum Newsletter 18:5

SANTOS, J. H. R., and CARMO. C. M. 1973. Evaluation of resistance of sorghum lines from Cameroon, Africa, collection to *Contarinia sorghicola* (Coq. 1898) at Pantecoste, Ceara, Brazil. Progress report, sorghum project activities for 1973, Depart, de Fitotecnia, Centra de Ciencias Agrarias, Federal University of Ceara. Fortaleza, Brazil.

SANTOS, J. H. R, CARMO. C. M., and LIMA. C. B.1974 Evaluation of resistance to *Contarinia sorghicola* by sorghum lines from the Purdue collection in Cara, Brazil. Sorghum Newsletter 17:12-13.

SESHUREDDY, K. V.andDAViES. J. C 1978 The role of the entomology program with reference to the breeding of pest resistant cultivars of sorghum at ICRISAT. Presented at the Symposium on the Strategies for Insect Pest Control through Integrated Methods. August 1978. IARI. New Delhi.

SHARMA. G. C. JOTWANI, M. G.. RANA. B. S.. and RAO. N. G. P. 1977. Resistance to the sorghum shoot fly. *Atherigona soccata* (Rondani) and its genetic analysis. Journal of Entomological Research 1 :1-12.

SINGH, S. P., JOTWANI, M. G.. RANA, B. S.. and RAO, N. G. P. 1978. Stability of host plant resistance to sorghum shoot fly, *Atherigona soccata* (Rond). Indian Journal of Entomology 40:376-383.

TARUMOTO, 1.1980. Inheritance of glossiness of leaf blades in sorghum. *Sorghum bicolor* (L.) Moench. Japanese Journal of Breeding 30: 237-240.

WIDSTROM, N. W., WISEMAN, B. R„ and MCMILLAN, W. W.1972. Some gene effects conditioning resistance to midge and webworm injury in sorghum. Sorghum Newsletter 15:22-23.

WISEMAN. B. R„ and MCMILLAN, W. W.1968. Resistance in sorghum to sorghum midge, *Contarinia sorghicola* (coquillet) (Diptera: Cecidomyiidae). Journal of the Entomological Society of Georgia 3:147.

WONGTONG, S., and PATANAKAM JORN, S.1975. Entomological research during 1975. Pages 301 -302 *In* Thailand National Com and Sorghum Program 1975. Annual Report. Kasetsart University, Dept. of Agriculture, Bangkok.

Breeding for Disease Resistance in Sorghum

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Sorghum has many disease problems. The description of their symptoms, causal organisms, distribution, and importance in crop loss up to 1960 are covered by Tarr (1962). A recent publication (Williams et al. 1980) is an excellent update on the sorghum disease situation in the world. It contains current information on importance, distribution, control strategies, and screening techniques. We will not attempt to list diseases in order of priority here, because Frederiksen (1982) gives a complete listing of diseases, their common and scientific names, prevalence, and relative importance.

The use of host plant resistance has been and continues to be the most important method of controlling sorghum diseases. Many diseases have been successfully controlled in certain countries or parts of countries through the use of host plant resistance during the past 10 years. Classic examples include head smut, downy mildew, anthracnose, and maize dwarf mosaic in the USA and portions of Latin America. Progress in other diseases is somewhat harder to establish, but host plant resistance has obviously been very important elsewhere in reducing or preventing losses. In many cases, the disease is "managed" through the use of sorghum varieties and hybrids that may not contain high levels of resistance but have sufficient levels to escape damage and/or to reduce pathogen buildup. This appears to be an important method of disease control in countries where many indigenous local varieties are used under traditional farming systems. Disruption of such balanced systems by widespread development of improved varieties with less disease resistance can lead to severe disease problems and grave losses (Williams et al. 1980).

The past 10 years have brought about some changes in the disease situation in sorghum. Grain mold is now recognized as one of the most important diseases of sorghum (Williams and Rao 1981). In the tropics where new high yielding, earlier maturing photopenod insensitive sorghums are introduced, it is probably the most important disease. As earlier maturing photoperiod insensitive cultivars are planted so that they mature during a higher rainfall period of the year, grain molding becomes a much more serious problem. Therefore more grain mold-weathering resistance will be required than in the local, photoperiod sensitive varieties.

Characoal rot is also associated with earlier maturing, higher yielding genotypes. Charcoal'rot develops under drought and heat stresses during grain development, and is related to the large sink size associated with high yielding genotypes.

Other recent important developments include a new virus strain prevalent in Venezuela which attacks heretofore tolerant lines and hybrids, and two new pathotypes of the downy mildew fungus in Texas.

Four essential requirements for a successful disease resistance breeding program are: (1) ability to identify and screen for the resistant traits, (2) that sources of resistance have sufficiently high levels of resistance, (3) the resistance must be heritable so that it can be transferred, and (4) the resistance must be sufficiently stable across environments.

The sorghum species is blessed with a broad and diverse genetic base. Screening has identified sources of high levels of resistance for most sorghum diseases many of which are listed in this paper. Two recent publications, i.e.. Sorghum Diseases, A World Review (Williams et al. 1980),

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81. Patancheru. A.P., India. Patancheru. A.P. India: ICRISAT

and a paper by Frederiksen and Rosenow (1980) list many newly identified sources of resistance to essentially all the important sorghum diseases. The Sorghum and Pearl Millet Disease Identification Handbook by Williams et al. (1978) is ideal for disease verification in the field.

Breeding for disease resistance is, or should be, an integral part of any plant breeding program. A successful program requires close cooperation and collaboration between breeders and pathologists. Research should be planned cooperatively and field nurseries should preferably be cooperative nurseries. Unfortunately, there are many cases where nurseries are planned and maintained independently by either breeders or pathologists. It is important to identify disease resistance in early generations of breeding. This often can best be accomplished by a pathologist working in a nursery with a breeder, where the pathologist concentrates on disease observations and the breeder concentrates on other breeding traits. However it is done, the critical aspect is for them to cooperate fully.

Pedigree line breeding, backcross breeding, and population breeding can all be used successfully in breeding for disease resistance. When individual plants with resistance can be readily identified, improvement through populations works well. Other factors to consider are the inheritance patterns, the agronomic desirability of the resistant source lines, and the breeding system currently used by the breeder.

Efficient and effective screening of a large number of sorghum genotypes is a critical part of a successful disease resistance breeding program. In many cases, field screening is a very effective method as with downy mildew, head smut, charcoal rot, and many foliar diseases. Sometimes inoculation in the field enhances disease development as with anthracnose, leaf blight, maize dwarf mosaic (MDM), and charcoal rot.

Large field disease screening nurseries at one or more locations where a number of important diseases occur naturally is ideal. This permits breeders to select for several diseases simultaneously.

In Texas, we plant large disease screening-breeding nurseries in the humid areas of south Texas where usually a large number of internationally important diseases occur. Nearly every year we observe excellent development of grain mold, downy mildew, head smut, zonate leaf spot, and grey leaf spot. Less often, but frequently, we obtain development of charcoal rot, rust, bacterial streak, MDMV. and head blight. In other areas of Texas, we plant field screening nurseries for evaluating charcoal rot and MDMV.

Our breeding lines identified from such nurseries are eventually tested more extensively in Texas and other areas in the ADIN (All Disease and Insect Nursery), in various head smut, downy mildew, charcoal rot, and lodging tests, and eventually in the IDIN (International Disease and Insect Nursery) which is distributed worldwide to anyone requesting seed.

ICRISAT has an effective multi-location uniform disease nursery screening program for several diseases. International nurseries have been established for downy mildew, grain mold, charcoal rot, and leaf diseases. INTSORMIL and other institutions distribute international nurseries for anthracnose and viruses.

Breeding and screening techniques and strategy should consider the nature of the host-parasite interaction and the apparent genetic vulnerability for each disease. These are summarized in Table 1. Inheritance of resistance and disease screening techniques are summarized in Table 2. Some sources of resistance to certain diseases are given in Table 3 (Frederiksen and Rosenow 1980; Williams et al. 1980; Frederiksen and Rosenow, unpublished data).

In conclusion, here are some keys to a productive disease resistance breeding program:

1. Have a large amount of genetic diversity in the program.
2. Plant diverse breeding material in a few large prime screening locations. Use other nurseries in locations where only one disease is present.
3. In order to develop multiple disease resistant lines, screen the same material for as many diseases as possible in the same year.
4. Test the best sources of resistance extensively at additional locations and under different environments.
5. Sources of resistance should be stable across locations and environments.
6. Recombine best sources of resistance, even among early generation sources. Select parents to complement each other, and at the same time select for agronomically superior traits.
7. Pathologists and breeders must work cooperatively.

Table 1. Characteristics of certain sorghum disease problems.

Disease	Genetic nature of host-parasite interaction	Degree of genetic vulnerability
Grain Mold	General	Low
Downy Mildew	General and specific	Intermediate—High
Charcoal Rot	General	Low
Anthracnose	Intermediate	Intermediate— High
Maize Dwarf Mosaic Virus	High	Intermediate
Head Smut	General and specific	High
Ergot	General	Low
Fusarium Head Blight	General	Low
Fusarium Stalk Rot	General	Low
Rust	Intermediate	Intermediate
Leaf Blight	Intermediate	Low
Zonate Leaf Spot	General	Low
Grey Leaf Spot	General	Low
Bacterial Stripe	General	Low

Table 2. Summary of inheritance of resistance and screening techniques on some diseases of sorghum.

Disease	Inheritance pattern	Screening technique*
Gram Mold	Intermediate dominant	Field (N* & A*)
Downy Mildew	Dominant	Field, laboratory
Charcoal Rot	Recessive	Field (N & A)
Anthracnose	Dominant	Field (N & A)
Maize Dwarf Mosaic	Dominant and recessive	Field (N & A), laboratory
Head Smut	Dominant	Field (N & A), laboratory
Fusarium Head Blight	Intermediate	Field (N & A)
Rust	Dominant	Field
Leaf Blight	Dominant	Field (N & A), laboratory
Sooty Stripe	Dominant	Field
Zonate Leaf Spot	Intermediate—recessive	Field
Grey Leaf Spot	Recessive	Field
Bacterial Stripe	Recessive	Field
Periconia Root Rot	Recessive	Field, laboratory
Acremonium Wilt	Recessive-?	Field (A), laboratory

* N = Natural. A = Artificial.

8. Breeder must be able to rate for disease resistance.
9. Pathologists must work in breeding material.
10. Both must work in the field and look for resistance.

A summary of sorghum diseases, describing inheritance of resistance, pathogen specificity. availability of sources of resistance, and screening procedures, is given below. They are grouped under each disease, as follows:

1 = Nature of inheritance of resistance
2 = Specific pathogen differences
3 = Sources of resistance
4 = Screening procedure

Table 3. Soma sorghums with disease resistance (most identified and selected within Texas—a few identified by ICRISAT and others).

Sorghums resistant to head smut	
White Kafir (P1 48770)*	Lahoma Sudangrass*
SC 324-12 (IS 2861 der)*	SC 325-12 (IS 2462)
SC 33-14 (IS 12553)	Tx430
TAM 428	IS 2403C (SC 103)
Early Hegari (SA 281)	IS 12658C (SC 167)
Spur Feterita (FC 6601)	IS 2508C (SC 414)
FC 8927 (D. Wh. Milo)	TAM 618**
Tx3048"	Tx7000 (Caprock)**
Tx 399 (Wheatland)"	(other converted lines)

* Also resistant under needle inoculation
•* Low level of field infection (stable so far)

Sorghums resistant to anthracnose in USA	
Brandes**	MN 960 (SC 972)**
Rio (IS 17459)	SC 326-6(IS 3758 der)**
IS 7173C (SC 283)	SC 748-5IIS 3552 der)**
SC 328-14 (IS 8263C)**	TAM 428
Tx430	Tx623
IS 2403C (SC 103)	IS 12612C (SC 112)
IS 1261-C (SC 110)	IS 1309CISC 322)*
IS 3574C (SC 239)*	IS 7778QSC 389)*
IS 12573C (SC 17)*	IS 12615C (SC 124)*
IS 2816C (SC 120)*	IS 7382C (SC 344)*
IS 12677C(SC 186)*	IS 7254C (SC566)
SC 490-14E (IS 6392C)*	SC 60-14E (IS 2569C)*
SC 37-14E (IS 12557C)*	SC 589-14E (IS 6338C)*
IS 2508C (SC 414)	Many other resistant in USA

* Also resistant in Brazil (1 year)
** Also resistant in Brazil (several years)

Sorghums resistant to downy mildew	
QL3 (India source)*	IS 12541C (SC 21)
Tx430**	IS 12543C (SC 23)
SC 170-6-17"	IS 12557C (SC 37)
CS 3541**	IS 12558C (SC 38)
IS 2816C*	IS 12608C (SC 108)
IS 2508C*	IS 12609C (SC 109)
SC 972-14 (MN 960)	IS 12646C (SC 155)
IS 1335C (SC 418)	IS 12649C ISC 158)
IS 2573C (SC 64)	IS 12657C (SC 166)
IS 2462C (SC 325)	IS 12658C (SC 167)
IS 2482C (SC 311)	IS 12685C (SC 224)
IS 2685C (SC 692)	IS 12611C (SC 111)
IS 3452C (SC 780)	IS 12612C (SC 112)
IS 3553C (SC 575)	IS 12617C (SC 126)
IS 3579C (SC 425)	IS 12618C (SC 127)

Continued

Table 3. *Continued*

Sorghum resistant to downy mildew	
IS 6418C (SC 493)	IS 12628C (SC 137)
IS 7093C (SC 726)	IS 12632C (SC 141)
IS 12158C (SC 984)	
IS 12522C (SC 2)	
IS 12533C (SC 13)	

Converted lines (IS-C numbers) above with high levels of field resistance to primarily race 1 in Texas, Some likely susceptible to race 3, but many not yet tested.

* Known to be resistant to race 3 also
"* Known to be susceptible to race 3

Sorghums resistant to zonate leaf spot	
SC 326-6 (IS 3758 der)	77CSI (IS 2930 x IS 3922)
R 1880 (SC 599 x SC 134)	SC 330-9 (IS 8187 der)

Sorghums resistant to *Fusanum* head blight	
SC 599-6 (R 9188) (IS 17459 der)	SC 599-6 (R 9247) (IS 17459 der)
SC 630-11E (IS 1269 der)	SC 650-11E (IS 2856 der)
GPR-148 (CSV 5)	

Sorghums resistant to grey leaf spot	
77CSI (IS 2930 x IS 3922)	R 1880 (SC 599 x SC 134)
CV 54	TP5RB0-330
SC 748-5 (IS 3552 der)	SC170 (134x170)
GPR-148 (CSV 5)	B 1887 (599x134)

Sorghums resistant to grain mold	
SC 279-14 (IS 7419)	IS 7254C (SC 566)
SC 748-5 (IS 3552 der)	SC 630-11E (IS 1269 der)
SC 650-1 IE (IS 2856 der)	IS 9530
SC 719-11E (IS 7013 der) (Brown)	SC 170-6-17
CS 3541	IS 2327
IS 2328	E 35-1

Sorghums resistant to charcoal rot	
SC 599-6 (R 9188) (IS 17459 der)	SC 599-6 (R 9247) (IS 17459 der)
IS 12568C (SC 56-14)	SC 56-6 (IS 12568 der)
SC 170-6-17 (IS 12661 der)	R 1584 (SC 56 x SC 170)
SC 35-6 (IS 12555 der)	B4R (BTx406 x Rio)
1790E (SC 56 x SC 33)	1790L (SC 56 x SC 33)
1778 (SC 56 x SC 33)	NSA 440

Sorghums resistant to rust	
SC 326-6 (IS 3758 der)	TAM 2566
IS 2816C (SC 120)	IS 12666C (SC 175)
SC 599-6 (IS 17459 der)	SC 748-5 (IS 3552 der)
TAM 428*	Tx 623

* Slow rusting.

Continued

Table 3. *Continued*

Sorghums resistant to sooty stripe	
SC 326-6 (IS 3758 der)	QL3
SC 599-6-10 (IS 17459 der)	Redlan
SC 414-12 (IS 2508 der)	940 (Niger var)
Sorghums resistant to leaf blight	
SC 326-6 (IS 3758 der)	IS 8337C (SC 574)
IS 12658C (SC 167)	IS 1335C (SC 418)
IS 6882C (SC 320)	IS 7254C ISC 566 141
SC 325-12 (IS 2462 der)	R 6956 (326x103)
Sorghums resistant to MDMV*	
QL1. QL2. QL3. QL4. QL11**	*Rio Reaction""*
Tx398 (Martin)*"	Rio (IS 174591
Tx399 (Wheatland)***	IS 12666C ISC 175)
(Many other lines)***	TAM 2566
	IS 2816C (SC 1201
	IS 12612C (SC 1121
	IS 2548C (SC 228)

• Lines tolerant or having Rio reacton in the USA are generally tolerant to Venezuela virus
"* Resistant to infection
**" Tolerant
**** Some field resistance but infected plants severely damaged

Grain Mold and Weathering

1. Some dominant, some overdominant in F, hybrids, some intermediate.
2. *Fusarium moniliforme* and *Curvularia lunata* are the principal pathogens. Many fungal species are associated with weathering or the post-maturity grain deterioration phase. They differ in importance based on location, and stage of maturity of the grain when infection takes place.
3. Only a few good sources of resistance (but there are distinct heritable differences)
   (a) None completely resistant.
   (b) Brown seeded (high tannin) lines are generally more resistant than nonbrown.
4. Field (natural and inoculated).
   (a) Rate for overall grain mold and grain weathering—delay harvest—plant so that rain or wet conditions occur at or after maturity. Rate for overall discoloration, amount of evident mold, and deterioration (including sprouting) of the grain. This rating obviously involves more than early season grain mold infection as such, but most types selected this way also show grain mold resistance under inoculation techniques.
   (b) Inoculate in field with specific pathogens.
   (c) Water spray or sprinkler mechanisms in the field to create a wet environment to enhance grain mold.

Downy Mildew

1. Dominant (field reaction).
2. Some differences, e.g., India vs USA. Three pathotypes in the USA.
3. Several resistant lines under field conditions in Texas. Only a few are resistant under artificial conidial inoculation, or in India under natural conditions. QL3 is immune.
4. Field and laboratory.

Charcoal Rot

1. Recessive—few intermediate.
2. No known differences in pathogen
3. Few lines with good resistance.
   (a) None is completely resistant if high yielding and severe moisture stress occurs during grain development.
   (b) Problems of relationship with grain yield, late maturity, and time of stress. Plants must be predisposed by moisture (and heat) stress in later stages of grain development before they are susceptible.
4. Field (moisture stress late)—natural and artificial (toothpick inoculation). In Texas, screening is part of our lodging and drought stress nurseries. We rate for senescence during the late grain development stage when plants are under moisture stress, and this accurately predicts their response to charcoal rot. Nonsenescent types possess better charcoal rot resistance.

Anthracnose

1. Dominant
2. Some changes have occurred in the USA.
   (a) Isolates from Puerto Rico are possibly different but this may be due to environment.
   (b) Brazilian isolates are definitely different from those in the USA.
   (c) West African isolates differ from those in the Americas.
3. (a) Very few resistant in Brazil (but a few good sources, most of which are also resistant in the USA).
   (b) Several resistant in the USA.
   (c) Major differences in host reaction in West Africa, USA, and Brazil.
4. Field—natural and inoculated.

Maize Dwarf Mosaic Virus (MDMV)

1. Several reactions.
   (a) Tolerant reaction (e.g., Martin)—dominant over "red leaf" (e.g., Redlan). Tolerant lines take virus but are not affected adversely. Red leaf development is dependent on cool temperature.
   (b) Rio reaction—susceptibility is dominant over "tolerant" and "red leaf" reactions. Plants are severely mottled, chlorotic, and stunted, but do not have typical "red leaf". Mottling remains in older leaves. Most lines with Rio reaction have low incidence under field conditions, but can have high incidence when inoculated with high inoculum pressure in the field. Reaction is not temperature dependent.
   (c) Venezuela strain susceptibility is dominant over tolerance, red leaf, and Rio reactions.
   (d) QL (Krish source) is dominant overall (not infected).
2. Significant differences.
   (a) Argentina and Australia—somewhat different from MDMV in the USA.
   (b) Venezuelan strain (of sugarcane mosaic virus)—differs from MDMV in the USA based on host reaction.
3. (a) QL (Krish source) is immune; one of the few sorghum lines resistant to infection.
   (b) Many sorghum lines are tolerant.
   (c) Several have the Rio reaction, e. g„ IS 2816C (SC 120), IS 12666C (SC 175), TAM 2566, Rio and several sweet sorghums.
4. Field (natural—greenbug and corn leaf aphid vectors—and hair brush inoculation) plus laboratory.

Head Smut

1. Dominant (some intermediate and recessive).
2. Rapid changes in pathogen in the USA (sources have broken down).
3. Several resistant lines.
   (a) Not known if they will hold under thick populations.
   (b) Some appear to have stabilized general resistance.
   (c) May be few to several major dominant genes.
   (d) Are many modifier genes.

4. Field (natural and artificial) plus laboratory. Inoculation breaks down some lines that are resistant in the field.

Covered Kernel Smut

1. Dominant.
2. Many races.
3. Many resistant lines. Easily controlled with seed treatment.
4. Laboratory—Mix spores with seed.

Loose Kernel Smut

1. Dominant.
2. Two races.
3. Many resistant lines. Controlled with seed treatment. Side branches or late tillers sometimes smutted even though seed treatment fungicides were used.
4. Laboratory. Some problems in getting infection.

Long Smut

Not present in Western Hemisphere
1. Unknown.
2. Unknown.
3. Some resistant lines reported.
4. Field.

Ergot (sugary disease)

Not present in Western Hemisphere
1. Inheritance unknown.
2. No known differences in pathogen.
3. Some resistance reported. Resistance related to heavy pollen shedding. Sterile plants highly susceptible. Male steriles in hybrid seed production are often vulnerable if not pollinated soon after flowering.
4. Field inoculation.

Fusarium Head Blight

1. Intermediate
2. No evidence of major differences in pathogen.
3. Only a few lines with good resistance.
4. Field (natural and artificial).
   (a) Artificial (infected toothpicks in peduncle) overcomes much of the field resistance.
   (b) Natural the best, but hard to screen, because plants must be at correct stage of growth (late grain development appears to be the most susceptible stage), and must have correct environment. Disease usually develops at or near maturity and may be difficult to distinguish from natural drying and colonization by saprophytic fungi. Internal reddening of the pith is the best diagnostic tool. Marbling of pith due to anthracnose is distinct from pith discoloration due to *Fusarium.*

Fusarium Stalk Rot

Not much known. Often occurs when moisture stress is followed by wet conditions at or near maturity. Enters at nodal areas. Resistance to *Fusarium* head blight and *Fusarium* stalk rot may be related.

Rust

1. Dominant.
2. Some differences in host reaction between Texas, Puerto Rico, and Mexico, but may be due to environment. New race suspected in Louisiana, USA.
   (a) Rio, TAM 2566 rust in Puerto Rico but develop very little in the USA.
   (b) Slow-rusting types such as TAM 428 and SC 170 derivatives hold up well in Mexico.
3. Several resistant lines—distinct sources of resistance. Slow rusting trait is useful.
4. Field.

Leaf Blight

1. Dominant.
2. No known differences in pathogen.
3. Only a few lines with good resistance.
4. Field—natural and inoculation plus laboratory.

Sooty Stripe

1. Dominant.
2. No known differences in pathogen.
3. Several sources.
4. Field and laboratory.

Rough Leaf Spot

Little known, but there are some distinct differences in susceptibility under field conditions.

Zonate Leaf Spot

1. Intermediate to recessive.
2. No known differences in pathogen.
3. Only a few resistant—none completely resistant.
4. Field—somewhat maturity related. Generally plants become more susceptible after flowering and near maturity. Also, sterile plants are less susceptible.

Grey Leaf Spot

1. Recessive.
2. No known differences—some location variation in symptom expression.
3. Only a few resistant—none completely resistant.
4. Field—somewhat related to grain development. Sterile plants are less susceptible.

Bacterial Stripe

1. Recessive.
2. No known differences in pathogen.
3. Some very susceptible when others have little if any damage.
4. Field—related to spacing as end plants or nonbordered plants may have much stripe.

Bacterial Streak

1. Recessive to somewhat intermediate.
2. Not known.
3. Some resistant lines.
4. Field.

References

FREDERIKSEN, R. A. 1982. Disease problems in sorghum. These Proceedings: ICRISAT.

FREDERIKSEN, R. A., and ROSENOW. D. T. 1980. Breeding for disease resistance in grain sorghum. Pages 137-167 *in* Biology and breeding for resistance to arthropods and pathogens in agricultural plants. Proceedings, International Short Course in Host Plant Resistance, 22 July-4 Aug 1979, Texas A&M University. College Station, Texas, USA.

TARR, S. A. 1962. Diseases of sorghum, sudangrass, and broom corn. Kew, Surrey, UK: The Commonwealth Mycological Institute.

WILLIAMS, R. J., and RAO, K. N., 1981. A review of sorghum grain moulds. Tropical Pest Management 27:200-211.

WILLIAMS, R. J., FREDERIKSEN, R. A., and GIRARD, J. C. (eds.). 1978. Sorghum and pearl millet disease identification handbook. Information Bulletin No. 2. Patancheru, A.P., India: ICRISAT. 88pp.

WILLIAMS, R. J., FREDERIKSEN, R. A.. MUGHOGHO, L. K., and BENGTSON, G. D. (eds). 1980. Sorghum diseases, a world review. Proceedings of the International Workshop on Sorghum Diseases. ICRISAT, 11-15 Dec 1978. Hyderabad, India. Patancheru, A.P., India: ICRISAT. 469 pp.

Session 5 Genetics and Breeding for Improvement

R. G. Henzell* Discussant—1

I once read that the objective of a discussant is to disagree as often as possible with the principal speakers in order to stimulate animated discussion from the floor. This I am decidedly uneasy about doing when one considers the eminence of the speakers. And of course one of the speakers. Dr. Keith Schertz, was my major professor.

However, let me press on by first discussing the papers by Dr. Fred Miller, N. G. P. Rao, and B. S. Rana dealing with the use of temperate-tropical crosses and on tropical adaptation, and by Mr. Bhola Nath on the population breeding technique. These topics on the availability and utilization of the germplasm are of the utmost importance to breeders—they in fact comprise breeding. It is particularly important at this point in time because I believe that breeders are dealing with a genetic yield plateau in grain sorghum at least in the Western world. Last night I was interested to hear Mr. Quinby express a similar opinion about the prehybrid period.

There is no doubt, however, that grain yields realized by farmers have increased during the 25 years since the advent of hybrids and that breeders can claim at least a part of the credit for this increase. However, I believe that most, if not all, of the portion we can assign to breeding involves the incorporation of genes for characters that indirectly affect yield; characters such as insect and disease resistance and later maturity in environments where later maturity can be supported. (Height is a qualitatively inherited trait that could be, but has not been, used to date except maybe in the tropical regions—height per se does affect yield.) Our breeding over a very long period of time has had little or no positive effect on the many quantitative genes that affect yield!

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The ways by which breeders can lift sorghum off this apparent yield plateau are of considerable concern. I believe the answers lie in our closer attention to the setting of objectives, to our breeding methods and to the judicious use of the vast array of genotypes available to us. In essence, if our objective is yield we should consider the variation we have for yield itself as well as the variation in yield caused by variation in such traits as disease and insect resistance, height, and maturity. Our breeding methods should be designed to deal with this quantitatively inherited trait—I suggest that the population breeding techniques involving recurrent cycles of selection and recombination are the most efficient in this respect. Our utilization of the available germplasm should be such that we maximize the genetic variation for yield itself without significantly decreasing the yield level of the selected population.

On the point of our utilization of the variation found in the tropical (tropical in that they are tall and photoperiod sensitive) genotypes, I find it disturbing that Drs. Rao and Rana in the first part of their paper are less than optimistic. They propose that the simple alteration from tropical to temperate by altering the height and maturity genes has other more profound physiological effects. As a result, they consider that the two groups are so different that the taxonomists should be called in and recombination of desirable attributes from each is "difficult if not impossible." This is disturbing because the majority of genotypes available is "tropical." However, the results quoted in the latter part of their paper happily do not bear testimony to their earlier pessimism. Elite lines such as CS 3541, 148/168, PD 3-1-11, 36A, and 296A. which I believe are widely used in Indian hybrids, have all come from

International Crops Research Institute for the Semi-And Tropics 1982 Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2-7 Nov 81, Patancheru, A P., India Patancheru. AP India: ICRISAT.

temperate-tropical crosses, and in addition resistances to diseases, insects and *Striga* have been found and utilized.

Dr. Miller in his paper exhibits his usual optimism with respect to the beneficial utilization of tropical germplasm. He outlined the TAES-USDA conversion program and listed 36 important plant characteristics obtained from the program. He considered that the products of the program are having and will have a dramatic effect on the sorghum industry.

Dr. Miller's paper also raised the question of tropical adaptation—adaptation with respect to relatively high grain yield in the tropics of photoperiod-insensitive genotypes. We have data in Queensland that indicate that hybrids based on ATx623 exhibit the tropical adaptation characteristic there too. This type of tropical adaDtation has very important implications because of the vast potential for improvement of sorghum for the tropics. Tx623 was selected from a cross between CK-60 and a SC 170 selection. CK-60 is not tropically adapted and SC 170 is a product of the TAES-USDA conversion program—a case of the beneficial use of exotic germplasm.

The cause of this type of tropical adaptation is of obvious interest. Miller's implication that it is caused by a low base temperature (for germination) is open to debate. His argument as to how sorghums, native to the tropics, evolved low base temperatures is logical, but surely tropical adaptation as in the ATx623 hybrids would arise in spite of their low base temperatures. It seems to me that their relatively high yields are due largely to their relatively later flowering (height and some disease resistance may also be involved). For their later maturity to occur they have to be less sensitive to higher temperatures, at least with respect to phenology. Maybe it is a lack of temperature response that is the cause of the tropical adaptation.

I suggested above that the population breeding approach may be a more effective breeding method to deal with quantitative characters such as yield. The method's effectiveness is well established in maize but we need results in sorghum. In this respect the paper on population breeding is of interest. Mr. Bhola Nath's excellent paper relating the obviously well planned ICRISAT program contains some superficially very promising results from (a) Doggett's Uganda program where 3 cycles of S_1 line selection resulted in a 75% increase in yield of the population which then outyielded the best local varieties Dobbs and Serena, (b) Thailand, where the yield of NP3R was increased by 50-70% after 3 cycles of selection, and (c) ICRISAT where one cycle of S_1 line followed by 2 cycles of S_2 line selection resulted in 45 and 30% yield increases in two populations which then had yields comparable with the hybrid CSH-6.

Such increases are fine where they are acceptable but the point is that if the increases were due to these qualitative characters, similar increases could likely have been obtained by the easier conventional breeding approach. We need some positive results from selection practiced for yield unaffected by the qualitative characters which indirectly affect yield and in populations which Start at an acceptable yield level. I believe these results will be forthcoming.

A point that needs emphasizing is that the best breeding method may well be a combination of the population and conventional approaches where possibly the population approach is used to accumulate the quantitative genes into lines which, if necessary, could be fine tuned for the qualitative characters by the conventional methods.

Apomixis is potentially a very powerful tool for the utilization of heterosis particularly in countries where the seed production industry is not active. However, for apomixis to be useful it needs to be obligate or nearly so and stable over environments, the diploid embryo sacs need to be produced in such a way as to maintain heterozygosity, and the genetics governing its expression need to be simple so that when superior hybrids are bred, apomixis is easily incorporated into them. When those requirements are considered, the future for apomictic sorghums is not encouraging.

Drs. Murty, Rao, Kirti, and Bharathi's paper reflects this situation and is a very honest account of the present situation and future prospects. The paper is excellent in that it leads us through the nature of apomixis in sorghum, the difficulties encountered in its study and suggestions as to how it could possibly, even in its present state, be used, e.g., their "Vybrids." Surely, however, the future is not without hope when one considers the tremendous potential of the character, the progress made in the development of techniques used in its study and the fact that very few of the vast array of sorghum genotypes have been studied so far. Breeders will look forward to hearing of the progress made in the 1980s.

Drs. Schertz and Pring in their paper on the cytoplasmic-genetic sterility systems in sorghum reemphasized the importance of diversity of both the nucleus and the cytoplasm not only in hybrids but also in varieties. The extensive use of the diverse germplasm from the world collection has been a tremendous boost in helping to remove us from the perils of a narrow nuclear genetic base. As they point out, considerable progress has also been made, mainly in the USA and India, in identifying (identifying both with the usual sterility restoration method and also with the interesting and time-saving electrophoretic separation of cytoplasmic polypeptides) diverse cytoplasms—diverse at least in respect of the conditions so far imposed on them. As they point out, the presence of these diverse cytoplasms allows additional nuclear diversity as well. For example, some genotypes which restore male fertility in the A, cytoplasm do not in the A_2 cytoplasm, i.e., they can be used as females. Also, most if not all genotypes which are partial restorers in the A, cytoplasm are nonrestorers in the A_2 cytoplasm—this is particularly important in cases where B lines (nonrestorers) are required from a BxR cross.

Breeders have an important responsibility to keep abreast with developments in the field and to utilize the cytoplasmic diversity available to them.

An obvious need now is an understanding of the genetics of these new systems. Indeed the published information relating to the presently used A, cytoplasm certainly does not explain the situation and this brings us to Mr. Quinby's paper. In a typical piece of original thinking, he has proposed a simple model to explain the cytoplasmic, genetic sterility systems, and apomixis in sorghum. I do not intend to discuss the details of the model but merely to emphasize that there is now a model against which data, as it is collected, can be fitted. In so doing the model will be verified or modified accordingly.

Session 5 Genetics and Breeding for Improvement

M. Riccelli* Discussant—2

First of all. I would like to congratulate the authors of the papers of this afternoon for their excellent presentations and coverage of the field.

The papers by Drs. Murty, Rao, Kirti. and Bharathi did an extremely good job of presenting a comprehensive review of apomixis in the sorghum plant, of the progress made so far and of the problems that need to be solved before this phenomenon can be utilized in one of the most spectacular goals of plant breeding, i.e., the fixation of heterosis. They have drawn attention to the formidable difficulties encountered in this field; from the practical standpoint, the most important seem to be its lack of stability and the hardship in achieving obligate apomixis. We must remember that during the evolution of all annual crops produced for seed there has been an intensive selection for reproductive normality; it is not rare, then, that apomixis is found with a very low frequency in the sorghum species. However, the results presented here are encouraging and we should feel optimistic and look forward to the time when both general and specific combining ability will be fixed and fully exploited as the efficiency of selection permits.

In considering the need to avoid in sorghum a major catastrophe, like the one that occurred in maize in the 70s when all cultivars having male-sterile cytoplasm were severely damaged by a virulent strain of *Helminthosporium maydis,* the papers presented by Drs. Schertz and Pring and the one delivered by Dr. Quinby are extremely interesting because they summarize the effort to identify new male-sterile cytoplasms, and to understand the interactions between genes and cytoplasm in the sex expression of sorghum. The availability of new sources of male sterility and of new cytoplasms not only represent a guarantee against possible epidemics (Schertz 1975), but also a tremendously important tool to explore new heterotic combinations for the increase of yield and stability. New alternatives for the "old" sterility system caused by the interaction of "milo" cytoplasm and "kafir" genes, that is being used to produce almost all of our present sorghum hybrids, can now be considered. Since the first new discoveries in the early 60s in India, Africa and the U.S., many male steriles have been isolated in different groups or races of sorghum. A number of them seem to be of different nature, as shown by both test crosses and DNA analysis.

In spite of the progress achieved in the last two decades, it is essential that additional information is gathered to fully understand the genetics and physiology of sex expression in sorghum for its possible agronomic application. Theories on the action of sex expression genes and the interactions among themselves and with different cytoplasms, on the chemical and hormonal effects on the sexuality of the sorghum plant, and on incompatibility and apomixis have been proposed in the paper by Dr. Quinby. An effort has been made to assign a particular genotype-cytoplasm combination to a number of sorghum cultivars. This presentation suggests to me that there is still another very important phenomenon within the so-called flowering abnormalities which deserves considerable attention, i.e., head blasting.

Head Blasting

This trait is similar to the one that Ayyangar and Ponnaiya (1939) have described as florets at the tip of the panicle that were mere whitish scales,

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but, in our nurseries, the atrophied portion may extend to more than half, and in severe cases to the whole, panicle. Barren-type sterility was also noticed by Jaisani and Drolsom (1972) who suggested that this character is controlled by two pairs of genes.

From the practical standpoint, head blasting causes considerable losses in hybrid sorghum seed production. It is less severe in the temperate areas than in the tropics where one can notice up to 70% loss of grain in the field due to blasted florets.

After observing the occurrence of this phenomenon in the tropics during the last 13 years, one can conclude that the following components must be dealt with in studying this trait:

1. A genetic component, since some A lines (Kafir 3197, Redbine, Redlan, Texioca, TAM 618, KS 23, KS 24, OK 12 and Combine Sagrain) are much more susceptible to blasting than others (Martin, Wheatland, Tx 621, Tx 622, Tx 623, Tx 625, Tx 2758, Tx 2759 and 1391) under many different environments.
2. A cytoplasmic component, since head blasting is observed in male-sterile (A lines), but not in their fertile counterparts (B lines).
3. An environmental component, since the amount of blasting in a particular A line may vary drastically under a different set of environmental conditions.

Head blasting has been frequently associated with moisture and heat stresses (Wilke and Rosenow 1976). In our nurseries, head blasting has been observed even without any moisture stress and/or during the mildly warm months of December and January. It looks like this trait is much more complex; strong interactions seem to take place among the different components. An understanding of this phenomenon is essential for hybrid sorghum seed production in the tropics and it is hoped that in the coming decade, with increasing international cooperation, it will be clarified.

Breeding Sorghum in the Tropics: Tropical and Temperate Adaptation

The presentation by Dr. Miller has drawn attention to several basic facts about the sorghum plant that are essential to its breeding for improvement. His hypothesis that adaptation to different regions of the world might be due to differences in the base temperature of the different cultivars and that a measurement of such base temperature could be used in predetermining areas of geographical adaptation, is extremely interesting.

In order to develop a global sorghum improvement program, I would like to add a few more factors for consideration in this meeting:

Different Environmental Conditions

An understanding of the different environmental conditions of each country, which cannot be described only in terms of its latitude, temperature and rainfall pattern, is essential. Within the so-called "Tropical Grassland" (between 23½°N and S latitudes), the natural area of adaptation of sorghum, there is an enormous array of different environments in which different sorghum types have evolved with specific adaptation. A sorghum cultivar may show a very different growth pattern when it is moved, for example, from Venezuela to Nicaragua, from there to Puerto Rico, from there to Mexico and from there into South Texas, even if all these sites are regarded to be within the tropical climatic type. Generalizations of broad adaptation of sorghums are often misleading. One could explain the success of some U.S. hybrids in certain subtropical areas of Mexico and Brazil on the basis of latitude similarities, but as one moves closer to the Equator, the same hybrids appear quite unacceptable, especially those that are known as first and second cycle U.S. hybrids. Downes (1972) suggested that the decrease in grain production of standard U.S. cultivars when grown in the tropics is due to an adverse effect of high temperatures to which they are exposed between emergence and floral initiation.

Having spent most of my life in tropical America, I shall discuss briefly only those environmental factors limiting yields in the area between 13° N and S latitudes which show specific and unique interactions among climate, diseases, insects, weeds, soil and sorghum utilization. Therefore, it is important that tropical adaptation be identified in situ.

Tropical adaptation in sorghum has been defined in Texas as "the ability to produce high yield when planted in short days, and grain fill occurs in longer days and hot nights." This definition would describe better a subtropical type of adaptation as the one needed in South Texas or Northern Mexico. As we get closer to the Equator, daylength and temperature during planting and grain fill are about the same.

Within the same tropical latitude and elevation, one can find regions with a long rainy season, semi-arid areas, locations with only one rainy season per year (sometimes occurring during the longer days and sometimes during the shorter days), and with two rainy seasons per year. Outside a particular zone of adaptation a cultivar may be either too late or too early; therefore, sorghums of proper maturity must be utilized in each case. Within these areas, a large part of the soils are very acid, high in exchangeable aluminum and show low fertility and water holding capacity (for example, the "cerrado" in Brazil and the western part of Venezuela). Some diseases are widespread throughout regions of high humidity: rust, grey leaf spot, zonate leaf spot, *Helminthosporium* leaf blight, charcoal rot, *Fusarium.* anthracnose, and grain molds. Others are specific to certain areas: sorghum downy mildew and a new virulent strain of SCMV limited to Venezuela (Riccelli 1980) and, perhaps, Northern Brazil (Sharvelle 1975) to which a large number of elite lines from Texas are susceptible (for example, Tx 2536, Tx 430, Tx 2723, Tx 2728, Tx 2737, Tx 2744, Tx 2748, SC 170-6-17) with susceptibility being dominant over resistance. Some insects are widespread in their distribution (fall armyworm, midge, stem borers, webworms) while others are restricted to certain locations (for example, *Platylellus costalis,* Miridae, Hemiptera. a grain sucking insect observed by the author this year in Venezuela). The absence of a winter season and the presence of wild sorghums (S. *arundinaceum, S. halepense, S. verticilliflorum* and many crosses among them) that serve as alternate hosts make disease and insect problems much more severe in the tropics than in temperate zones. Fall armyworm, for example, can become a very serious pest, and since the crop must be sprayed several times, resistance to the phytotoxic reaction of certain insecticides is necessary. It has been found that resistance to phytotoxicity of a common insecticide is recessive to susceptibility (Riccelli 1971). Local and migratory birds may be a problem in some areas but not in others.

Breeding objectives in the tropics should, by necessity, depart from traditional patterns established by plant breeders working in other parts of the world. On the other hand, when a sorghum breeder is located close to the Equator, he can screen and utilize in his crosses almost the whole germplasm available since every sorghum entry will flower within a reasonable amount of time. Furthermore, he can get up to three generations per year in the field at the same location.

Thirteen years of sorghum breeding in that part of the world has resulted in high yielding cultivars that meet specific requirements of adaptation. Some can take full advantage of a long rainy season and mature at the beginning of the dry season, while others are earlier and better adapted to locations of low rainfall or erratic rainfall distribution. With no intention of stating a precise order of importance, the following are traits shared by the best cultivars developed independently in Venezuela and Colombia:

1. Photosensitivity and ability to grow and flower 6 to 10 days later than standard U.S. hybrids. This factor contributes substantially to yield increases (Dalton 1967).
2. Higher tolerance to low pH.
3. Improved water-use efficiency or ability to withstand moisture stress and resume growth after a new rain.
4. Height between 1.7 and 1.9 m with dense leaf canopies. This would be unacceptable in the U.S., but it is necessary in the tropics, on one hand, to hold weeds in check because of their luxuriant and rapid growth and, on the other, to obtain maximum yields. In spite of this height, they do not lodge because of their strong stalk and root systems and, contrary to what is commonly believed, mechanical harvest is feasible.
5. Semi-open panicles and brown grains. Although selection for brown seeded sorghums has not been intentional, it seems that the presence of tannins contributes in some way to tropical adaptation.
6. High tillering potential and ability to produce a ratoon crop when feasible.
7. Resistance to the new virulent strain of SCMV, charcoal rot and anthracnose.
8. Weathering resistance. This trait is essential because maturation and harvest may take place during unexpected rains. It has been observed that preharvest seed germination is very low in these cultivars, a fact that confirms the results by Harris and Burns (1970).
9. Bird resistance. Damage by parakeets and dickcissel *(Spiza americana).* a migrant sparrow that breeds in summer in the Great Plains of the U.S., has been a perennial problem which

has been carefully studied (De Grazio and Besser 1974).

In Armero, Colombia, (4° N), the Colombian varieties Iea Nataima and Prosemillas, the Colombian hybrids Tropical 4 and Tropical 9, the Venezuelan varieties Guarico and Monagas and the Venezuelan hybrids Chaguaramas 2 and Chaguaramas 3 show good adaptation and high yields throughout the year, while in Maracay, Venezuela, (11°N) all of them show good performance during the long rainy season that occurs under longer days (12 hr 30 min), but behave poorly under irrigation during the dry season when daylength approximates 11 hr 30 min. When planted in South Texas, the same cultivars took more than 100 days to flower.

It is worth mentioning that when a tropical adapted cultivar is used to pollinate a temperate male-sterile line, the resulting hybrid is also tropically adapted. This is the case of the four hybrids mentioned above.

Keys to Profitable Grain Production

The real needs and problems of each country must always be kept in focus. Priorities in breeding for improvement must be identified in each country. High yields and stability are universal goals, but others are quite specific. For example, *Striga* resistance is important in Africa and Asia, but not in Central or South America; intercropping with sorghum is important in Central America, but not in North or South America; photosensitivity must be avoided in the temperate zones, but is sometimes needed in the tropics where more flexible planting dates are required (Webster 1975). Adjusting length of maturity to match critical stages of crop development is one of the most formidable tasks facing a tropical breeder. However, in the semi-arid regions of the tropics, where early varieties are needed, photoperiod insensitivity is required.

As far as grain quality and culinary acceptability are concerned, we must first distinguish between those countries which use grain sorghum for feeds or any other industrial purpose (U.S., Argentina, Brazil, Venezuela, Colombia) and those which use grain sorghum for human consumption (Central America, Africa. Asia). Within the countries of the first group, we must distinguish between those where brown seeded sorghums are unacceptable (U.S.) and those where they are not discriminated against (Venezuela, Colombia). Final breeding products are different in each case. In Argentina, Colombia and Venezuela, brown sorghums have been very successful and are preferred by farmers because of some good agronomic traits, high yield potential, insensitivity to low pH, weathering, midge and bird resistance, low preharvest seed germination and ratoonability. In the tropical humid lowlands, white and yellow sorghums have been disappointing so far.

In Venezuela, grain sorghum is produced mainly by cattlemen, not by farmers. After harvesting the grain, cattle graze on what is left of the sorghum plant. The "stay-green" or nonsenescence trait, an abundant leafage and high stem sugar content are very important characters in this case.

Some unique farming systems have been adopted in response to unique climatic requirements. There are areas in the tropics where heavy rains start suddenly after a long dry season and from there on, it may rain almost every day. Planting large areas becomes difficult because farm machinery cannot work in the mud. One practice adopted by almost 100% of the grain sorghum producers in Venezuela is to carry out a light seedbed preparation, broadcast the seed by a fertilizer spreader and disk it under immediately. In this way hundreds of acres can be planted daily at the very beginning of the rainy season. Sorghum cultivars that are planted in this way must respond favorably to the following requirements;

1. Seedlings must emerge with vigor even if seeds had been disked too deeply under the land surface. This character is quite common in tropical cultivars as has been reported by Miller (1977).
2. Plants must have a good tillering capacity, with tillers flowering at the same time as the main stem, to make up for those plants missing due to an uneven planting.
3. Plants must be taller than usual and form a dense canopy to achieve better weed control since no tractor can enter the field after planting, and cultivation is impossible. The use of herbicides sprayed from helicopters or small planes is not always effective.
4. Since mechanical cultivation is impossible, plants must develop a good root system, even in acid soils, and a strong stalk to avoid lodging. Lodging resistance seems to be highly correlated to nonsenescence (Rosenow 1977) which is a very desirable character where stover is used after the grain is harvested.

Most of the sorghum breeding in the past has been done in the U.S. At the beginning, the germplasm in this country had a narrow base, but it has become increasingly richer through the conversion of exotic photosensitive introductions (Stephens et al. 1967). In recent years an effort has been made both in India and the U.S. to improve sorghums according to a global scheme which will benefit a large number of countries around the world. Breeders working in the tropics should realize that they have an excellent opportunity to select from the Tropical Bulks released from the Conversion Program instead of using finished lines selected in Texas with emphasis on short and early plants. Each Tropical Bulk should contain an array of maturities and heights to fit many different tropical environments. However, in many agriculturally underdeveloped countries there are relatively few breeders; they must also take care of seed prodution, certification and extension. Interdisciplinary teams sometimes are totally absent. Incipient national programs need the support and significant contribution from international institutions to become more efficient and useful. However, results of research will be meaningful only when they are successfully applied by the farmer. In this sense, production and distribution of certified seed plays a major role. However, hybrid sorghum seed production in the tropics is limited and faces many problems. We thought that the best answer to the problem would be to develop well adapted open pollinated varieties since their seed can be produced more easily. Some F_6 selections from crosses between E-75 (IS 8622), a variety from Uganda, and SC 103-C, and between E-75 and CS 3541 were tested this year for the first time and outyielded every imported hybrid except one. In Colombia, where international companies locally produce seeds of hybrids developed in the U.S., two open pollinated varieties are planted in more than 60% of the total sorghum acreage.

Social and Economic Structure

An understanding of the social and economic structure of each country must exist. Although it would seem too simplifying, for the purpose of this discussion one could classify any country of the world into one of the following four classes:

1. Rich and agriculturally developed (example: the U.S.)
2. Rich but agriculturally underdeveloped (example: Venezuela and other OPEC countries)
3. Poor but agriculturally developed (example: several countries in South America, Southern Europe, Africa, and Asia)
4. Poor and agriculturally underdeveloped (many countries in Central America, Asia, and Africa)

Countries belonging to the first class have invested substantially in agricultural research, can afford to undertake basic as well as applied research and move the findings from the experiment station to the farmer. Hybrid sorghum seed production is feasible and there is a surplus to export to other countries. Maximum yields are attained through effective utilization of the environment and the best adapted heterotic combinations.

Countries in the second class can also afford research and can buy all kinds of technology and equipment, but results remain in the experiment stations. For example, in my own country tropically adapted hybrids have been developed that, locally and in Central America, have outyielded any other hybrid developed elsewhere, but seed production of these hybrids has encountered many difficulties because of poor farming systems. In spite of the availability of very modern seed processing plants, grain sorghum production is carried out using a number of hybrids that international companies have poured in without any previous local testing in a number of cases. Very often these cultivars show very little tropical adaptation. Even those with a wider range of adaptation are easily outyielded by some tropical hybrid combination. Again, high yielding and well adapted varieties can still be the answer where a developed agriculture has not been reached yet.

The economies of countries belonging to the third class have been based traditionally on a solid and well developed agriculture. Any little progress that is made is easily applied by the farmer. They can take full advantage of international cooperation. The almost miraculous increases in yield of wheat in Mexico, India, and the Near East and of rice in Colombia (the "green revolution") are good examples.

Countries in the fourth class can afford to undertake only very modest research programs and even if they can get help from international collaboration, the results very rarely are fully utilized by the farmer. In this case, also, high-yielding and well-adapted varieties could be the initial goal of the sorghum breeder.

The majority of agriculturally underdeveloped countries have a tropical climate. Their main advantage for improving quantity and quality of food production is a full 12-month growing season, if water is available for irrigation during any dry period. Sorghum cultivars should be developed to fit any planting date throughout the year.

Finally, there are countries where sorghum production is feasible only because their governments are subsidizing it (present price in Venezuela is U.S. $ 0.15/lb). In this case production can increase only to the point where domestic needs are satisfied. Thereafter, they cannot expect to be able to export any amount of grain unless productivity increases dramatically and prices become competitive in the international market. This can only be achieved if cultural practices are improved and high yielding cultivars are developed.

Closing Remarks

In spite of all the existing problems pointed out in this discussion, we must recognize that in the last decade a tremendous amount of work has been done in order to find a practical solution to each of them. Undoubtedly, we have advanced a lot and, even if there is still a great task to be accomplished ahead of us, we now have a much closer picture of what needs to be done in the next 10 years.

Plant breeders are now asked to incorporate increased insect and disease resistance into modern cultivars as well as specific traits to fit the environments and the needs of each country. This carries a formidable responsibility, particularly for the low income countries in the tropics. In these countries, host resistance and specific adaptation are the only keys to profitable production since, on one hand, pesticides are expensive and the daily rains wash them away before they can be effective and, on the other, financial, biological and chemical resources (for example water, lime, fertilizers) and farm machinery to modify the environment, are quite limited. Plant breeders must then develop cultivars that can resist or tolerate the adverse soil and climate conditions. They must also seek new methods that can shorten the time required and make cheaper the development and testing of varieties, lines and hybrids.

Sorghum improvement in the 1980s is linked to the imagination, ingenuity and diligence of the sorghum breeders working around the world. We must strive for increased production and productivity because such increases are essential if world hunger is to be avoided.

References

AYYANGAR, G. N R , and PONNAIYA, B. W. X 1939. The occurrence and inheritance of panicle-tip sterility in sorghum. Current Science 8:116-117.

DALTON, L G 1967. A positive regression of yield on maturity in sorghum. Crop Science 7:271.

DE GHAZIO, J. W., and BESSER. J. F. 1974 Bird damage to crops in Africa and Latin America. United States Department of the Interior, Fish and Wildlife Service. AFR-632, 682-D 321 a, 8 pp

DOWNES, R W 1972 Effect of temperature on the phenology and grain yield of *Sorghum bicolor.* Australian Journal of Agricultural Research 23 : 585-594.

HARRIS. H. B. and BURNS, R. E 1970. Influence of tannin content on preharvest seed germination in sorghum. Agronomy Journal 62:835-836.

JAISANI, B G.. and DROLSOM, P. N. 1972. Studies of nonrandom and barren-type sterility in *Sorghum bicolor* Crop Science 12:37-40.

MILLER, F. R. 1977. Tropical adaptation. Pages 179-195 *in* Development of improved high yielding sorghum cultivars with disease and insect resistance. Third Annual Progress Report. Texas Agricultural Experiment Station.

RICCELLI, M. 1971 Differential phytotoxic reaction of sorghum cultivars to insecticides. I. Genetic resistance to trichlorfon. Crop Science 11 :923-926.

RICCELLI, M. 1980. Current strategies and progress in breeding disease-resistant sorghums in Venezuela Pages 434-453 *in* Proceedings, International Workshop on Sorghum Diseases. ICRISAT, 11-15 Dec. 1978. Hyderabad, India. Patancheru, A.P., India: ICRISAT.

ROSENOW, D. T. 1977. Breeding for lodging resistance in sorghum. Pages 171-185 in Proceedings, 32nd Annual Corn and Sorghum Research Conference, 6-8 Dec, Chicago, Illinois, USA. ASTA Publication No. 32.

SCHERTZ, K. F. 1975. Use and potential of the sorghum conversion program to reduce genetic vulnerability in sorghum. Pages 360-378 *in* Proceedings, International

Sorghum Workshop, 7-11 Jan 1975, University of Puerto Rico, Mayagliez.

SHARVELLE, E. L. 1975. Sorghum diseases in Brazil. Pages 212 222 *in* Proceedings, International Sorghum Workshop, 7-11 Jan 1975, University of Puerto Rico, Mayaguez.

STEPHENS, J. C , MILLER, F. R., and ROSENOW, D. T. 1967. Conversion of alien sorghums to early combine genotypes. Crop Science 7 : 396

WEBSTER, O. 1975 Use of tropical germplasm in a sorghum breeding program for both tropical and temperate areas. Pages 1-12 *in* Proceedings, 30th Annual Corn and Sorghum Research Conference. 9-11 Dec, Chicago. Illinois, USA, ASTA Publication No 30

WILKE, O., and ROSENOW, D. T. 1976. Observations on head blasting in water-stressed sorghum Progress Report 3387. Texas Agricultural Experiment Station 3 PP

Session 5 Genetics and Breeding for Improvement

Discussion

de Wet

I suggest that care should be taken in introducing gametophytic apomixis into breeding programs as a means of stabilizing hybrid or selected genotypes. In my experience with apomixis, both apospory and diplospory, sexual and asexual pathways to seed production are not genetic alternatives and operate simultaneously in the same genotype. This leads to a substantial amount of genetic recombination through sexual reproduction. Both the sexual and asexual female gametophyte are usually able to function sexually or develop parthenogenetically. The offspring of a gametophytic apomict may therefore include diploid and haploid maternal genotypes, as well as diploid and triploid "hybrid" genotypes. Seeds harvested by the farmer may therefore differ substantially in genotype combination from samples obtained from the plant breeder or commercial producer.

Another danger in apomictic seed production involves differential selection against particular gene combinations within the hybrid or adapted population that may contribute to overall yield stability.

Jain

Mr. Bhola Nath's work on population improvement procedures will be of great interest to the statistical geneticists who need some real world examples of such work. I have always challenged my students to search for examples where quantitative genetic theory has helped a breeder. They are hard to find, but now a large number of selection experiments and some computer simulation work have been reported. I believe these have made it feasible for developing theory for guidance, and not for simply a posteriori analyses of data. Gains with multiple trait selection and the rates of desired recombination should be goals of this theoretical work.

Niangado Oumar

Can I have the results of comparison of different methods of selection used for the improvement of populations?

Bhola Nath

We have not made comparisons of different recurrent selection procedures ourselves. The conclusion drawn from Hallaeur's paper indicates that all methods are almost equally effective. As our program is production-oriented, we did not put our priorities on theoretical aspects. We expect such studies will be undertaken at universities.

Blum

Percent gain per cycle is used as a measure of selection efficiency in population breeding. Since gain by selection for yield is dependent on base population yield level, do we have a measure (coefficient?) that will express percent gain in relation to yield of the base population?

Bhola Nath

We have given the grain yields of different cycles along with the percent gains per cycle. Not only that, we have also included the grain yields of different cycles of populations along with the released variety and hybrids in India for comparison. I am not aware of any other parameter (coefficient) for measuring progress.

Goud

M35-1A and M31-2A are indicated as *Cernuum dochna* and Cernuum races respectively. Both of them are sister lines of the same cross. Is there any evidence of differences in the mitochondrial DNA fractions of these two cytoplasms? I feel both of them belong to the *dyrra* type rather than the *Cernuum* type.

Schertz

We do not have information from our studies on the differences between M35-1 and M31-2 cytoplasm. Nagur and Menon indicated that they were different. Tripathi found no difference in sterility response.

Webster

Recurrent selection of parents of hybrids should increase their yields. It should be possible to approach the F1 seed size and this needs more attention. Seed size is one of the factors which affects yields of hybrids.

Parvatikar

Breeding for various traits like drought tolerance, improved nutrient utilization, pest and .disease resistance, *Striga* resistance, etc., has been very rightly emphasized in almost all the Sessions till now. Breeding for such traits appears to be a good and fairly lasting solution for these problems but we could look for some other lines of work also to solve these problems. As indicated by Dr. Quinby the genes responsible for height operate by the regulation of auxins and gibberellins in the plant body.

Our own experiments have shown that exogenous application of cytokinins (kinetin) to the panicle of sorghum has resulted in increases of up to 50-60% in the grain yield (mobilization and enhanced uptake of nutrients). My suggestion is that exogenous application of growth regulators (inhibitors and promoters) and the stimulation of enzymatic activity and the like, could be resorted to, though these have certain limitations. At present, the difficulties (limitations) for such studies appear to be the lack of personnel for such work and more so, the facilities provided for them.

Balasubramanian

(n view of differing patterns of agricultural technology and the environment associated with it, is it worthwhile to test sorghum cultivars for disease resistance across locations? Is it not good enough to breed for disease resistances which are. location specific?

Rosenow

I believe it depends on the extent of the area of responsibility of the breeder. If one has international responsibility, then broad based screening is essential. If one is breeding for one location for a local area, then screening in that area only may be entirely sufficient. Worldwide, there are good reasons for screening across locations, namely for the identification of stable resistance and for finding different biotypes of the organism.

Balasubramanian

How best can we rely on the glossy character to select for shoot fly resistance when it was said earlier that it is a fading character after the seedling stage.

Agrawal

According to the information which we have on glossiness, it appears that it has a very close linkage with shoot fly resistance and works as an indicator trait. However, these results need further confirmation. In case these results hold true in future it can surely be utilized as a selection criterion for shoot fly resistance. In such a situation we have to simply identify glossy plants from early segregating populations and later purify them. After deriving homozygous lines under diverse backgrounds, their resistance can be confirmed under varying fly pressures over seasons and locations.

Weibel

I would like to make a strong case for backcross breeding. When we have something good we can build on it. There are examples of success such as the head smut and MDMV resistant combine 7078 lines, the diease resistant combine kafir-60 lines, and the greenbug resistant Tx 2536 lines. I could have made a greater contribution if I had bred a Redlan with combined resistance to diseases and insects. I suggest to you young breeders, do not be stamped into complete dependence on population breeding which is not yet proved. The pedigree and backcross methods of breeding have brought us this far and they should not be discarded. In fact, the backcross method could be used more extensively.

Nagur

I would like to make a few comments on the presentation of Dr. K. Schertz. In his studies, he has used one of the two male-sterile lines of M35-1 developed in India. They have different backgrounds. One was identified and developed by Dr. N. G. P. Rao as a spontaneous male-sterile mutant in M35-1. The second one was developed when the identified spontaneous male-sterile mutant from AS 9018 "Irungu Cholam" belonging to *Sorghum dochna* was crossed and backcrossed to M35-1 at Koilpatti, Tamil Nadu, India.

I believe Dr. Schertz has used the male-sterile M35-1 that was developed by Dr. Rao. But Dr. Schertz presumed that he has been using the one with dochna cytoplasm, since he (Dr. Schertz) obtained the description of the M35-1A male-sterile line from my studies.

As already mentioned by Dr. Schertz, I could classify the six male-sterile cytoplasms into the four groups—CK 60A in th first group, M35-1A (dochna cytoplasm) and G1 into the second group, VZM1A and VZM2A into third group and M31-2 into the fourth group.

Dr. Schertz brought out in his presentation the necessity to study the effect of different male-sterile cytoplasms on the expression of different agronomic traits. I have studied the effect of different male-sterile cytoplasms on a common genome, looking at the expression of agronomic traits, and differences were found among the four groups of male-sterile cytoplasms used.

The differences in the effects between male-sterile and fertile cytoplasms and between two fertile cytoplasms were also studied and significant differences were observed for the expression of agronomic traits.

As already pointed out by Dr. Schertz, there is every necessity in the future to give cognizance to the specific type of cytoplasm used in breeding programs in order to derive maximum benefits.

Colleagues have enquired about the origin of the male-sterile line G 1A since it is being variably identified as G 1A and G 2A. In 1957, I identified spontaneous male-sterile plants in the line G 2, a *rabiseason* yellow grain variety, and I crossed the male-steriles with the pollen of G 1 (a sister line of G 2) for want of G 2 pollen. G 1 could maintain male sterility, and I continued backcrossing it with G 1. It was established as G 1A (Nagur et al.1965). G 1A has G 2 cytoplasm and the nuclear factors of G 1. (Nagur, T., Narasimhamurthy, K., and Partharasarathy. 1965. A note on the male-sterile yellow grain Jowar. Andhra Agricultural Journal 12(5): 183 -184.)

Gebrekidan

A lot has been said on the importance and utility of population breeding. However, the Texas Program, which has made considerable progress, has utilized mostly conventional breeding methods. Can anyone comment?

Miller

In Texas, we use both methods (concepts) of qualitative and quantitative genetic manipulation. I subscribe to Dr. Weibel's comment. My program is based on pedigree and backcross breeding almost entirely. I have populations in which I store a wide base of genetic diversity. This population concept is used to identify sources of resistances or the quality factors needed. These are then added to the pedigree or backcross breeding program. We are not involved in population improvement systems. We do subscribe to the use of both methods but find that conventional pedigree and backcross methods contribute most toward our objective.

Maiti

We have consistently observed that a simple morphological trait like glossy is related to a high level of tolerance to shoot fly as well as resistance to seedling drought. Therefore we should examine the feasibility of incorporating it into elite breeding lines.

Agrawal

Before we capitalize on this trait, we should try to examine its role on multiple resistance more critically and confirm our existing results.

Maiti

In collaboration with K. E. Prasada Rao we have screened 21 000 germplasm lines for the glossy trait. Although glossy lines mainly originate from the Deccan peninsular (India) region, there are some lines from other taxonomic and geographic groups.

Rana

The glossy trait and its association with shoot fly resistance was reported two decades back. The glossy trait conditions the nonpreference to oviposition. The trait is expressed due to a low N content in the leaf. Selections of glossy types have been made. As far as trichomes are concerned, some susceptible lines also have trichomes. Perhaps resistance is expressed due to the interaction of trichome with some other traits rather than trichome per se.

Maiti

I agree with you. but people have mentioned it casually. These traits have not been used to my knowledge in the screening of germplasm.

Rana

When simultaneous selection is practiced for resistance to several insect pests in early segregating generations, what resistance level could you recover for each insect in the next generation? Did you notice the gene erosion for yield and other economic characters? What breeding method do you use to develop resistant lines?

Agrawal

At ICRISAT we try to expose early generation segregating materials to a low pressure of various insects and diseases in a pesticide-free area to eliminate highly susceptible types. Selections are continuously tested with increasing insect pressures as the generation is advanced. During this period, selection pressure is applied only for one insect at a time. When the material is sufficiently good, it is tested against other insects and diseases. In this way, some progenies are found to have reasonable levels of resistance for more than one trait. Several shoot fly resistant lines have been found to possess resistance to stem borer and other insects.

The best answer I believe is the adoption of the population approach for simultaneous incorporation of several resistant traits.

Shinde

In the F2 population of tall x dwarf sorghum crosses the frequency of dwarf segregants remain exceptionally low and the segregation pattern of tall and dwarf plants do not conform to the allelic system of height genes reported by Quinby in temperate sorghum. Is there a different genetic system for height genes in tropical and temperate sorghums?

N. G. P. Rao

I have had a similar experience. I therefore feel that the allelism for height genes between temperate and tropical dwarfs needs to be tested.

Miller

There seems to be confusion resulting from differences observed in India (and other tropical/short day growing areas) and the temperate USA between height and maturity inheritances. There must be some realization that photoperiod sensitivity can completely mask or hide the influences of these important traits (height and maturity). Data by Miller and Quinby (Crop Science 1968) and Miller et al. (Crop Science 1968) explain the influences of photoperiod. If photoperiod sensitive materials are crossed to these identified genotypes and such crosses are grown in the short days (of less than 12 hr) the inheritance can be seen. But if the crosses are grown in longer days (more than 12 hr) the photoperiod sensitivity completely masks the expression of the genes. It must be kept in mind that one must be able to observe materials in both daylengths (less than 12 hr and greater than 12 hr) to fully understand what is going on in height and maturity. With this understanding one can relate the correlation of height and maturity to yield and yield components.

Jotwani

Glossy trait' has been suggested as a marker for selecting shoot fly resistant lines. However, every resistant line may not have the glossy character. There are now glossy lines which possess moderate levels of shoot fly resistance. Pale yellow color of leaves and glossy character are generally associated with oviposition nonpreference. Some of the lines showing antibiosis may be nonglossy. Thus by selecting only the *giossy character* we may *iose some lines* possessing antibiosis.

Agrawal

I agree with your comments. At this point of time, we need to confirm further the usefulness of the glossy trait as an indicator for shoot fly resistance in breeding projects. Our results indicate that the correlation between shoot fly resistance and the glossy trait is not perfect. The association between the glossy trait and oviposition nonpreference could be due to the presence of trichomes. I agree with your last comment. But if I look at our breeding material, the proportion of nonglossy types is really very low and I feel that losing a small. proportion of resistant nonglossy genotypes may not be very important, particularly if we are able to transfer resistance faster and more effectively using the glossy trait. What we are doing is to find easily identifiable, tightly linked, simply and highly heritable traits correlated with resistance, i.e., major genes which are much easier to handle and transfer than minor genes. At this stage we cannot say that glossy is the only trait which is associated with shoot fly resistance. Its real role still has to be critically examined.

Bapat

Dr. Rao reported limited progress with temperate x tropical crosses in single crosses, backcrosses and double crosses. Do you think that some other breeding method like population breeding with reciprocal recurrent selection will be more efficient in getting better segregants?

N. G. P. Rao

In crosses involving the "tropical and temperate" sorghums, once the necessary corrections are made for height and maturity, the population breeding approaches may be rewarding. If we want to start with the original tall or dwarfs as base populations, disruptive selection approaches may be more rewarding.

Shinde

Nowadays there is a problem of female sterility in sorghum. This aspect is very important from the seed industry point of view.

Mushonga

What method of population improvement would you advocate for developing countries for the immediate results which will benefit the farmer?

Bhola Nath

Depending upon the resource availability, one could use either mass selection or S, testing.

Safeeulla

Have we explored the possibility of collecting resistant sorghum germplasm in disease hot spots? At least for major diseases? What is the possibility of a few persons working in different countries in this direction?

Rosenow

I am not aware of any international effort to collect disease resistant germplasm in disease hot spots. Regarding persons working in this direction, I believe this would be a very good idea. At least, persons doing collections now should be familiar with the major sorghum diseases to be able to note their presence in the area where they are collecting and, if possible, select some types with resistance.

Goud

The phenomenon of apomixis is suggested to be due to structural chromosome hybridity. We have observed apomixis in different crosses in M35-1 x IS84 and BH4-1-4 x IS 84. If structural hybridity is the reason for apomixis we should expect the same mechanism to operate in all cases where apomixis is observed. Dihaploid nuclear fusion is suggested as one of the mechanisms of apomixis. What type of embryosacs are developed in sorghum—whether monosporic or bisporic—and what is the frequency of such parthenogenetic seed development?

U. R. Murty

While it is possible that structural hybridity per se might have caused apomixis in R473, it may not be the rule. It is more likely that structural hybridity causes cross sterility and has secondary effects on apomixis. Dihaploid production could result in sorghum from three processes: (1) second division restitution, (2) synkaryogenesis or automixis in the egg apparatus, and (3) synkaryogenesis or automixis in the antipodal cells. The embryo sacs are of the normal monosporic *polygonum* type.

Ibrahim

Under Sahelian conditions where it is difficult to get good production with locals, I think that we should not expect miracles with new varieties.

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