Agrometeorology of Sorghum and Millet

In the Semi-Arid Tropics

International Crops Research Institute for the Semi-Arid Tropics

Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics

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Foreword

Sorghum and millet are important food crops in the semi-arid tropics, but their yields have remained low and unstable because of a range of environmental constraints. Increasing and stabilizing their production is thus an important part of ICRISAT's mandate, and we were pleased to sponsor with the World Meteorological Organization (WMO) this symposium on the agrometeorology of sorghum and millet.

The main objective of the symposium—the fourth in a WMO series on the agrometeorology of single crops—was to encourage the practical use of climatic data to improve production, by assessing the extent and intensity of climatic risks and by studying the response of the crop to its growing environment. In the Sahel region of Africa, for example, such studies may play a key role in helping farmers adjust age-old cropping practices to meet changes in climate.

The symposium brought together 112 participants from 18 countries to review current knowledge of agrometeorology and to plan future research. Besides the scientific papers and discussions, the symposium included a practical workshop on computer techniques, during which participants used ICRISAT computers and operational models to analyze data from their own countries. Work is already under way to translate some of the symposium recommendations into practice.

I hope these proceedings will be of help to both researchers and agricultural planners throughout the semi-arid tropics.

L.D. Swindale
Director General, ICRISAT

Part 1

Summary and Recommendations

Summary and Recommendations of the Symposium

Agriculturists and climatologists from 18 countries joined ICRISAT scientists for wide-ranging discussions on putting agroclimatology to better use in improving the production of sorghum and millet.

The planning meetings and international symposium on "The Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics" were jointly sponsored by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the World Meteorological Organization (WMO), an agency of the United Nations. Cosponsors were the Food and Agriculture Organization of the UN (FAO); INTSORMIL, a program of international research on sorghum and millet, sponsored by the U.S. Government; and the Texas A & M University, USA.

A total of 112 scientists—teachers, researchers, and agricultural planning experts—participated in the sessions, which began with a series of preplanning meetings and ended with a 5-day symposium that included 1 day of planning future research.

The general objective of the meetings was to promote the use of climatic data to increase the production of sorghum and millet while reducing their vulnerability to climatic hazards. Specific aims were (1) to evaluate techniques to describe and understand the extent and intensity of climatic risks, especially drought, and to quantify the response of sorghum and millet to their growing environments; (2) to identify research priorities, emphasizing interdisciplinary approaches to arrive at solutions fast; (3) to involve international and national institutions in exchange of ideas and collaborative work, and in disseminating existing techniques and research results to all levels, including farmers.

Besides the scientific papers and discussions, the meetings included two unique features. One was a preparatory meeting before the symposium, during which participants used ICRISAT computers to apply various techniques to analyze data from their own countries.The second was a full day's planning for future research, during which three groups—Asia and Australia; Africa; and the Americas—discussed future data needs and experiments to acquire basic crop and environmental information and ways of getting this information to the users and of applying it.

Participants reviewed the present state of knowledge regarding agroclimatic factors that influence the growth and development of sorghum and millet.They also identified the gaps in current knowledge of how weather affects these crops and suggested directions to take in future research.

In his summing up of this symposium/planning meeting, the session chairman—R.W. Gibbons, Director of Research at ICRISAT—noted that yields of sorghum and millet have remained low and unstable in the SAT chiefly because of the undependable rainfall and harsh environments in which these crops are grown.The recommendations of this symposium, he said, would undoubtedly help significantly to identify priorities in agroclimatological research related to sorghum and millet.

Summaries of the five symposium sessions follow.

Opening Session

In his welcome, A. Bozzini—Chief, Crops and Grassland Production Services, FAO—said that sorghum and millet are essential cereals in the semi-arid tropics (SAT), where most developing countries and a large part of the world's population, are located.

Meteorologists, agronomists, and plant breeders have distinct but complementary and interdependent functions in increasing food production. Thus changes or action proposed by any one group must be considered from various angles to judge the possible outcome in all areas.

L.D. Swindale, Director General of ICRISAT, also

International Crops Research Institute for the Semi-Arid Tropics. 1984. Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics: Proceedings of the International Symposium, 15-20 Nov 1982, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

welcoming the participants to the symposium, explained the Institute's mandate to improve crop production in the SAT. He stressed the importance of the conference, because it is vital that we understand more about climate and its effects on farming and that we improve weather forecasting.

Merely gathering and analyzing data is not an end in itself; the data must be synthesized and applied to raising food production. Because sorghum and millet are food crops primarily of the developing world, practical recommendations from the symposium would help extend the benefits of science and technology to a large number of people in the world.

H.M. Choudhury, Additional Director General, India Meteorological Department (IMD), welcomed the participants on behalf of India. He reminded them that production of sorghum and millets is attended by severe natural constraints and reviewed the history of dryland agriculture in India and the efforts of the Indian Council of Agricultural Research (ICAR) to promote research in dry farming. He discussed recent progress by the India Meteorological Department in weather forecasting and farm advisory work.

V. Krishnamurthy from the World Climate Program office of the World Meteorological Organization (WMO) welcomed the participants on behalf of the Secretary-General of WMO. He outlined WMO activities in agrometeorology and in cosponsoring the symposium. He said that WMO, with UNESCO, has been making agrometeorological surveys of various regions; these activities have been intensified to understand the effect of weather and climate on food production.

S.M. Virmani, Leader of the Farming Systems Research Program at ICRISAT and coordinator of the symposium, discussed the need, relevance, and objectives of the symposium. Our task, he said, was to review and discuss the technological advances made in environmental studies, particularly the application of climatic studies to help increase and stabilize agricultural production in the semi-arid tropics. The SAT form a large ecological zone where famine and drought have recurred in cycles. The widening gap between production and demand stems partly from lack of suitable technology to increase yields. The purpose of this meeting, he said, was to review the status of agricultural research on sorghum and millets, with particular reference to research planning and development in the next decade, and to promote the use of climatic information and knowledge to reduce the vulnerability of sorghum and millet to natural calamities.

in a keynote address to the conference, N.J. Rosenberg—Director, Center for Agricultural Meteorology and Climatology, University of Nebraska, USA—discussed the role of the meteorologist and climatologist in improving food production capabilities in the semi-arid tropics. He stressed that water is the key to increased food production and emphasized the importance of increasing the water-use efficiency of crops, describing a few practical ways to manipulate the environment to use water efficiently. Crop modeling, he said, is a useful exercise that should not be overdone.

Global Production of Sorghum and Millets

The first session of the symposium, chaired by A. Bozzini, was devoted to global production of sorghum and millets.

Of the five papers presented, the first two contained general information on the "Ecological zones of sorghum and millet production in the world" (M. Frere) and on "Global production and demand for sorghum and millet to the year 2000" (J.G. Ryan and M. von Oppen). Using FAO data, Frere compared production and productivity of sorghum and millet with maize, the other important coarse-grain cereal. The growing areas of the three cereals were analyzed in relation to agroecological and climatic factors. Possible trends in expanding or contracting area and production of each cereal were discussed with special reference to competition between maize and sorghum and between sorghum and millet.

The second paper analyzed more specifically the seven semi-arid tropical regions of the world and the place of sorghum and millet in the nutrition of millions of people in developing countries.

Future trends were projected, based on the recent past, and taking into account the possible role of recently established national and international research and development efforts. Global and regional production and demand also were projected as a function of growing populations. Special emphasis was given to the Indian subcontinent and Africa south of the Sahara, with projections on sorghum and millet production, consumption, and prices to 2000 A.D. Possible factors modifying the projected trends were also discussed, with particular reference to food habits and preferences, sociopolitical influences, and basic food availability connected mainly with climatic conditions in critical areas.

The next three lectures gave more detailed information on sorghum and millet production, with emphasis on the agroclimatic environments in south Asia, West Africa, and the Americas. Each paper proposed a methodology for assessing and improving sorghum and millet production. M.V.K. Sivakumar ("Physical environment of sorghum- and millet-growing areas in South Asia") considered soil fertility, water retention, temperature, and precipitation extremes and variations in relation to production. He emphasized the possibility of increasing production stability by breeding short-season varieties to match the growing period. Using 3 years' data from a multilocation sorghum-modeling experiment, he showed how to collect appropriate data for use in designing crop-development models.

M. Konate ("Climate of the sorghum and millet cultivation zones in the semi-arid tropical regions of West Africa") reported on the mechanisms of weather behavior in West Africa, related to winter (dry) and summer (wet) conditions. In the western part of the continent, where rainfall ranges from 250 to 500 mm, millet is grown; from 500 to 1000 mm, both millet and sorghum. Maize is generally grown in areas where rainfall exceeds 1000 mm. Photoperiodic response affects several landraces that are specifically selected and adapted to narrow ecological conditions.

R.E. Neild("Agricultural climatology of sorghum—the Americas") underlined the dramatic increases in sorghum production in the USA, Mexico, and Argentina, where hybrid vigor and genetic dwarfing have been used to develop cultivars that permit mechanical harvest with the same harvester used for wheat. To improve sorghum and millet cultivation in less developed areas, Neild proposed a model that considers climatic data and crop physiology and phenology and their interrelations to determine the best planting time for each area. The model considers also the duration of the growing season and evaluations of different varieties or even different species (like maize) in monocropping or multiple-cropping sequences.

Discussion

All papers were followed by lively discussions. Important points considered were:

1. The criteria for classification and the extent of areas that could be considered as belonging to the SAT.
2. The importance of stabilizing yields in SAT areas and using agrometeorology to help do so.
3. The value of simulation models, their limitations, and advantages in providing information for agronomists, plant breeders, and even farmers to improve production levels and stability.
4. The advantages of interdisciplinary research to achieve the basic goals mentioned in (2) and (3).
5. The need for more information on the basic value of simulation models and the possibility of improving them by considering other important factors, including variation among locations, varieties, and management systems.

Recommendations

The recommendations from Session 1 can be summarized as follows:

1. Set up an interagency data bank on agroclimatological information.
2. Assure that data relevant to agroeconomic conditions are being properly collected.
3. Make data available for application in various fields such as forecasting, planning, and monitoring. Models that simulate water balance, phenology, crop production, and other plant characteristics will be required to understand the complexity of the relationships measured and to help identify gaps in existing knowledge.
4. Establish a system to disseminate knowledge on agroclimatology in relation to agricultural and other research areas. In the interests of general agricultural development, the system should not be restricted to sorghum and millet or the SAT but should be made available for global use on all crops.
5. Train persons to collect and use agroclimatological data.

Climatic Requirements of Sorghum and Millet

The second symposium session, chaired by V. Krishnamurthy, considered the climatic requirements of sorghum and millet crops.

The first paper, "Response of pearl millet to light and temperature," by C.K. Ong and J.L. Monteith, stressed the influence of temperature on the rate at which pearl millet grows and develops. It gave information useful for modeling temperature and light effects on pearl millet; however, as all the work was done in growth chambers or greenhouses, Ong stressed that their results need to be verified in field experiments. He suggested further work on response of plants to damaging temperatures.

The paper on "Light and temperature responses in sorghum," by J.M. Peacock and G.M. Heinrich, demonstrated that some germplasm sources can withstand extremely high temperatures, a characteristic that should permit better establishment and development of sorghum and stabilized yields.

The authors suggested that agrometeorologists develop a clearer picture of temperature conditions, particularly the timing and range of extremes, throughout the sorghum-growing areas of the world.

The third paper, by N. Seetharama et al., on "Response of sorghum and millet to drought stress in semi-arid India," concluded that breeding and management strategies to obtain consistently high yields should take into account the rapid establishment of the crop canopy to maximize transpirational water use during the rainy season and ability to withstand sporadic droughts. The paper also stressed conservation of water during vegetative growth in the postrainy season and considered both transpiration during grain filling and the ability of sorghum to use water from deeper soil layers. "Water use and water-use efficiency of pearl millet and sorghum," by E.T. Kanemasu et al., provided information useful to modeling this important SAT crop, emphasizing the importance of water-use efficiency in planning production strategy.

G.H. Hargreaves' paper, "Developing practical agroclimatic models for sorghum and millet," touched on several basic issues, stressing improved management for increased production, and wider application of knowledge on basic relationships among climate, management, and crop yields. He identified energy, water, and fertility as three cardinal factors governing yields of sorghum and millet and presented procedures for estimating the dependability of rainfall amounts and for developing an economic model relating yield to applied nitrogen.

Recommendations

1. A multidisciplinary team should assess in laboratory and field the thresholds of damaging temperatures, both high and low, for sorghum and millet, especially in relation to crop emergence and establishment, and to possibilities for extending these crops into high-altitude regions.

2. First experiments in crop physiology have demonstrated sources of high-temperature resistance in sorghum; a systematic screening of sorghum germplasm for evidence and appropriate use of this characteristic are essential to stabilize crop yields. ICRISAT, cooperating with other interested organizations, should initiate such a study.

3. The adequate use of soil water has demonstrated critical factors in the drought resistance of millet and sorghum crops. Root penetration is a characteristic that should receive increased attention in germplasm evaluation and crop selection. Appropriate cultural practices should also be developed to aid penetration of roots.

4. Adaptation of crop life cycles to available length of growing season remains a key to improving the agriculture of the semi-arid tropics. These characteristics should be systematically evaluated through sound methods based on energy and water balances. The WMO and FAO should provide the leadership to encourage all research institutes and development projects to do so.

5. Assessing the climatic requirements of sorghum and millet has demonstrated many interactions among climatic elements, soil characteristics, and cultivars. The symposium recommends that a multidisciplinary approach to this problem be taken by groups of agrometeorologists, agronomists, crop physiologists, soil scientists, genetic resources specialists, and other interested specialists.

6. The results of past crop experiments should be reassessed from a critical agrometeorological viewpoint for evidence of crop reactions to the

environment. Additionally, future experimentation on millet and sorghum crops should be carefully monitored with regard to soil and atmospheric environments to evaluate the contribution of climatic factors. A series of multilocation experiments, similar to those done for rice by the International Rice Research Institute in cooperation with WMO could be launched. WMO, in cooperation with ICRISAT, should initiate such action.

Agroclimatological Studies in Sorghum- and Millet-growing Regions

The four papers in this session were devoted to agroclimatological studies in sorghum- and millet-growing areas. Several models and analyses of climatic data, already used or with potential for delineating possible sorghum and millet regions were presented.

P. Franquin, reporting on results of his studies in Africa, spoke of the problem of establishing probability characteristics based on the duration and time of the vegetative growth period. The simplest, most immediate procedure is to analyze rainfall at suitably spaced intervals, but it is more useful to calculate a water balance as the results can be used to evaluate and statistically analyze the AET:PET ratio as an index of dry-matter production. That index has been used for constructing a probability model of the growth period.

R.P. Sarker presented an analysis of rainfall and calculation of assured rainfall in different periods of the sorghum crop cycle in India. Evapotranspiration data from three stations were examined in relation to rainfall, evaporative power of air, and crop growth. The weekly distribution of the ratio of evapotranspiration to evaporation indicates the critical period of peak water consumption by sorghum. Shifting sowing to an earlier period appears worth considering. He also suggested harvesting the dryland crop on the basis of physiological maturity to conserve root-zone moisture.

R.P.Peregrina-Robles showed present practices in sorghum and millet cultivation in Mexico with a set of pictures describing the different regions, different altitudes, and variations in temperature where sorghum is cultivated, emphasizing environmental effects on pest and disease incidence.

The last paper on the influence of rainfall patterns on fluctuations in sorghum yields, by F. Forest and B. Lidon, presented a water-balance model and demonstrated that yield fluctuations can be explained by patterns of moisture supplied to the crop during its life cycle—an interesting approach to characterizing the growing season in terms of crop response to water availability.

Recommendations

1. Proper analyses of available meteorological information, suitable for use by farming communities are a prime necessity. Such analyses, either of basic or derived data, should be encouraged.
2. Close interaction between meteorologists and agricultural scientists is necessary and should be further encouraged.
3. Studies of general atmospheric conditions, which could be associated with agricultural drought conditions, particularly on a medium- to long-term basis, should be undertaken.
4. Crop-weather models are useful for making agroclimatic assessments. Existing models need to be critically examined and validated for application, keeping in mind the specific uses for which the models were intended.

Modeling of Climatic Response

Session 4 had four papers on the use of crop-growth models (CGMs) for predicting crop response to climatic factors and helping in decision making. The paper by G.F. Arkin and W.A. Dugas—"Evaluating sorghum production strategies using a crop-growth model"—reviewed the use of this new technique and illustrated the utility of CGMs in selecting proper long-term (strategic) and within-season (tactical) production practices. Two papers by A.K.S. Huda et al. ("Modeling the effect of environmental factors on sorghum growth and development" and "Problems and prospects in modeling pearl millet growth and development") described specific details of a revised version of the sorghum model SORGF (originally developed by Arkin and associates) and a suggested framework for adapting the SORGF revision for use on pearl millet, on which little modeling work has been done so far. G.F. Popov's paper on "Crop monitoring and forecasting" described a mechanistic model for relating crop growth and water supply.

The fifth paper ("Agroclimatological research in the service of the sorghum and millet farmer: need for a network" by S.M. Virmani) made a plea for establishing a network to evaluate meteorological data in agronomically relevant terms for the use of research and development agencies. Rainfall probability estimates, length and variability of growing season and predictions of drought through water balance studies were some of the examples cited of analyses that could be supplied on a uniform comparative basis.

Discussion

The discussion of sorghum and millet models fell roughly into three categories: requests for information about details; comments on deficiencies and limitations; and skepticism about the value of modeling. Some of the skepticism was based on imperfect understanding of what modelers are trying to do. The authors spiritedly defended their work and convinced most of the audience of its current and potential value. They made no attempt to disguise weaknesses in their models.

Questions to be clarified concern the procedure for estimating soil evaporation and foliar transpiration, the choice of plant population, generation of variances associated with different types of management, applicability to many cultivars, and extrapolation to nearby areas. Deficiencies identified in the current model include: the lack of a subroutine for tillering; inability to deal with soil nutrient status or with extremes of temperature and photoperiod; the empirical and unrealistic treatment of water stress (especially in relation to leaf expansion and root elongation); the arbitrary assumption of a constant plant population, because losses during germination and establishment cannot yet be modeled; and doubt about the appropriateness of base temperatures derived by extrapolation. Still, the sorghum model probably has been tested as thoroughly as other models of crop growth, most of which share similar defects.

It appears that SORGF can be adapted for millet with little structural change but much less information is available about physiological responses of millet to weather. Questions about millet concerned tillering, leaf area in relation to temperature, partitioning dry matter, and modeling losses to pests.

Discussing the paper by G.F. Popov, M. Frere, who presented the paper, said the model could be used to forecast crop yields quantitatively and that it took account of drainage but not runoff.

The discussion of S.M. Virmani's paper returned to defining the distribution of the semi-arid tropics. He confirmed that ICRISAT has adopted Troll's method. The Farming Systems Research Program at ICRISAT has made substantial research contributions on intercropping. An IARI participant referred to improving sorghum yields by retaining ideotypes with shorter stems and larger harvest indices. Virmani agreed with another IARI participant that the technology developed by government and international institutes could not be applied directly to SAT farms until relevant environmental factors have been defined and measured.

In a more general discussion, another participant suggested that soil fertility and socioeconomic factors should be considered for defining the SAT. Because farmers in the SAT generally own little land (72% own less than 2 ha in India), technology, as summarized by models, should be specific to individual farmers as well as to sites. The problem of predicting yield from plant size at the time of spikelet initiation was dealt with briefly.

In summing up this session, the chairman said that, while some participants were unduly pessimistic about the utility of models, others were realistically expecting models to link together more than two levels of organization—the plant and the crop. No model can be expected to encompass the behavior of individual plants, of crop stands, and of farming systems.

It was perhaps unfortunate, he commented, that some of the time spent on a computer simulation of crop growth was not used on such relevant topics as the models used by microclimatologists and measurements they are trained to use. Their models provide subroutines for larger models of crops where information is extremely scanty in some areas. For example, we do not yet estimate well soil and meristem temperatures from canopy temperatures.

The session ended with a general feeling that modeling is to be encouraged, provided the components are based on repeatable observations. It is likely that model-building in the sense of computer simulation will remain the prerogative of a few groups, and it would be dangerous to distribute such models indiscriminately to potential users who do not understand how they work. Less complex mechanistic models such as the Penman formula (which would have been called a model had it been developed recently) are more appropriate for general use.

Finally, building a model that works can bring great satisfaction to the builders, but such activity should not be indulged in to excess, as Norman Rosenberg reminded participants in the opening session.

Planning Meeting

Two unique features of this symposium were: (1) a preparatory workshop during which 23 participants were introduced to the use of operational models and methodology developed at ICRISAT and (2) a full day's planning for future research.

Preparatory Meeting

During the first part of the planning meeting, S.M. Virmani of ICRISAT summarized the need for and objectives of the preparatory meeting which preceded the symposium. Reporting on the overall achievements of this 5-day workshop, V. Krishnamurthy of the WMO noted that this symposium—the fourth in a series on the agrometeorology of single crops—was part of the WMO's continuing effort to encourage the practical use of agroclimatology to increase food production.

The emphasis was on actively involving national and international operational and research workers in exchanging ideas, doing collaborative work, and disseminating proven techniques and research results.

To this end, the participants in the preparatory meeting used ICRISAT computers and readily available programs to analyze data from their own countries.

After the opening by B.C.G. Gunasekera, Acting Director for International Cooperation at ICRISAT, and the introductory speeches, participants were taken on a field tour of ICRISAT, during which Dr. Virmani stressed the importance of agrometeorology in assessing the crop potential of an area. He made the following points about:

Farming systems. ICRISAT, using agroclimatological data, has convinced farmers to raise two crops during the year in deep black soils, instead of using the traditional one-crop system.

Intercropping. ICRISAT has demonstrated that, taking into account crop maturity period, two crops could be raised at the same time.

Farming operations. Agroclimatic data have helped bring about efficient use of machinery for preparing fields well before sowing time.

Equipment. Hydraulic lysimeters are more useful than gravimetric ones for measuring evapotranspiration.

Wind-energy equipment should be recommended only after careful scrutiny of wind patterns, particularly of maximum speed in gusts over 24-hour periods.

The neutron probe to determine soil moisture is not particularly useful in clay soils when they are cracking from moisture deficiency.

Brief introductions to ICRISAT computers were then given by J.W. Estes and J.G. Sekaran. Programs available to participants included:

CONDRP	Conditional probabilities weekly, according to the Markov chain model.
GAMMA	Proportional probabilities using Gamma distribution.
MONTHSTD	Monthly statistics of rainfall
WATBAL	Soil water balance "Keig and McAlpine."
LAYER	Modified Ritchie's soil moisture model.
BAIER	Baier's soil moisture model.

Dr. Virmani lectured on "climatological features of the semi-arid tropics of agronomic relevance." This was followed by a workshop on probability analysis of rainfall using the Markov chain model and a practical exercise on rainfall probability analysis was given.

Three locations—Hyderabad, Dharwar, and Gulbarga—all having about the same annual rainfall and lying almost on the same latitude were chosen. From the rainfall probability estimates (Research Bulletin No. 1 of ICRISAT) the trainees were asked to locate the best station for raising a dryland crop (choosing 70% probability of rainfall as adequate for growth).

A lecture and an exercise on incomplete Gamma analysis of rainfall data were followed by a lively discussion. Several other analyses for a better understanding of the problem were proposed from the floor. It was made clear to participants that the preparatory planning meeting was attempting to inform trainees about available models in operation at ICRISAT; to introduce data analysis; and to let participants work on ICRISAT computers using any model of their own available.

Piara Singh, aided by slides, gave a detailed account of water-balance studies carried out at ICRISAT. He said that water-balance models were developed mainly to estimate soil moisture for use in crop-yield models.

M.V.K. Sivakumar lectured on the water-balance models operational on ICRISAT computers. He said that for dryland crops Ritchie's water-balance model, as modified at ICRISAT, gives highly comparable results. The general consensus among participants was that Baier and Robertson's versatile soil-moisture model, because of its simplicity and applicability, is more adaptable to all conditions.

Participants then briefly presented models used in their countries and expressed their interest in adopting one model or another to help serve the agricultural sectors of their countries. The participants and experts concluded that models should be simple and easily applicable and that more dialogue between meteorologists and agriculturalists is needed in this field.

N.V. Joshi, Indian Institute of Science, Bangalore, gave a stimulating lecture on the methodology and application of cluster analysis. He gave practical examples of agroclimatic classifications of India using cluster analysis. It was concluded that cluster analysis could be used to locate new meteorological stations and to transfer agrotechnology from a known region to a location to be determined.

J.I. Stewart gave some practical applications (from his work in California and Kenya) of climatic data for operational management. He stimulated an interesting discussion on further applications of climatic data for management practices.

Friday 12 November 1982 participants joined the meeting on a multilocation sorghum modeling research program.

The purpose of the preparatory planning meeting seemed to be fully met as participants were satisfied with the training and practical exercises given on modeling techniques, their applications, and usefulness. Many expressed a keen desire to use models in their own countries with modifications if needed.

Planning Meeting

Following the reports on the preparatory meeting, J.I. Stewart spoke on "Integration of available information for strategic planning," and M.V.K. Sivakumar on a bibliography of agrometeorology.

The participants then divided into three working groups: (1) Asia and Australia; (2) Africa; (3) the Americas.They discussed the kinds of data needed and methods of collection, disseminating research information, and training. Reports from all three groups were similar and centered around three broad topics.

Environmental Definition

1. Definition of the SAT.
2. Collection of a minimum macroclimatological data set using methods and instruments recommended by the WMO.
3. Computerizing of data where feasible, ensuring ready availability of data in a usable form.
4. Description of special data needs, e.g., soil moisture, rainfall intensity, wind speed.
5. Development of a standard microclimatic and crop data set for all research needs.

Research Needs

1. Increased synthesis of research results.
2. Increased farm-level research.
3. Increased basic and applied research, particularly on pearl millet, because it has received much less attention than sorghum.
4. Among the wide range of research topics then discussed, no single one appeared to have priority.

Information and Training

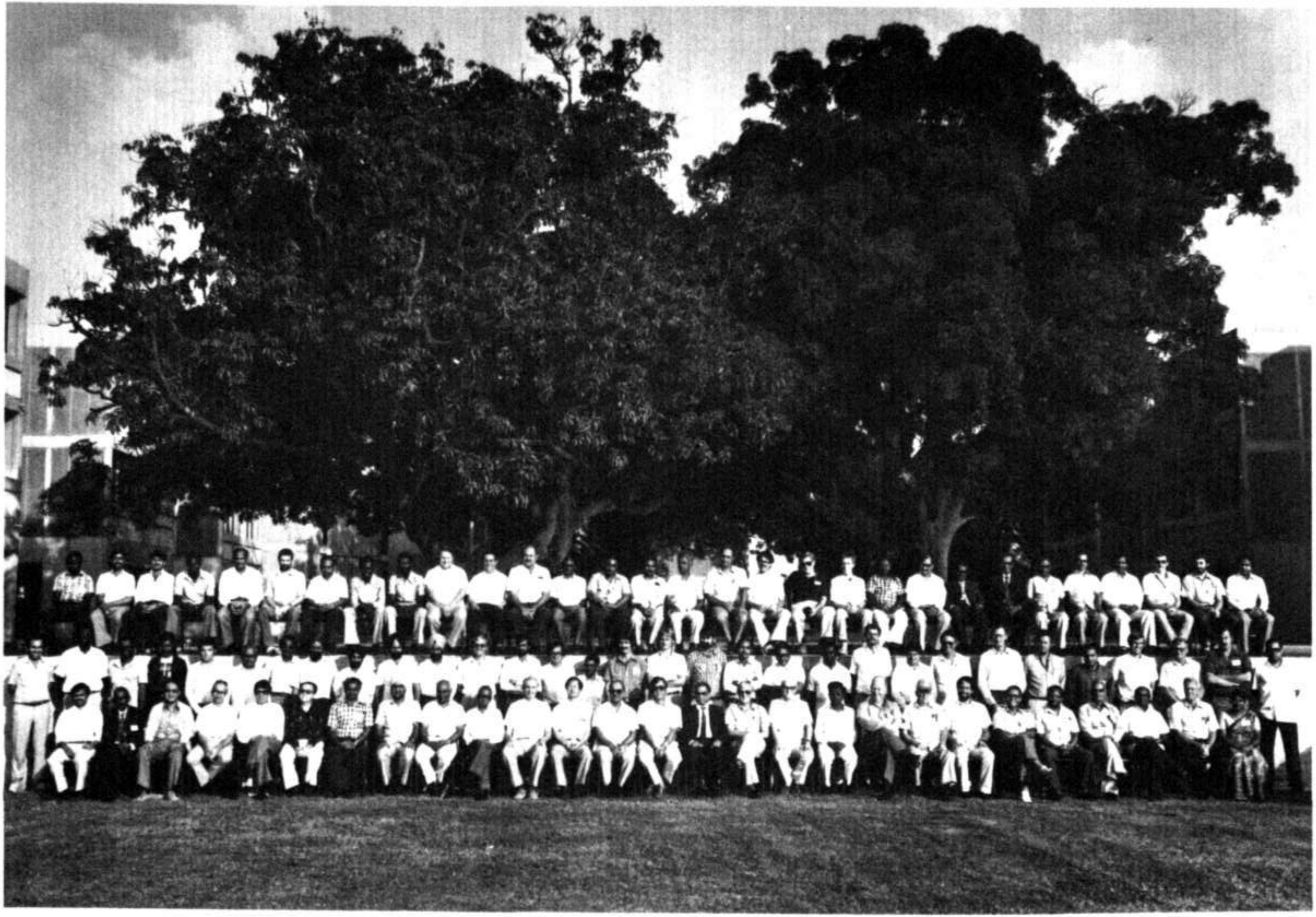
1. Another conference on the agroclimatology of sorghum and millet should be held within 3 years.

2. The next conference should be supplemented by regional and national conferences.
3. There should be wider circulation of data and results through printed and other media—both technical and popular information and involving the national extension services.
4. A list of resource persons knowledgeable in sorghum and millet agroclimatology should be drawn up for each country in the SAT.
5. More workshops in which the participants can work with their own data, learn measurement techniques, etc., should be held.
6. A training manual should be developed to cover meteorology and crop phenology, with clear instructions on how to take data and what measurement units to use.

Recommendations of the Symposium

The symposium recommended that researchers cooperate to

- establish an interagency data bank on agroclimatological information and a global system for disseminating it;
- expand training in the collection and use of agroclimatic data in the semi-arid tropics;
- assess damaging temperatures—both high and low—in relation to plant emergence and establishment in both sorghum and millet, especially for extending their cultivation to high altitudes;
- study root-penetration characteristics in evaluating germplasm and selecting crops that will be more resistant to drought;
- use crop-weather models to make agroclimatic assessments for particular regions, after validating existing models in the region of application for which they are intended.



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Part 2

Symposium Papers

The Role of the Meteorologist and Climatologist in Improving Food Production Capabilities in the Semi-Arid Regions

Norman J. Rosenberg*

Abstract

The semi-arid and subhumid regions of the world may provide the best opportunity to increase food production quickly. Sorghum and millet—two of the major crops with which ICRISAT deals—are among the best adapted to such climatic regions, which are generally characterized by an insufficiency of precipitation to meet the evaporative demand of the atmosphere, as well as by an uneven seasonal distribution of and a high year-to-year variability in precipitation.

The agrometeorologist has many contributions to make to increasing food production in the semi-arid regions, especially in the search for ways to increase the availability of water, to decrease the demand for that water in crop production, and to improve the water-use efficiency (photosynthesis:evapotranspiration or yield:total water consumption).

In this paper, a number of methods that may increase water-use efficiency—namely, windbreaks, reflectants, and plant architectural adaptations—are described in detail. Other important tasks for the agrometeorologist and climatologist are also considered; e.g., finding the range of climatic conditions best suited to particular crops, developing climatic analogues for locating new areas for cropping, developing planting strategies to make fullest use of the climatic advantages while minimizing the risks, and providing surveillance on crop-growing conditions for purposes of national planning.

Thoughts are also presented concerning the possible implications of the increasing concentration of carbon dioxide in the atmosphere for crop growth in the semi-arid and subhumid lands.

Résumé

Rôle du meteorologiste et du climatologiste dans l'amélioration de la productivité des cultures vivrières des régions semi-arides : Les régions semi-arides et sous-humides offriraient la meilleure solution pour accroître rapidement la production vivrière. Le sorgho et le mil, deux cultures importantes du mandat de l'ICRISAT, sont parmi les mieux adaptés à ce type de climat. En général, les régions semi-arides sont caractérisées par des précipitations insuffisantes pour couvrir la demande évaporative de l'atmosphère, elles sont mal réparties pendant la saison et très variables d'une année à l'autre.

L'agrométéorologiste peut contribuer de nombreuses façons à accroître la production vivrière dans ces régions. La plus importante serait la recherche de moyens permettant d'accroître la quantité d'eau disponible et de réduire la demande d'eau pour la production agricole. Une autre solution serait l'amélioration de l'efficacité de l'utilisation d'eau par les cultures (photosynthèse : évapotranspiration ou rendement : consommation totale d'eau).

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L'article décrit certaines méthodes qui permettraient d'accroître l'efficacité de l'utilisation d'eau, à savoir, les brise-vent, les réflecteurs ou les modifications architecturales des plantes. D'autres préoccupations de l'agrométéorologiste et du climatologiste sont aussi examinées : la détermination des conditions climatiques les plus convenables à une culture donnée; l'élaboration de tableaux comparatifs des conditions climatiques permettant d'identifier de nouvelles zones à cultiver; la mise au point de techniques appropriées de semis, afin de profiter des conditions climatiques favorables tout en minimisant les risques; et la surveillance des conditions culturales aux fins de planification nationale.

Les observations portent aussi sur l'incidence éventuelle de l'augmentation de la concentration de CO_2 dans l'atmosphère sur les cultures dans les régions semi-arides et sous-humides.

I have been charged by the conveners of this symposium with preparing a keynote paper: a broad, general view of agrometeorology and agroclimatology as these disciplines may serve in improving food production capabilities in the semi-arid regions.

In the pages that follow, I speculate about the future of the semi-arid and subhumid regions in meeting world food needs. That water supply to the crop is the key to increasing production will surprise no one here. I emphasize the importance of improved water-use efficiency as a goal and describe a few ways in which, by manipulating the environment, the crop, or both, this goal may be achieved.

I also describe what seem to me to be other very important opportunities for service by the community of meteorologists and climatologists who devote themselves to agriculture. My examples are limited in number. The topics I mention constitute a sampler, at best. I expect that many other concepts and methods will be brought to our attention this week and that all ideas will be subjected to thorough discussion.

Sorghum, Millet, and the Semi-Arid Regions

Sorghum and millet are crops suited to the semi-arid and subhumid lands in the tropical and temperate zones. Other crops with which ICRISAT deals—pigeonpea, chickpea, maize, etc.—are also suited to semi-arid zones. This paper will deal with cropping in the semi-arid regions generally, rather than with sorghum and millet specifically. The opportunities for agrometeorologists and agroclimatologists to assist in the development of sound, sustainable agronomic systems will be highlighted. But first, some thoughts about the future of the semi-arid regions.

How are we going to feed a world population that keeps growing and demanding more and better food? Furthermore, where can we grow this food? Short growing seasons and poor soils limit production in the far northern latitudes, and irrigation on a gigantic and impractical scale would be required to make large areas of the deserts fertile. When tropical rain forests are cleared for agriculture, the soil physical condition deteriorates quickly. In addition, the high concentration of aluminum in the soils of the tropics may be toxic to many plants.

Many agronomists, soil scientists, and agricultural climatologists think that the semi-arid and subhumid regions of the world are the best places to increase food production quickly. These regions range from the middle latitudes to the tropics and include the Great Plains of the USA and Canada, the steppes of Russia, the pampas in Argentina, part of northeastern Brazil, large areas in South Africa and Australia, large parts of the Indian subcontinent, Sahelian Africa south of the Sahara, and certain areas of dry summer Mediterranean climates, such as parts of Italy, Spain, and North Africa, and some coastal regions of the USA and Australia (Fig.1). Although some of the greatest grain- and meat-producing areas in the world can be found in these regions, it seems possible that they can be made to produce much more. They generally have abundant sunshine and wind—both important for growing crops. The sunlight provides energy for photosynthesis, and air turbulence keeps the plants supplied with carbon dioxide, which is used in the same process. But these areas are named for their major deficit—water.

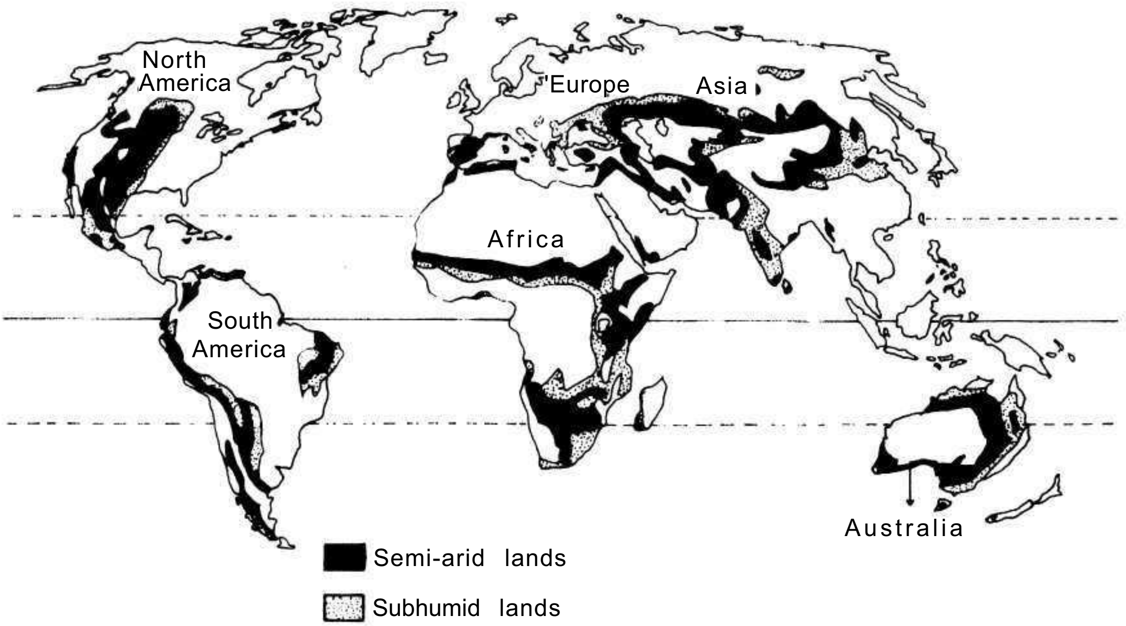

Figure 1. Location of the world's semi-arid and subhumid lands.

Climatologists define semi-arid and subhumid regions with formulas that relate rainfall and the potential water loss from the soil due to the effects of sun and wind on vegetation In general, the annual rainfall in these regions is less than the annual water loss by evapotranspiration. In addition, the rainfall is usually distributed unevenly during the year. For instance, Scottsbluff, Nebraska, in the U.S. Great Plains, gets 70% of its annual precipitation from May to October. In Niger, in the Sahelian region, almost all the annual precipitation falls between May and September. Jerusalem, Israel, gets 95% of its annual precipitation between November and April.

The quantity of precipitation also varies greatly from year to year in these regions. For example, Scottsbluff averaged 370 mm from 1941 to 1970, but with a standard deviation of 92 mm (25%). Rainfall at Niamey, Niger, shows a similar year-to-year variability. By contrast, the annual precipitation in the humid region around Columbus, Ohio, USA, is 940 mm, with a standard deviation of only 137 mm (15%).

Much of the land in semi-arid and subhumid areas is already being used for food production. If we can save and use more of the uncertain, and sometimes inadequate, water supply and also develop plants that use it more efficiently, we can produce more, and perhaps better, crops. In my view, this is one of the major challenges facing agronomic scientists—agronomists, engineers, and meteorologists—in the years to come.

It is widely accepted that yield is dependent upon transpiration. Bierhuizen and Slatyer (1965) and, most recently, Tanner (1981) have developed expressions describing such functional relationships.

That yield is related to transpiration is evident, but water shortages at critical times can have profound effects on yield that make regular linear or curvilinear relationships unreliable. Nor does it seem essential that transpiration rate must define the maximum yield opportunity for a crop. Transpiration is a response to the energy load (radiant and advective) to which the plant is exposed. Photosynthesis is a response to the photosynthetically active radiation, the supply of nutrients, the turbulent supply of CO_2, and the degree of hydration determined by the plant internal water status.

Instead we should ask whether it is possible to grow more crops with the same or less water and "harvest" the unused water for application to additional land area (or to leave it in storage for a subsequent crop). Thus, improvement in the water-use efficiency, defined by the ratio photosynthesis:evapotranspiration (or yield.total water consumption) should be the key measure of our success in coping with the semi-arid environments.

Altering Water-use Efficiency

In order for evapotranspiration to be reduced, the energy load on the plant must first be reduced, and the turbulent transport of vapor must be impeded. There are a number of ways in which the microclimate of the crop can be altered to effect such changes; some examples follow.

Windbreaks

Windbreaks reduce the effects of local or regional-scale advection of sensible heat from dry surroundings (e.g., Rosenberg 1975, 1979). Windbreaks also reduce turbulent transport of vapor from plants in the sheltered zone (Radke 1976). Windbreaks may be composed of rows of trees, constructed barriers, or, perhaps most practically, tall crops sheltering shorter ones. There is an ample literature of shelter effect—most of it indicating beneficial effects in terms of photosynthetic rates and harvestable yield (Van Eimern et al. 1964; Marshall 1967; Sturrock 1975). Evapotranspiration is usually reduced by windshelter as well. Much needs to be done to tailor windbreak systems to the agricultural practices of the semi-arid regions. Combinations of tall crops to shelter short ones (e.g., millet to shelter sorghum, sorghum to shelter chickpea, etc.) need to be subjected to thorough agronomic testing. Work of this kind is already under way at ICRISAT and a number of other locations.

Reflectants

Theories of Seginer (1969) and Aboukhaled et al. (1970) indicate that, by increasing the albedo of plants, the net radiant energy load upon them should be reduced and that this should result in diminished evaporation and transpiration. That this actually happens has been demonstrated with artificial coatings applied to rubber plants in growth chambers by Aboukhaled et al. (1970) and to soybeans by Doraiswamy and Rosenberg (1974), Lemeur and Rosenberg (1975,1976), and Baradas et al. (1976a, 1976b).

We do not yet fully comprehend the reasons for the reffectant effect on water use. However, Figure 2 (Baradas 1974) schematically illustrates the complexity of the reflectant action in modifying radiation and energy balance of the treated soybean crop in the field.

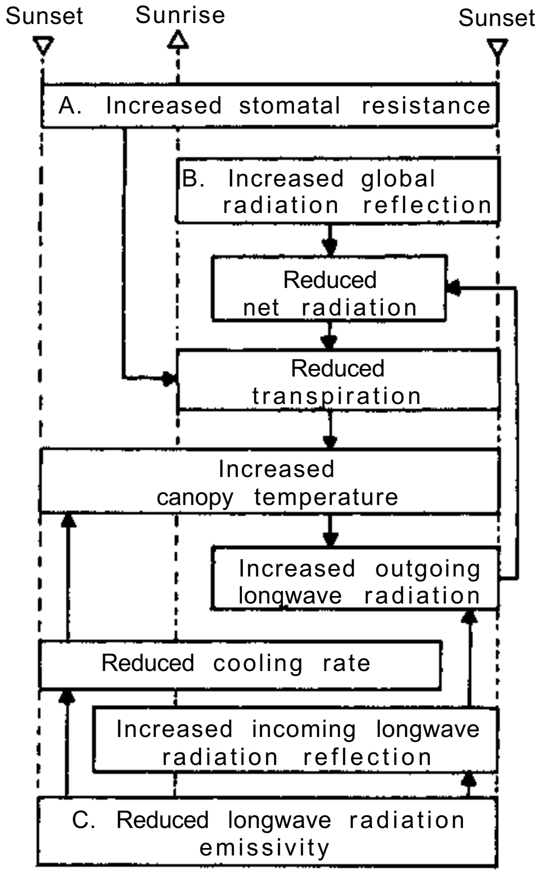

Figure 2. Possible mechanisms of reflectant influence on the radiation balance and transpiration rate of a coated soybean crop.

Reflectants may indeed reduce evapotranspiration, but water-use efficiency can increase only if photosynthesis is not reduced concomitantly. With soybeans we anticipated no major decrease in photosynthesis, since that crop is light-saturated under a global radiation flux density of about 700 W/m^2 under field conditions. In experiments conducted at Mead, Nebraska (cited above), we found that photosynthesis and yield were not reduced at all—apparently because the materials with which the plants were coated increased multiple reflection of light deep into the canopy where the plant is usually light-unsaturated.

We would expect that increasing reflectance in a C_4 plant such as sorghum, which is light-unsaturated, might diminish photosynthesis in that crop. Moreshet et al. (1977) found, indeed, that net photosynthesis in sorghum was reduced by 23% (solar radiation by 26%) immediately after application of a kaolinite coating. But grain yield was consistently increased by the treatment. They attribute this result to specific beneficial physiological effects at the time of panicle initiation and to early senescence in the treated plants that hastened translocation to the developing grain.

While the application of reflectant materials may be impractical on a large scale, it may prove useful as an emergency technique in times of drought or severe water shortage, especially where labor to apply the material is available.

Natural Reflectants and Plant Architecture

As shown above, there is theoretical support for the idea that increased reflectance should reduce evapotranspiration. There is also experimental evidence that by artificially increasing reflectance, evapotranspiration is reduced. And there are ways by which reflectance can be naturally modified.

Albedo varies from species to species and within species according to the age of the leaf, its turgidity, the presence of waxes or other materials on the surface, and the concentration of chlorophyll. For example, barley plants have been bred isogenically by Ferguson et al. (1972) for greater albedo through a reduction in chlorophyll concentration. Wooley (1964), Ghorashy et al. (1971), and Gausman and Cardenas (1973) found that pubescence on soybean leaves slightly increases their reflectivity in the visible waveband but more significantly in the near infrared. Wooley (1964) and Ghorashy et al. (1971) found, for single leaves, that pubescence decreases transpiration, both because of reduced radiation absorption and because of an increased boundary layer resistance. Ehleringer and Bjorkman (1978) and Ehleringer and Mooney (1978) have observed a greater visible reflectance, a reduced transpiration, and a slightly reduced photosynthetic rate in *Encelia farinosa* due to increased pubescence. However, Ghorashy et al. (1971) found no reduction in photosynthetic rate, and Hartung et al. (1980) found increased photosynthetic rate and yield associated with pubescence in soybean.

Drs. James Specht and James Williams of the University of Nebraska Agronomy Department have developed a range of isogenically paired soybeans bred back to differ in a single gene only. In these isolines, pairs differ only in the gene that controls a certain expression of the soybean plant's architecture. For example, they have provided us with seed of isogenically paired cv Harosoy soybeans, which differ only in the degree of pubescence on the leaves and stems.

These isolines were grown in plots of about 1. 5 ha in experiments conducted during 1980 at the University of Nebraska's Agricultural Meteorology Laboratory near Mead. Detailed measurements of radiation balance, energy balance, photosynthesis, and evapotranspiration (ET) were made in the field during the course of the summer. Results of the study are being reported in a number of papers (Baldocchi et al. 1983a, 1983b, 1983c).

For the purpose of this dicussion, however, it is sufficient to cite the following findings: ET was reduced overall by approximately 7% in the densely pubescent isoline. Over the season, photo synthesis and yield were unaffected by pubescence; however, on single days, especially days of strong regional sensible heat advection, the CO_2:H_2O flux ratio (a measure of water-use efficiencv) was increased by as much as 30%. The pubescence greatly altered the partitioning of net radiation (R_n) with deeper penetration into the pubescent canopy.

My purpose in describing the studies of reflectants and plant architecture is to illustrate what I consider to be an appropriate and balanced methodology for agrometeorologists who aim to make better use of crops in the environments in which they work. This methodology involves:

- theoretical studies—both physical and physiological—and modeling of the interactions of plants and the environment;
- field studies of microclimatic conditions and the exchanges of mass and energy between plant and atmosphere; and
- manipulations of the environment to increase or decrease (as appropriate) the capture of radiant energy and/or to minimize the consumption of water (especially important in the semi-arid regions) by "artificial" means (e.g., windbreaks or reflectants) or by "natural" means (e.g., plant architectural change).

This is not an exclusive strategy, but it is a systematic way for the agrometeorologist to assist the agronomist and other specialists in making the most of the environment with all the stresses it imposes.

Other Tasks for the Agrometeorologist and Climatologist

There are other, very important, roles for the meteorologist and climatologist. A few are described below:

1. Establishing the range of climatic conditions best suited to particular crops. This requires, of course, that the current environments in which the crop does well be adequately described. Automated weather stations now provide the opportunity to collect a proper set of data on weather and microclimatic conditions at experimental sites. A network of such stations has been developed in Nebraska to provide such data. Figure 3 is a schematic representation of the network and its functions.
2. Searching, by means of climatic analogue techniques, for new areas appropriate to particular crops. As a minimum, such critical factors must be known as the growing season length, the distribution of precipitation during the growing season, and the incidence of extreme air and soil temperatures that may impede or prohibit culture of the crop. In concert with other specialists, the agrometeorologist must also consider suitability of soil, its moisture-holding capacity, and nutrient availability before recommendations for introduction of new crops can be made.
3. Developing planting strategies to make fullest use of the growing season; to minimize risk of drought, extreme temperatures, disease, or insect damage; and to ensure a controlled flow of harvested crop where the crop requires processing before marketing or storage.
4. Facilitating rapid proving of new cropping systems by selecting testing sites to provide a wide range of soil and climatic conditions.
5. Providing surveillance and intelligence to national governments on the state of worldwide agricultural production to assist in planning of rational strategies.

No doubt there are many other important functions that can be defined for the agrometeorologist and climatologist and we shall hear of these in the papers that follow. As keynote speaker at this conference, I am charged with setting the stage and that, I hope, I have done.

The Carbon Dioxide Problem

I do wish to comment on another matter that may at first appear to be of academic interest only. It is known that C_3 plants respond with an increasing rate of photosynthesis to air enriched with carbon dioxide; C_4 plants respond with a decreasing transpiration rate. Thus, water-use efficiency may be improved if, as is projected, CO_2 concentration continues to increase to, say, double the pre-industrial concentration. Thus, what many call the "carbon dioxide problem" may be for us a "carbon dioxide opportunity." For all we know, the nearly 20% increase in atmospheric CO_2 concentration that has occurred since about 1860 may already have improved water-use efficiency in crop production (Rosenberg 1981).

This discussion presupposes a CO_2 fertilization effect with no climatic change. Of course, climatic changes are projected by global climatic models to follow on a doubling of CO_2 concentration (e.g., Manabe and Wetherald 1980). My purpose is to caution against extrapolation from the models to real continents with real topography and real agricultures, as some have done (e.g., Bach 1979; Kellogg and Schware 1981).

It does seem logical, however, to suppose that if a CO_2 doubling causes a significant climatic change, it will be the margins of the world's climatic belts (the transition from humid to arid, for example) that will be most critically affected—adversely or beneficially. The agrometeorologist can assist significantly in preparing for climatic change (whatever the cause) or changing variability (whatever the cause) by carefully evaluating the vulnerabilities of agricultural systems to climatic conditions as they now exist and by extrapolating to possible scenarios of future climates.

A Final Word

One last word on the role of modeling in agrometeorology and agroclimatology. Don't overdo it! No science is better than its basis in measurement,

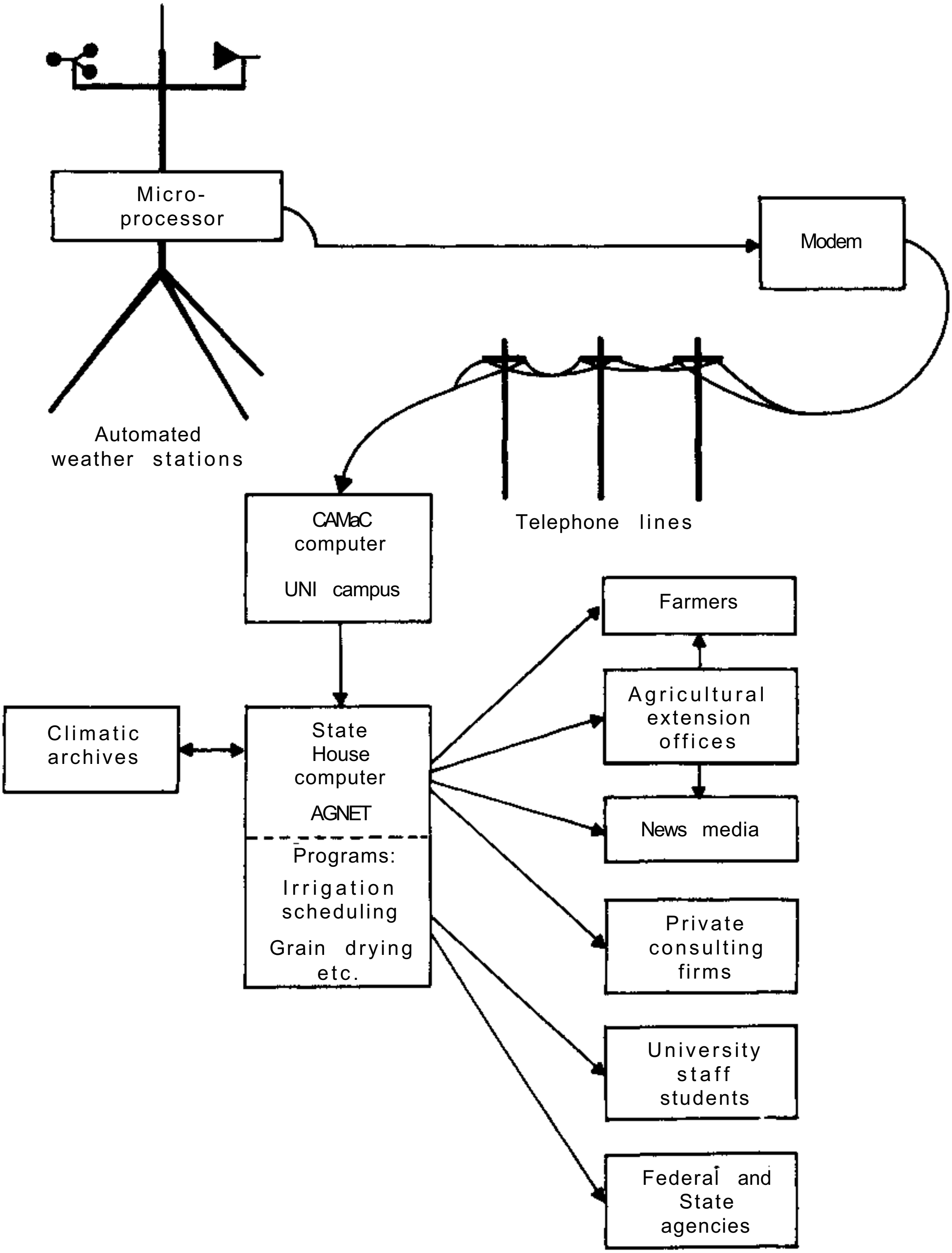

Figure 3. The Nebraska Automated Weather Data Network (AWDN).

observation, and interpretation of facts. Modeling, in my view, provides insights to complicated problems—it provides no answers. It may also (and not only in our field) provide a refuge from the need to provide tangible results and real methods for use by real farmers in real fields.

Acknowledgments

Much of the Nebraska research cited above was conducted with support of the U.S. National Science Foundation under Grants ATM-7727533 and ATM-7901017 and the U.S. Department of Agriculture, Grant SEA-AR 901-15-38. I am indebted to Professors B.L. Blad, S.B. Verma, K.G. Hubbard, and D.A. Wilhite for their review of this paper and to Dr. D.D. Baldocchi for the data concerning recent studies of the effects of soybean pubescence. Mrs. Betty James prepared the manuscript.

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Session 1

Global Production of Sorghum and Millet

Ecological Zones and Production of Sorghum and Millet

Michel Frere*

Abstract

This paper first considers the differences in ecology and in the physiological response of three of the main cereals cultivated in many environments of the semi-arid tropics—millet, sorghum, and maize—in order to assess the most suitable ecological area for these crops.

The paper also presents some information on the current situation and trends in millet and sorghum cultivation throughout the world. Problems posed by the willingness of countries to replace sorghum cultivation with maize are also touched upon.

Statistical figures of sorghum and millet production, compared with the areas harvested over the past 20 years, are presented for two countries. Some analogies to climatic conditions during the period are evident. The conclusion shows the wide possibilities for developing further the production of sorghum and millet, which remain indispensable cereals for dry regions.

Résumé

Les zones écologiques et la production de sorgho et de mil : Cette communication décrit les différences existant dans l'écologie et la réaction physiologique de trois céréales importantes cultivées dans de nombreux milieux des zones tropicales semi-arides, à savoir le mil, le sorgho et le maïs, afin de définir leur milieu d'élection.

Sont présentées quelques informations relatives à la situation et aux tendances actuelles de la culture du mil et du sorgho dans le monde. Sont évoqués aussi les problèmes posés par la volonté des pays de remplacer la culture du sorgho par celle du maïs.

Des données statistiques sur la production du sorgho et du mil et sur les superficies récoltées sont présentées pour deux pays. Ces données couvrant une période de 20 ans mettent en évidence certaines analogies avec les conditions climatiques au cours de cette période. La conclusion traite des nombreuses possibilités d'augmenter la production de sorgho et de mil, deux céréales indispensables dans les régions sèches.

As I have the privilege of being the first speaker at this symposium, I thought it would be useful, before going into agrometeorological details, to present in a synoptic way some physiological aspects that differentiate the three main rainfed cereal crops found in semi-arid tropical areas: maize, sorghum, and millet. I wish to mention maize because, despite its poor adaptation to dry areas, it is grown in noticeable quantities even in countries where ecologically it should not be grown at all. In some cases, despite its poor performance, maize is preferred to sorghum and millet, because of socioeconomic conditions or because the crop is better protected against grain-eating birds.

The physiological similarities and differences of the three cereals are summarized in Table 1. While the bulk of cereal production in tropical countries is represented by maize, the production of the areas

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with less than 600 mm of seasonal rainfall is mainly represented by sorghum and millet, totaling about a quarter of the maize production.

The data illustrate some of the morphological and ecological differences between maize, sorghum, and millet that make each of these cereals more or less suited to a given environment. It must be emphasized that the rational exploitation of these characteristics would normally allow higher yields to be obtained from these crops. However, it must be recognized that maize is sometimes cultivated in environments that are not appropriate; for example, in areas where "normal" rainfall is in the order of 500 mm. This implies many years with rainfall in the order of 400 mm and, consequently, maize plants developing only up to about 1.20 m, with yields of 150 kg/ha or less.

Regarding the distribution of sorghum and millet crops around the world, the FAO has completed the Report on the Agroecological Zones Project (FAO 1979a), in which the potential land use for the most important crops in the developing countries is presented by region and for different levels of inputs. The maps showing the various areas of cultivation are divided into very suitable, suitable, and marginally suitable areas according to the yields that may be expected, taking into account the various climatic, edaphic, and other constraints.

This report is made up of four volumes, volume 1 covering Africa; volume 2, southwest Asia; volume 3, South and Central America; and volume 4, southeast Asia. Volumes 1 and 3 include a detailed presentation of the methodology followed for the preparation of this work, which was initiated in 1976 and completed in 1982.

The methodology for assessing land potentialities for various crops was based, on the one hand. on the ecological requirements of the crops considered and. on the other hand, on the available climatic and edaphic resources compatible with the ecological requirements of the crop. Climatologically. the main constraints to crop cultivation in tropical rainfed areas are water availability and—to a lesser extent, mainly in the highland zones—air temperature.

In the FAO survey, the basic derived parameter assessed is the length of the growing season; i.e., the length of time during which water and temperature do not represent on an average a constraint for crop growth. This study does not take into account rainfall variability; however, to compensate for this. particularly at the beginning and end of the growing cycle, crop evapotranspiration has been taken as

Table 1. Physiological similarities and differences, yields, and total production of maize, sorghum, and millet.

	Maize (*Zea mays*)	Sorghum (*Sorghum vulgare*)	Millet (*Pennisetum typhoides*)
Rooting system	Superficial, in the upper 50 cm	Stronger and deeper than maize	Stronger and deeper than sorghum
Water requirements (mm) over the growth period	500-600	400	300-350
Temperature requirement (°C)	Optimum 25 Minimum 15 Maximum 45	Sorghum and millet have temperature requirements similar to maize but can support higher maximum temperatures without damage to the crop	
Yield (kg/ha)			
High inputs	4000-5000	3000	1000-1500
Low inputs	1000	750-1000	500- 700
World annual production (000 tonnes)	392000	58000	29000

equal to potential evapotranspiration. In fact this shortens the period when full water availability is assured and eliminates the periods when the rainy season is beginning or fading away.

At the same time, observed crops have provided information for establishing criteria of suitability of the various climates, expressed in terms of length of growing period. Figure 1 shows the lengths of growing periods in 30-day segments, and the suitability of maize, sorghum, and millet to the growing season available: VS denotes very suitable zones, where yields will be at least 80% of the maximum yields of the crop for the area; S, suitable zones, where yield is between 40 and 80% of the maximum; MS, marginally suitable areas, where yields will be only 20 to 40% of the maximum yield. Areas where observed yields are below 20% of the maximum yields are classified as not suitable.

Observing Figure 1, we will see for the short growing season a progressive shifting from maize to millet, which shows greater tolerance for shorter lengths of growing season. At the other end of the scale, limitations are imposed by the existence of a possible humid period at the end of the growing cycle, inducing disease problems and the possibility of seed germination on the plant itself, as well as problems of drying and post-harvest conservation.

The average yields obtained for different lengths of growing season for maize, sorghum, millet, and cassava are shown in Figure 2. It can be seen that for short growing seasons the crop that will give the highest relative yield is millet. Where the growing season is longer, the advantage goes to sorghum and maize, higher yields being obtained with the latter. Sustained yields will be obtained for maize even in humid conditions represented by growing seasons exceeding 250 days.

For comparison, the yields of cassava have also been shown. Cassava, although particularly well adapted to humid climates, has a very wide range of tolerance as regards the available length of growing season, which explains the appreciable production of cassava in drier countries such as Mali and Upper Volta. These figures come from the compilation of the data used for the preparation of the agroecological zones report.

Maps appearing in the agroecological zones reports show the extent of sorghum and millet in the various continents. In Africa a large band spreads from West Africa to Ethiopia and Somalia; this represents the Sahelian zone, extending to Sudan and Ethiopia. This area extends through the drier

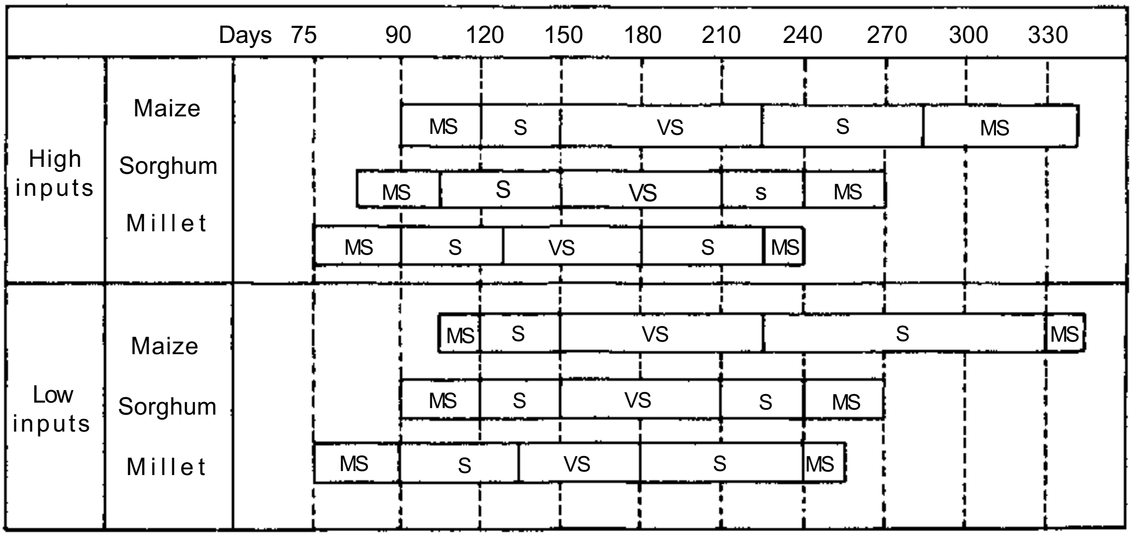

Figure 1. Suitability of various available lengths of growing season for maize, sorghum, and millet at two levels of inputs.
VS = very suitable areas, where yields will be at least 80% of maximum yield for the area; S = suitable, 40-80% of maximum; MS = marginally suitable, 20-40% of maximum. (Source: FAO 1976b.)

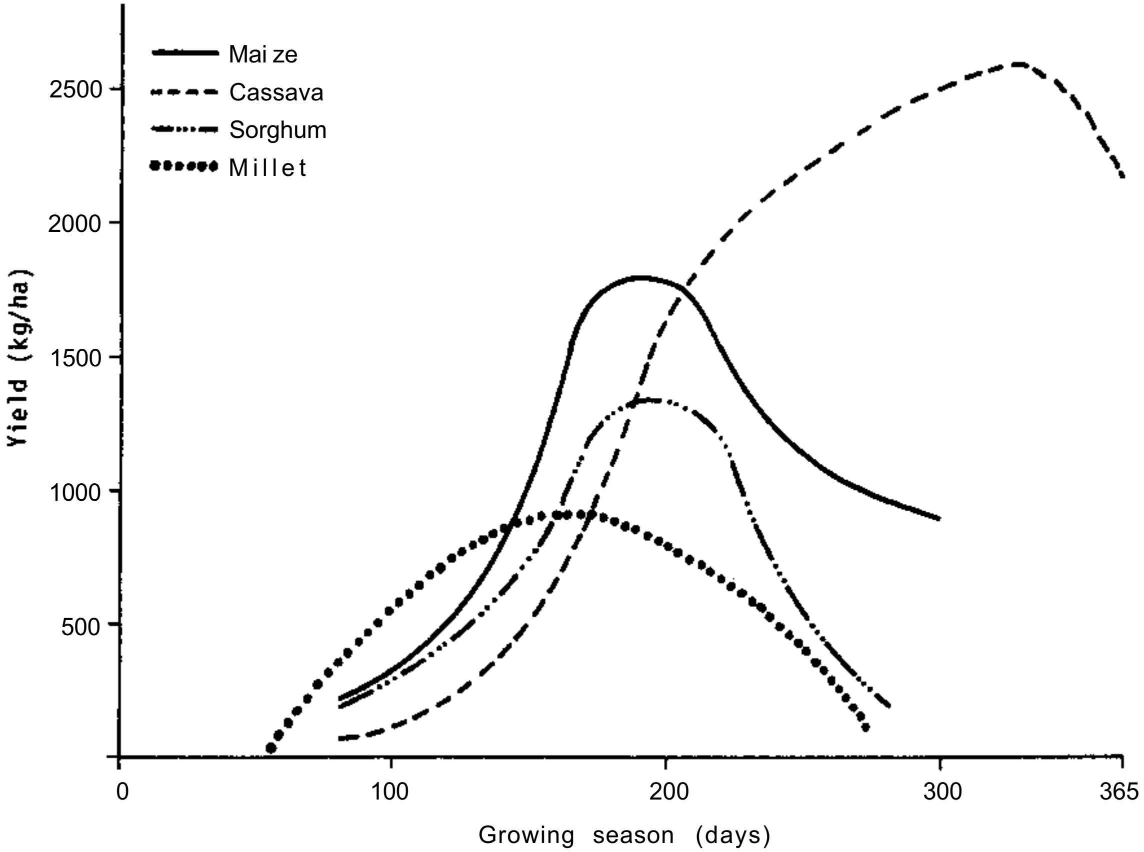

Figure 2. Fluctuations of average yields of millet, maize, sorghum, and cassava in relation to available lengths of growing season.

areas of eastern Africa to southern Africa, although in that area maize is generally cultivated more, sometimes even in very marginal conditions.

In Central America and the Caribbean, millet and sorghum are widely cultivated in the drier zones of Mexico and on the main islands; however, preference is given to maize whenever possible.

In South America these crops are cultivated in the dry areas of northern Venezuela and Colombia, northeast Brazil, and the dry lowland interior areas of Bolivia and Argentina.

Finally, in Asia, sorghum and millet are extensively cultivated in the Indian subcontinent, Burma, Thailand, Lao People's Democratic Republic, Kampuchea, and part of the Philippine islands and Indonesia, although in this region preference is given to rice whenever possible.

Sorghum is also cultivated in other subtropical and temperate areas of the world but mainly for animal feed.

In similar presentations made at previous symposia on the agrometeorology of the wheat and maize crops, I attempted to give some statistical information for the various areas where the crop was grown. This detailed presentation has not been possible for sorghum and millet, however, because in many cases national statistics tend to lump together the figures pertaining to both the crops. An additional difficulty is the lack of information on the production in China from 1960 to 1977. However, some statistical information is presented hereafter; it is based on the data of the FAO Production Yearbook of 1980.

Table 2 shows that the total world cereal production can be roughly divided into four parts: the first three parts covering wheat, rice, and maize, and the last one divided more or less as follows: some 9% for barley, 7% for sorghum and millet, and some

Table 2. World cereal production in 1960 and 1980 and relative production increases.

	Wheat	Maize	Barley	Rice	Sorghum and millet	Other	Total
Production (000 tonnes) 1960	249200	217100	84500	227400	68800	96900	943900
Percentage of total 1960	26.4	23.0	9.0	24.0	7.3	10.3	100.0
Production (000 tonnes) 1980	444553	392248	162402	399779	87353	84138	1 570673
Percentage of total 1980	28.3	25.0	10.3	25.4	5.6	5.4	100.0
Percent increase 1960-1980	78	81	92	76	27(65)[a]		

a. See text for details

10% for other minor cereals like oats, buckwheat, and rye. The comparisons between the figures of 1960 and 1980 show a large increase in the production of maize, wheat, rice, and barley, varying from 76% for rice to 92% for barley. The figures for sorghum and millet show a smaller increase, of about 27%; however, this is because until 1976 the production of sorghum in China was overestimated. With the re-evaluation of the Chinese production, the 1980 figures appear correspondingly lower. Taking this situation into account, the increment should be of the order of 60 to 70%. This relatively low increment in production is partly due to urbanization, which favors the consumption of bread or other imported cereals.

A final statistical aspect that is interesting to note is the increase of sorghum/millet production by region (Table 3). While increases in Africa and Asia have been 66% and 100% respectively, production of sorghum and millet in Latin America has seen a spectacular sixfold increase, particularly of sorghum. Mexico and Argentina, which are the main sorghum producers have doubled their production over the last 20 years. In both cases this has been done by putting new lands into use and by increasing yields. Other countries, although producing less in absolute terms, have also had a dramatic change in sorghum production over the last 20 years. The cultivated area of sorghum in Colombia, for example, has increased from 2000 to 200000 ha, and the increase in Venezuela has been even more striking. On the other hand, some other countries of Central America and the Caribbean, where sorghum is an important food and fodder crop, have shown much less progress in yield and production.

Table 3. Production (000 tonnes) of sorghum and millet in 1960 and 1980 in Africa, Asia, and Latin America, and relative production increases.

	1960	1980	Increase (%)
Africa	12330	20454	66
Asia	19280	38707	100
Latin America	1470	9685	650

To complete this general picture of sorghum and millet cultivation in the developing countries, I wish to present some production statistics for the past 20 years for three countries. First, Figure 3 presents the statistics for Upper Volta. It can be seen that over the past 20 years the area cultivated and the production have remained stagnant and irregular, with some important drops in production in 1968 and in the years 1971 to 1974. The latter drop is from the Sahelian drought and the subsequent year 1974, when area cultivated remained low because of lack of seed. What is most striking in the graph is the marked drop in the area harvested for the year 1968—30% of the area harvested in the other years. It is also interesting to note that during the same year sorghum and millet production was also affected in other neighboring countries such as Niger, Nigeria, Sudan, Ghana, and Mali. This would mean that 1968 was in fact the first of a series of drought years which culminated in 1972 and 1973. However, the fact that 1968 was isolated and followed a series of wet and favorable years caused this event to go largely unnoticed.

As a second example, we have prepared Figure 4, showing the combined sorghum and millet production for India. There are some parallels between the fluctuation in area harvested in the Sahel and India; in particular, the drop in area harvested in 1972 and some "lows" in production in 1965 and

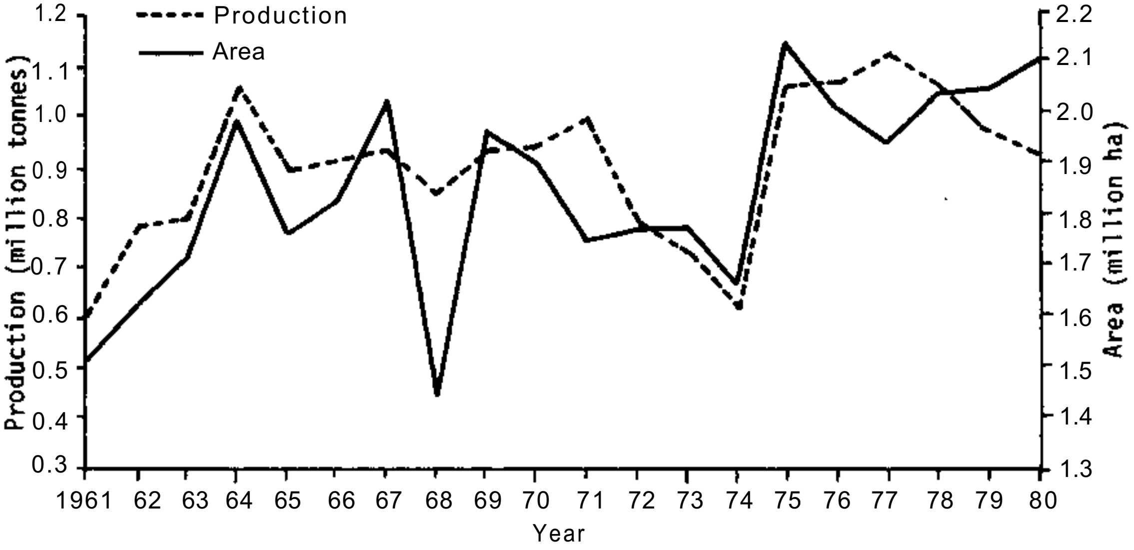

Figure 3. Area cultivated and total production of sorghum and millet in Upper Volta, 1961-1980.

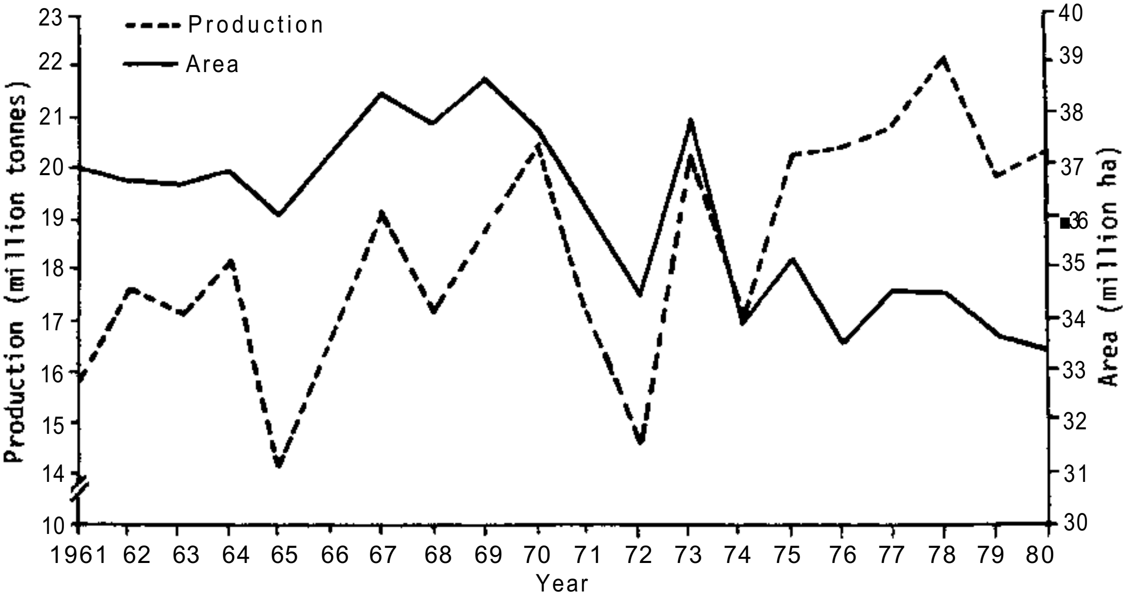

Figure 4. Area cultivated and total production of sorghum and millet in India, 1961-1980.

1968 are noticeable. Another interesting consideration is that yields in India have increased considerably over the 20-year period under consideration; over the past 10 years, total production has also been at the same time higher and much more stable, showing fewer extreme fluctuations.

Finally, I should like to mention as a demonstration of what could be done in many other areas of

Table 4. Sorghum production in Mexico, 1961 to 1981.

	1961	1971	1981
Area (ha)	107000	965000	1767000
Yield (kg/ha)	1700	2687	3562
Production (tonnes)	183000	2593000	6296000

the world, the results obtained with sorghum cultivation in Mexico. The characteristics of sorghum production in 1961, 1971, and 1981 appear in Table 4.

With these examples I wanted to show that sorghum and millet, although considered less important cereals on the world market, remain absolutely indispensable for dryland areas, which represent a very large part of the available cropland in the developing countries. Efforts made over the past 20 years by research institutions in India and elsewhere, and since 1972 by ICRISAT, have shown results, and will no doubt be pursued to improve the food situation in the semi-arid areas of the world.

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Global Production and Demand for Sorghum and Millet to the Year 2000

James G. Ryan and M. von Oppen*

Abstract

The present status of production of sorghum and millet in the seven semi-arid tropical regions and the world is shown, together with the contribution from these crops to total calorie availability and consumption.

Future yields are projected from past trends and taking into consideration estimates of the impact of ongoing and planned research and extension efforts; also future demand is projected, taking into account income and population growth rates.

The projected supply and demand are compared. Two scenario analyses, one at the all-India level and the other at the global level,are presented,projecting sorghum and millet production, consumption, and prices into the year 2000.

Issues are raised concerning the possibilities and requirements for improving the projected situations. Various strategies are discussed, such as breeding for stability vs yield; maize vs sorghum; and fodder vs grain.

Résumé

Production et demande globales de sorgho et de mil jusqu'à l'an 2000 : Cette communication présente l'état actuel de la production de sorgho et de mil dans chacune des sept régions tropicales semi-arides et dans le monde, ainsi que la contribution de ces cultures à l'apport et à la consommation des calories.

Les projections des rendements sont établies à partir des tendances dans le passé et d'estimations de l'impact des activités, en cours ou prévues, de recherche et de vulgarisation. Les projections de la demande tiennent compte des taux de croissance démographique et du revenu.

Suit une comparaison des projections de l'offre et de la demande. Sont présentées deux analyses, l'une au niveau indien et l'autre au niveau global, présentant les projections de la production, de la consommation et des prix du sorgho et du mil jusqu'à l'an 2000.

Sont soulevées des questions concernant les possibilités et les impératifs pour améliorer les pronostics. Diverses options sont étudiées : phytosélection visant soit à stabiliser le rendement, soit à l'accroître; culture du maïs ou du sorgho; culture pour le fourrage ou le grain.

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International Crops Research Institute for the Semi-Arid Tropics. 1984. Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics: Proceedings of the International Symposium, 15-20 Nov 1982, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

Sorghum and millets[1] are staple cereals in the diets of most of the 750 million people living in the semi-arid tropics (SAT) of the world. Those relying on these cereals often consume up to 700 g of them per capita per day. At this level of consumption, sorghum and millet provide the bulk of dietary energy and protein, particularly for consumers in Africa and India. Such people are amongst the poorest in the world, with annual per capita incomes generally less than U.S.$100, and farmers who grow these crops market only about 10 to 20% of their production, which is primarily subsistence-oriented. The future production performance of these two crops will hence directly affect the welfare—perhaps the very existence—of the most disadvantaged people in the world.

The income of people living in semi-arid tropical regions is both low and unstable largely because the agroclimatic environment of the SAT is marginal for crop production; indeed, this is the major reason sorghum and millets are grown there. Both crops have a comparative advantage in such marginal regions, and research that aims at increasing and stabilizing their production will both generate a major welfare or equity improvement and enhance the productivity of scarce resources in the SAT. Research on the agrometeorology of sorghum and millet can play a key role in providing the basis for this much-needed increase in productivity and stability.

This paper provides background information required for planning research to achieve these objectives. The current world and regional food situation is first discussed, together with projections to the year 2000. The present and future status of sorghum and millet production and demand are then addressed, with emphasis on the SAT regions most likely to be at risk by the turn of the century. The implications of the projected differentials in feed versus food demand growth for coarse grains are also presented. Likely sources of future increases in production of sorghum and millet are then identified, with particular emphasis on possible yield scenarios and their research and policy implications.

The Current World Food Situation and Recent Trends

World agricultural production grew at an annual rate of 2.2% per year from 1971 to 1980 (FAO 1981). With world population growing somewhat less than this at 1.85% per capita, world food output was able to improve marginally by 0.5% per year, during the same period (World Bank 1982). However, these trends mask some significant differences in agricultural production performance between regions (Table 1). Although the 90 developing countries analyzed by the FAO (1981) achieved higher growth rates of agricultural production (2.9%/year) than did the developed countries (1.4-2.1%/year), the much higher population growth rates in the former (2.6%/year) eroded most of their production gains. This was especially true in Africa, where the 2.7% per annum growth in population led to an annual decline of 1.1% in per capita food output (World Bank 1982). The countries of West Asia, where population is growing at the rate of 2.6% per annum, experienced no growth in per capita food output during the 1970s. East Asia had a l.4% per annum increase; Latin America, 0.6%.[2]

If similar trends in production and population continue for the next 20 years, the FAO (1981), in its publication *Agriculture: Towards 2000,* projects that demand growth in 90 developing countries (2.9%) will exceed projected agricultural production growth (2.8%). The imbalance will be greatest in Africa and in West Asia (Table 1). Self-sufficiency in cereals in the developing countries would decline from 91% in 1979 to 83% in 2000. again with the situation being much worse in Africa and West Asia than in other regions (Table 1). The 90 developing countries (including China) are projected to have a cereal deficit of 165 million tonnes by 2000, compared with 36 million tonnes in 1979. The most vulnerable countries could have a deficit of 77 million tonnes, or more than three times their 1979 deficit of 22 million tonnes. These countries are least able to pay for cereal imports, as they are generally net importers, have low incomes, and are land-locked or island countries.[3] The FAO con-

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1. Refers to all millets, including pearl millet (*Pennisetum amencanum*). finger millet (*Eleusine coracana*). foxtail millet (*Setana italica*), and barnyard millet (*Echinocloa crusgalli*).

2. The FAO refers to East Asia as the Far East and to West Asia as the Near East We choose to use the Asian nomenclature throughout the paper even when referring to FAOs data for the Far and Near East.

3. Cereal self-sufficiency will probably decline faster in the middle-income than in the low-income developing countries: however, this gap will probably be filled by greater trade in the middle-income countries as they increase commercial cereal imports.

Table 1. Selected indices and projections of world agricultural development.

Index	World total (124 countries)	Developed market economies (26)	Developed centrally planned economies (8)	Developing countries (90)	Latin America	Africa	East Asia	West Asia	Low income	Middle income
Annual growth in agricultural production 1971-80 (%)[a]	2.2	2.1	1.4	2.9	3.2	1.4	3.1	3.0	2.3	3.5
Projection of trend per capita calorie consumption in 2000[a,b]	na	na	na	2369	2698	2306	2208	2848	2174	2693
Population growth (%)										
Projected trend 1980-2000[a]	1.7	0.6	0.7	2.4	2.6	3.0	2.1	2.6	2.3	2.6
Actual 1970-80	1.85[c]	0.8[d]	0.8[d]	2.6[e]	2.8[e]	2.7[e]	2.5[e]	2.6[e]	2.1[d]	2.4[d]
Agricultural demand projected trend growth 1980-2000 (%)[a]	na	1.2		2.9	3.0	3.4	2.6	3.2	2.7	3.1
Annual food output growth per capita 1970-80 (%)[d]	0.5	na	na	0.4[f]	0.6	-1.1	1.4[f]	0.09[f]	-0.3	0.9
Agricultural production projected trend growth 1980-2000 (%)[a]	na	1.1-1.5		2.8	3.0	2.6	2.7	2.8	2.6	3.0
Cereal self-sufficiency 1975-79 (%)	na	na	na	91	98	75	95	82	92	90
Trend projection to 2000[a]	na	na	na	83	87	56	93	67	86	79

Continued

Table 1. *Continued.*

Index	World total (124 countries)	Developed market economies (26)	Developed centrally planned economies (8)	Developing countries (90)	Latin America	Africa	East Asia	West Asia	Low income	Middle income
Sources of added crop output (%) in FAO scenarios [a]										
Arable land	na	na	na	26	55	27	10	6	na	na
Cropping intensity	na	na	na	14	14	22	14	25	na	na
Yield	na	na	na	60	31	51	76	69	na	na
Arable area in use 1975 (%) [a]	42 [g]	na	na	40	25	30	79	63	45	34
Share of irrigation in arable land (%) [a]	na	na	na	14	7	2	25	23	18	9

a. Source: FAO (1981).

b. Requirements are fixed at 2295 per capita per day for all 90 developing countries; the range is from 2484 for East Asia to 2236 for West Asia

c. Calculated from population data in FAO (1980)

d. Source: World Bank (1982)

e. From 1963-75 only

f. The World Bank refers to these as All Developing Countries, Southeast Asia, and South Asia, respectively. The country coverage of FAO and the World Bank in the regions is also different.

g. Source: Hopper (1976).

cludes (FAO 1981, p.26): "It is probably unrealistic to think that food aid, which in 1978-79 had still not reached the current target of 10 million tonnes, could bridge the larger part of this gap." Even if these projected cereal deficits were filled, the FAO estimates there would still be almost 600 million undernourished people in the developing countries.

In various projections to the year 2000, the FAO (1981) indicates that expansion of arable land will provide just over one-quarter of the additional crop production in the 90 developing countries. This will be concentrated largely in Latin America and Africa, where the expansion in arable area to sustain food production growth will disturb the ecological balance and alter the agroclimate. Higher yields will be responsible for the bulk (60%) of future crop-production increases and greater cropping intensity will contribute the rest (14%). Irrigated areas could provide almost 50% of the projected expansion in crop production 1980 to 2000, but 84% of the total arable area will remain nonirrigated at the end of the century and supply 59% of total crop output, much of which will be sorghum and millets. Most of the irrigated land will be in the low-income, land-scarce countries of East and West Asia.

Trends in Sorghum and Millet Production

Sorghum and millet together occupy more than 100 million hectares of the world's cropland, from which about 100 million tonnes of grain are produced (Table 2). Although the SAT countries have more than two-thirds of the world's harvested area of sorghum and millet, they contribute only about half of the world's total production, because of low yields. Semi-arid tropical Asia and SAT sub-Saharan Africa are the world's major sorghum-growing regions, representing about one-third and one-quarter of the total area, respectively. The centrally planned economies (CPEs) are the third most important sorghum producers; and with more than one-third of the area and 40% of the production, they represent the most important millet region. The countries of SAT Asia (35% of the area and 30% of the production) and SAT sub-Saharan Africa (28%, 24%) are the only other major millet-growing zones.

In sub-Saharan Africa, Nigeria is the major sorghum producer, followed by the Sudan, Ethiopia, Upper Volta, and Chad (Fig. 1). Of the major producers of sorghum, the West African Sahelian countries generally have the lowest yields. In India, which grows about half the SAT sorghum, the state of Maharashtra is by far the largest producer, with Andhra Pradesh and Karnataka each producing only about one-third of Maharashtra (see Fig. 2, Sivakumar et al., these Proceedings). Sorghum yields are generally much higher in south India than in the northern states.

The foremost millet producers in sub-Saharan Africa are Uganda, Mali, Nigeria, Senegal, and Niger (Fig. 2), with the highest yields attained in Uganda and Mali, and the lowest in Niger. In India, Rajasthan leads in terms of area sown to pearl millet but it has by far the lowest yields (see Fig. 3, Sivakumar et al., these Proceedings). Gujarat produces most of India's pearl millet, due largely to its high yields, which result from the extensive use of irrigation on summer crops on the lighter soils of that state. Yields in Tamil Nadu are also high, but total production lags behind that of Maharashtra.

Growth Rates

Sorghum

The world area of sorghum currently exceeds 50 million hectares but has been growing at only 0.33% per annum or by 170000 ha (Table 3). Over the past 20 years, yield increases of around 28 kg/ha per year (2.47%) have enabled production to grow by more than 1.6 million tonnes annually, representing a compound growth rate of 2.8%. The SAT less developed market economies (LDMEs) had a production growth of 3.67% per annum, primarily as a result of a 3.11% annual increase in sorghum yields (Fig. 3). This enabled production to increase by almost 1 million tonnes a year. The fastest-growing sorghum-producing zones within the SAT LDMEs in the last 20 years were Latin America (12%), eastern Africa (2.7%) and Asian countries other than India (2.7%) (Table 4). However, in the last 10 years sorghum growth rates have markedly declined in these three zones and in southern Africa and West Asia. Indian and West African growth rates substantially increased in the 1970s. The fastest-growing region is the non-SAT LDMEs, where sorghum area has expanded by 75000 ha/year (8.2%), yield by 34 kg/ha per year (3.62%), and production by 134000 tonnes (11.8%) (Table 3). However, this performance began from a very low base. In spite of a steady decline of

Table 2. Area, production, and yield of sorghum and millet in various regions of the world (Annual average 1975-1979). [a]

Region	Sorghum			Millet		
	Area (000 ha)	Production (000 tonnes)	Yield (kg/ha)	Area (000 ha)	Production (000 tonnes)	Yield (kg/ha)
Semi-Arid Tropics (SAT)						
A. Developed market economies						
Oceania	482	965	2002	31	27	871
Subtotal (A)	482	965	2002	31	27	871
B. Less developed market economies						
Sub-Saharan Africa	13027	8761	673	15077	8515	565
North and Central America	1509	3903	2586	-	-	-
South America	2433	6642	2730	237	297	1253
Asia	17878	12382	693	19123	10669	558
				(12163) [b]	(5960) [b]	(490) [b]
Subtotal (B)	34847	13688	909	34437	19481	566
				(27477)	(14772)	(538)
Total SAT (A+B)	35329	32653	924	34468	19508	566
				(27508)	(14799)	(538)
Rest of the world						
C. Developed market economies						
Sub-Saharan Africa	341	405	1188	22	15	682
North and Central America	5721	19446	3399	-	-	-
Asia	4	13	3250	3	4	1333
Europe	148	576	3892	11	23	1917
Oceania						
Subtotal (C)	6214	20440	3289	36	42	1167

Continued

Table 2. *Continued.*

Region	Sorghum Area (000 ha)	Sorghum Production (000 tonnes)	Sorghum Yield (kg/ha)	Millet Area (000 ha)	Millet Production (000 tonnes)	Millet Yield (kg/ha)
D. Less developed market economies						
Sub-Saharan Africa	667	788	1181	863	1290	1495
North and Central America	326	379	1163			
South America	272	608	2235			
Asia	16	14	875	231	247	1068
Europe						
Oceania						
Subtotal (D)	1281	1789	1397	1094	1537	1405
E. Centrally planned economies	9475	11812	1247	18403	13987	760
Subtotal (E)	9475	11812	1247	18403	13987	760
Total rest of the world (C+D+E)	16970	34041	2006	19533	15566	797
World (A+B+C+D+E)	52299	66694	1275	54001 (47041)	35074 (30365)	650 (645)

a Includes China b. In SAT Asia the figures in parentheses refer to pearl millet only All figures outside parentheses refer to all millets.

150000 ha (-1.52%) in the area of sorghum grown each year since the early 1960s, the centrally planned economies have increased their annual production by 200000 tonnes (1.94%) due to a 37 kg/ha per year increase in yields (3.5%).

Millet

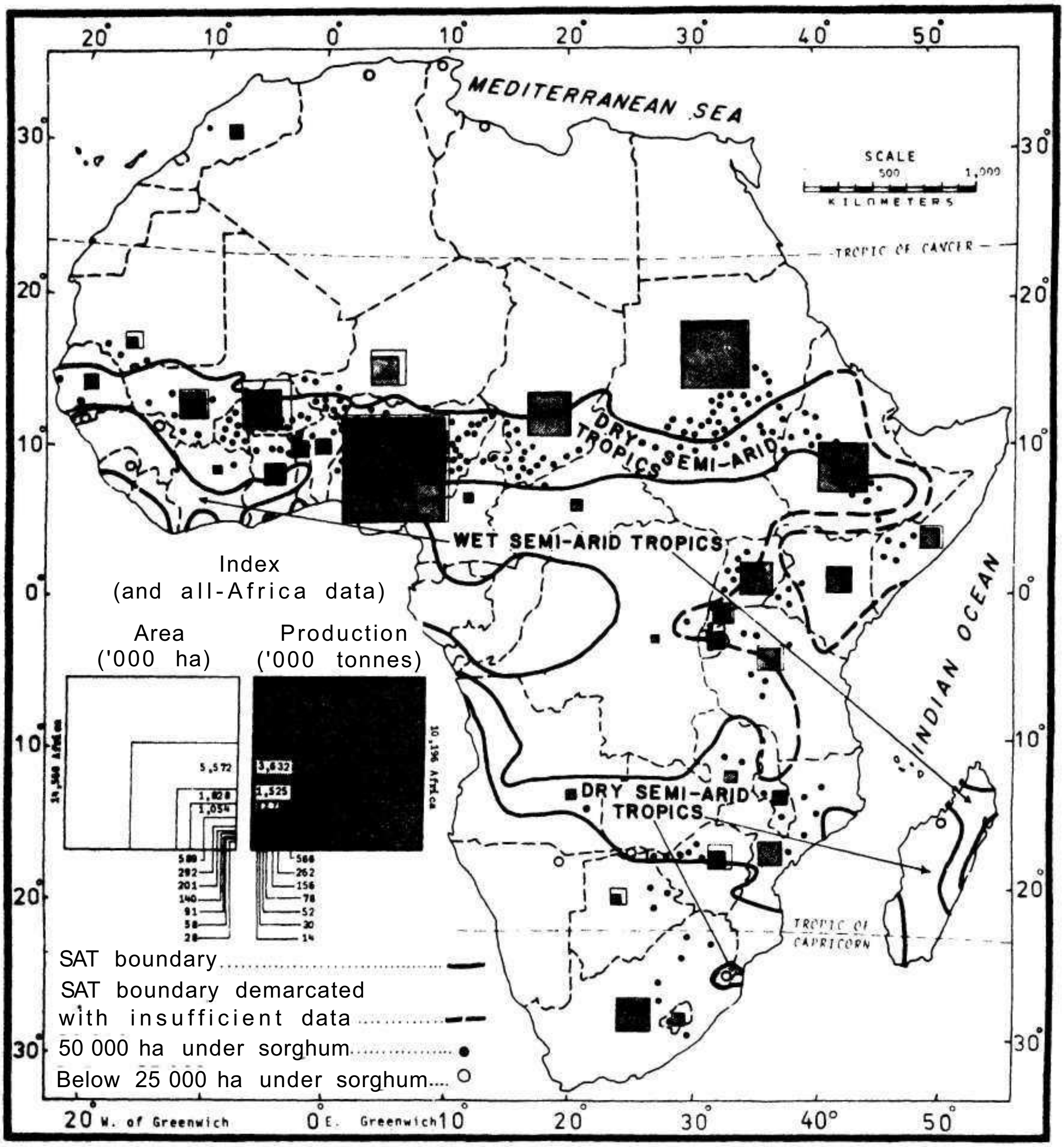
In the 1960s and 1970s (Table 3) world millet production grew by only 0.9%, or 250000 tonnes, annually. Yields increased less than 9 kg/ha per year and simultaneously area sown to millets declined by 300000 ha (-0.62%) per year. The CPEs had a better yield record (2.75%) than the SAT LDMEs, where yields were virtually stagnant (0.8%). However, because millet area declined by 343000 ha per year (-1.75%) in the CPEs, production rose by only 135 000 tonnes (1 %) (Fig. 4). In the SAT LDMEs a 0.35% annual increase in area, combined with a small yield increase, led to production growth of 1.15% (150 000 tonnes). The SAT LDME countries in Latin America had the highest millet production growth in the last 20 years (3.9%), followed by those in eastern Africa (2.9%) (Table 4). In all zones of the SAT except India, millet production has grown much faster *(or* declined less) in the 1970s than in the 1960s. The non-SAT LDMEs have had a drastic decline in millet production.

In the next section we match these historical production trends with various projections of growth in the future demand and production of coarse grains, with emphasis on the developing countries where problems of food imbalances loom largest.

Demand and Supply Projections

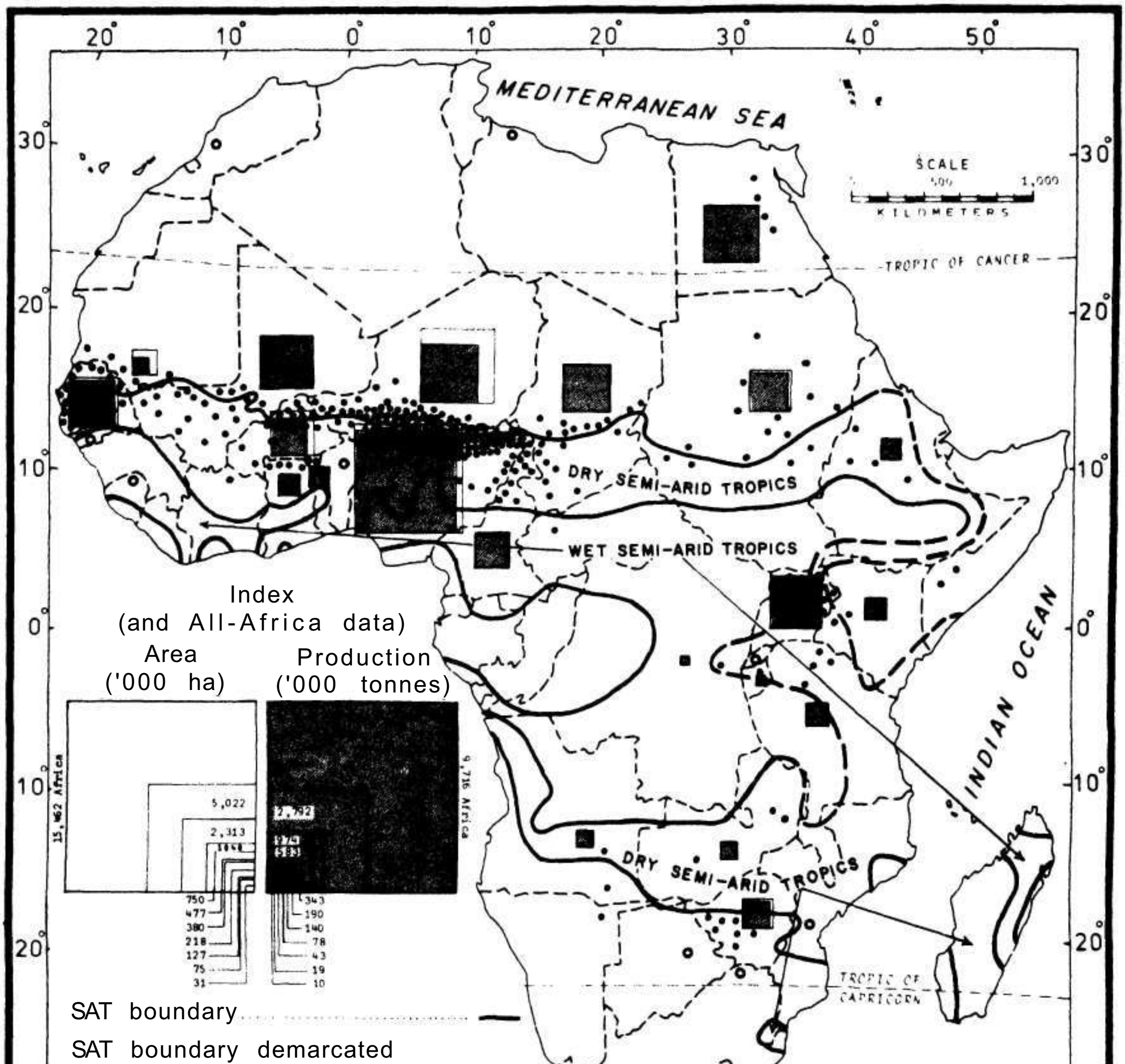
World demand for coarse grains is projected by Aziz (1976) to rise by 2.5% a year from 1970 to 2000 (Table 5). This is much less than the annual growth rate of sorghum production in the 1960s and 1970s (2.8%), but *far in* excess of that of millet (0.86%). On a worldwide basis, therefore, there may not be an imbalance in sorghum demand and supply but there may be in millet, particularly in the non-SAT countries, where millet production has been declining by more than 2% per year (Table 3 and Fig. 4).

The major deficit regions for sorghum and millets in 2000 would appear to be the SAT LDMEs (Table 5). Sorghum production in this region has grown at 3.67% per year since the early 1960s, and coarse grains are projected to grow by 3.45% to 2000,



Projection: Kolawole S. Adam Base map from The National Atlas of Senegal
Prepared by M.N.S. Bose, ICRISAT, Patancheru, A.P., India.
Sources: FAO Monthly Bulletin of Statistics 1981 4(12). World Agricultural Atlas.
ICRISAT Agroclimatology Subprogram progress report 5 (1980-81).

Figure 1. Sorghum distribution, area, and production in Africa.



Projection: Kolawole S. Adam Base map from The National Atlas of Senegal

Prepared by M.N.S. Bose, ICRISAT, Patancheru, A.P., India.

Sources: FAO Monthly Bulletin of Statistics 1981 4(12). World Agricultural Atlas. ICRISAT Agroclimatology Subprogram progress report 5 (1980-81).

Figure 2. Millet distribution, area, and production in Africa.

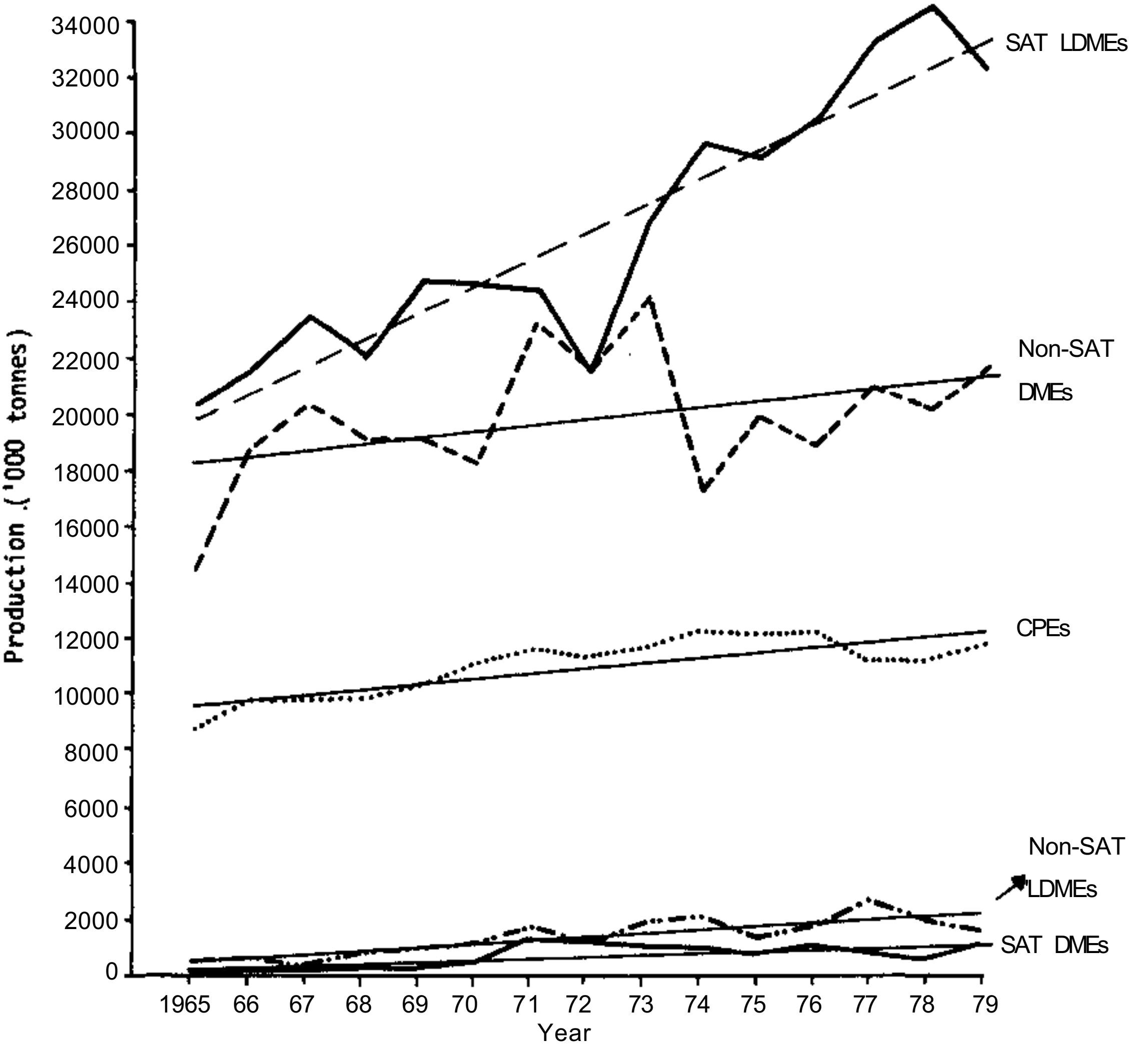


Figure 3. Sorghum production in five regions of the world.

using the FAO's more optimistic scenario, and at 2.78% using a more pessimistic one. These figures compare with those for projected demand growth generally in excess of 3.5%.

Examining more recent sorghum growth trends for the zones within the SAT, it appears that the major shortfalls in production may occur in West Asia, southern and eastern Africa, and Asia, other than India (Fig. 5). It would appear that the deficit in SAT millet production may be far greater in the future than that in sorghum production. In the past 20 years, millet production has grown by only 1.15% per year in the SAT LDMEs, far below projected coarse grain demand. In the last 10 years, millet production in all SAT zones except Latin America has also grown at rates well below future demand growth (Fig. 6).

The non-SAT LDMEs would not appear to have the prospect of deficits in sorghum in 2000, but they would in millets. The non-SAT developed market economies (DMEs) must dramatically alter their production trends if they are to avoid substantial coarse grain production deficits in 2000.

The major source of growth in future demand for coarse grains—particularly in the LDMEs and especially among those with the lowest incomes—

Table 3. Linear trends and compound annual growth rates of sorghum and millet: 1961-65 (average) to 1979.[a]

	Sorghum					Millet				
	Linear trend equations					Linear trend equations				
Region	Intercepts	Regression coefficients (t-value)	R^2	1979 trend value	Annual compound growth rate (%)	Intercepts	Regression coefficients (t-value)	R^2	1979 trend value	Annual compound growth rate (%)
A. SAT developed market economies (DMEs)										
Area	193	27.8 (3.4)	0.47	603	8.70	26	0.579 (1.07)	0.08	35	1.67
Production	273	62.0 (3.8)	0.52	1203	10.90	29	0.061 (0.10)	0.00	30	0.24
Yield	1496	39.5 (2.4)	0.31	2089	2.20	1079	-13.2 (-1.4)	0.13	881	-1.43
B. SAT less developed market economies (LDMEs)										
Area	32415	189.8 (3.6)	0.50	35262	0.56	26556	93.7 (1.81)	0.20	27962	0.35
Production	18755	985.9 (8.9)	0.86	33543	3.67	12689	153.6 (1.81)	0.20	14993	1.15
Yield	585	24.6 (9.5)	0.87	954	3.11	477	3.99 (1.59)	0.16	537	0.80
C. Non-SAT DMEs										
Area	5941	27 (0.91)	0.06	6346	0.47	56	-1.81 (-3.88)	0.54	29	-3.8
Production	17993	237.9 (1.74)	0.19	21561	1.30	52	-1.47 (-1.6)	0.16	30	-2.2
Yield	3013	27.2 (1.59)	0.16	3420	0.83	842	13.8 (1.3)	0.11	1049	1.6

Continued

Table 3. *Continued.*

	Sorghum					Millet				
	Linear trend equations					Linear trend equations				
Region	Intercepts	Regression coefficients (t-value)	R²	1979 trend value	Annual compound growth rate (%)	Intercepts	Regression coefficients (t-value)	R²	1979 trend value	Annual compound growth rate (%)
D. Non-SAT LDMEs										
Area	405	75.4 (5.1)	0.67	1536	8.19	1790	-50.8 (-6.2)	0.75	1028	-3.76
Production	328	133.6 (6.27)	0.75	2332	11.81	2142	-41.0 (-4.2)	0.58	1527	-2.37
Yield	1126	33.9 (1.17)	0.10	1645	3.62	1184	18.1 (2.8)	0.37	1455	1.39
E. Centrally planned economies (CPEs)										
Area	11790	-149.0 (-3.0)	0.40	9555	-1.52	23444	-342.9 (-4.2)	0.57	18299	-1.75
Production	9400	205.2 (5.28)	0.68	12477	1.94	12709	135.2 (2.1)	0.25	14737	1.00
Yield	761	36.7 (11.1)	0.90	1311	3.46	525	18.63 (5.66)	0.71	804	2.75
F. World										
Area	50724	171.2 (1.88)	0.21	53293	0.33	51872	-301.3 (-2.8)	0.38	47353	-0.62
Production	46749	1624.6 (10.4)	0.89	71118	2.8	27621	246.4 (2.1)	0.26	31318	0.86
Yield	922	27.95 (11.5)	0.91	1341	2.47	528	8.86 (4.53)	0.61	661	1.49

a. Area in 000 ha, production in 000 tonnes, and yield in kg/ha. Calculated by ICRISAT using FAO data tapes at IFPRI.

Table 4. Annual compound growth rates (%) of sorghum and millet production in the less developed semi-arid tropical regions.

	Region						
Crop	India	West Asia	Other Asia	Eastern Africa	West Africa	Southern Africa	Latin America
Sorghum							
1961-65 (av.) to 1978	1.64	-3.11	2.65	2.68	0.67	2.04	12.0
1968-70 (av.) to 1979	5.26	-4.5	0.35	0.75	4.71	-0.31	8.75
Millet							
1961-65 (av.) to 1978	1.81 (1.32)[a]	-5.0	-1.14	2.88	1.01	-0.51	3.87
1968-70 (av.) to 1979	1.83 (0.58)[a]	6.60	0.99	3.20	1.68	-0.01	9.50

a. Pearl millet only.

Table 5. Summary of trends and projections of growth in demand and production of coarse grains (%/year).

	Region							
Source	Developed market economies (DMEs)		Less developed market economies (LDMEs)		Low-income developing countries	All other developing countries	Centrally planned economies (CPEs)	World
			Demand					
World Bank[a] (1977)			3.6					
Aziz (1976)[b]								
Food	0.52		2.49				1.16	1.92
Feed	2.16		5.30				2.74	2.72
Total	2.14		3.50				2.12	2.50
FAO(1971)[c]			2.74					
FAO(1979)[d]								
Food			2.41		2.28	2.55		
Feed			5.65		7.40	5.54		
Total			3.81		2.70	4.30		
			Production					
FAO(1981)[e]								
Scenario A			3.45					
Scenario B			2.78					
Ryan and von Oppen (1982)'	SAT	non-SAT	SAT	non-SAT				
Historical 1961-65 to 1979								
Sorghum	10.86	1.30	3.67	11.81			1.94	2.80
Millet	0.24	-2.2	1.15	-2.37			1.00	0.86

a. Projection up to 1985.

b. Projections from 1970 (actual) to 2000.

c. Projections from 1980-90.

d. Projections from 1975-2000 for barley, maize, millet, sorghum, and other cereals (except rice and wheat) using the optimistic scenario A in FAO(1981).

e. Projections for 1975-79 to 2000 for millet, sorghum, and other cereals (except rice and wheat).

f. Compound growth rates computed from the data files at the International Food Policy Research Institute, Washington, DC, USA

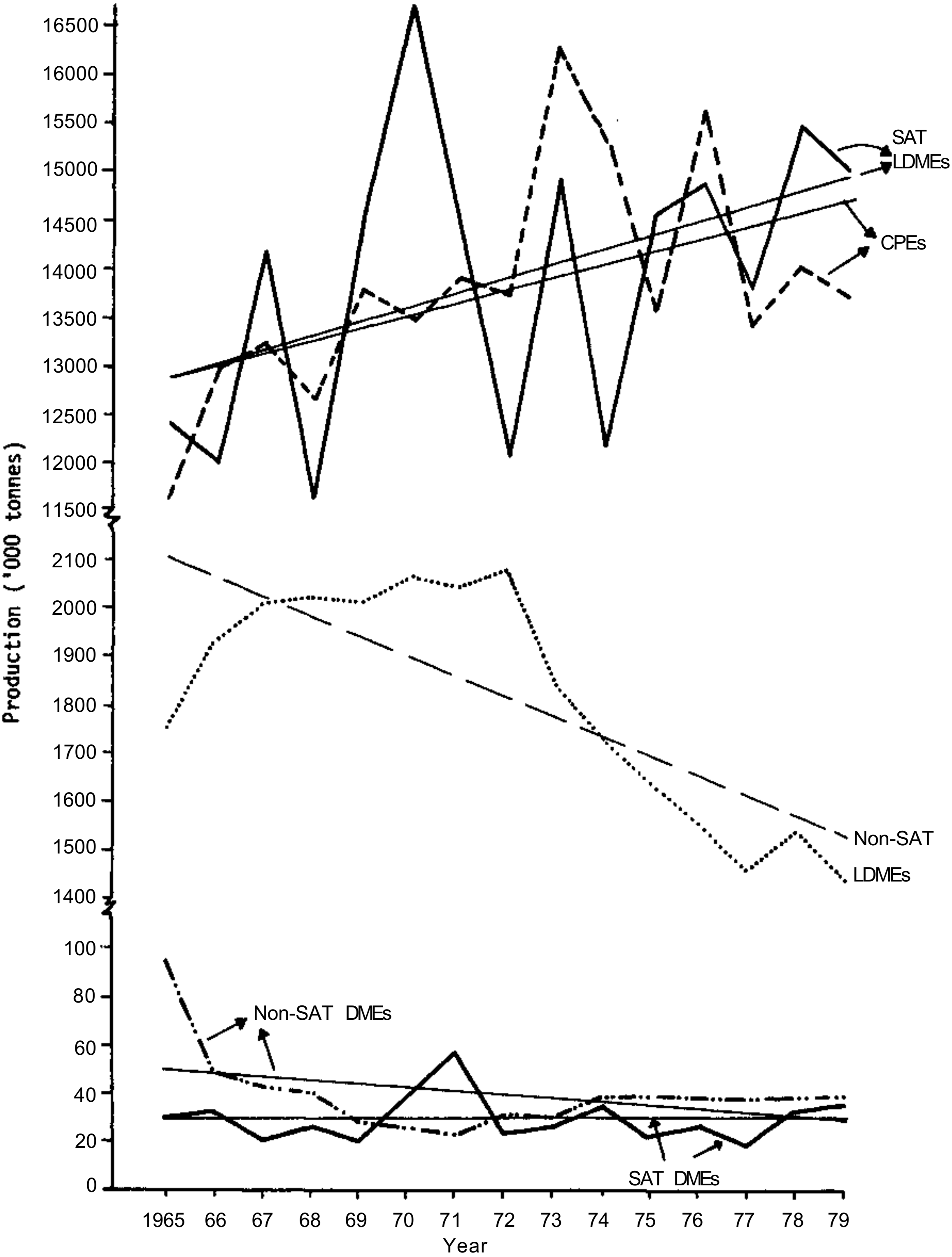


Figure 4. Millet production in five regions of the world.

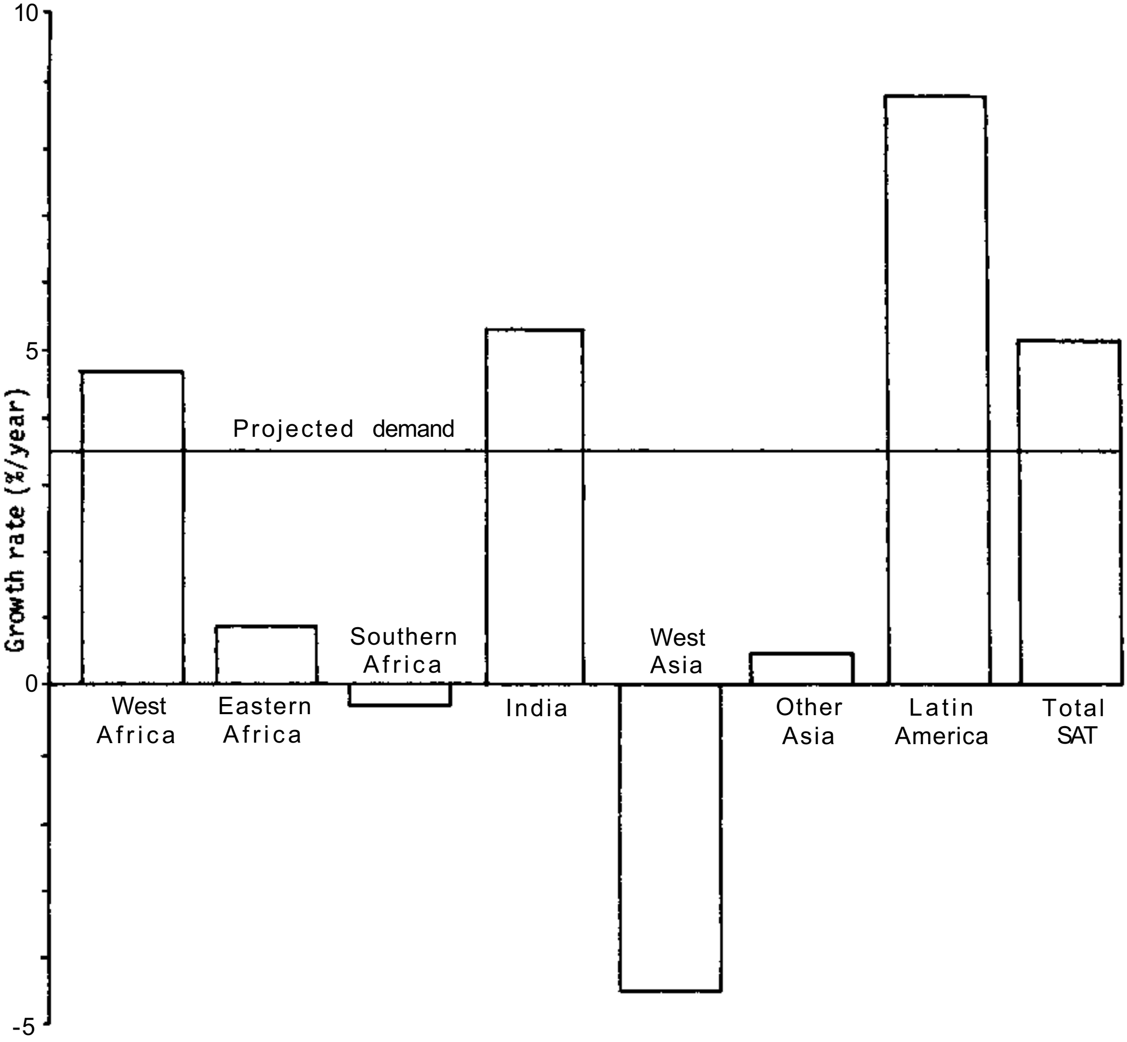


Figure 5. Growth in sorghum production 1968-70 to 1979 and projected demand to the year 2000 (%/year).

is likely to be their use for animal feed. Both Aziz (1976) and the FAO (1979) project that LDME demand for coarse grain feed will grow by around 5.6% per year compared with less than 2.5% for human food. In 1975, feed demand in 90 developing countries represented 19% of total domestic consumption of sorghum, millet, and other cereals, except rice and wheat. By 2000, the FAO (1979) projects that this figure will rise to 32%, with the proportion consumed directly by humans declining from 70 to 56%,

Sorghum and millets have considerable value in a traditional farming system as a source of fodder, fuel, and building material. In modern economies the vegetative growth of these plants in dry areas might be increasingly exploited through the breeding of special fodder varieties, sugar varieties for ethanol production, or other varieties for special technologies.

It seems clear from the above analysis that the developing countries within ICRISAT's mandate region will experience either increasing shortages of sorghum and millet at present prices or, more likely, at much higher prices, and will have large

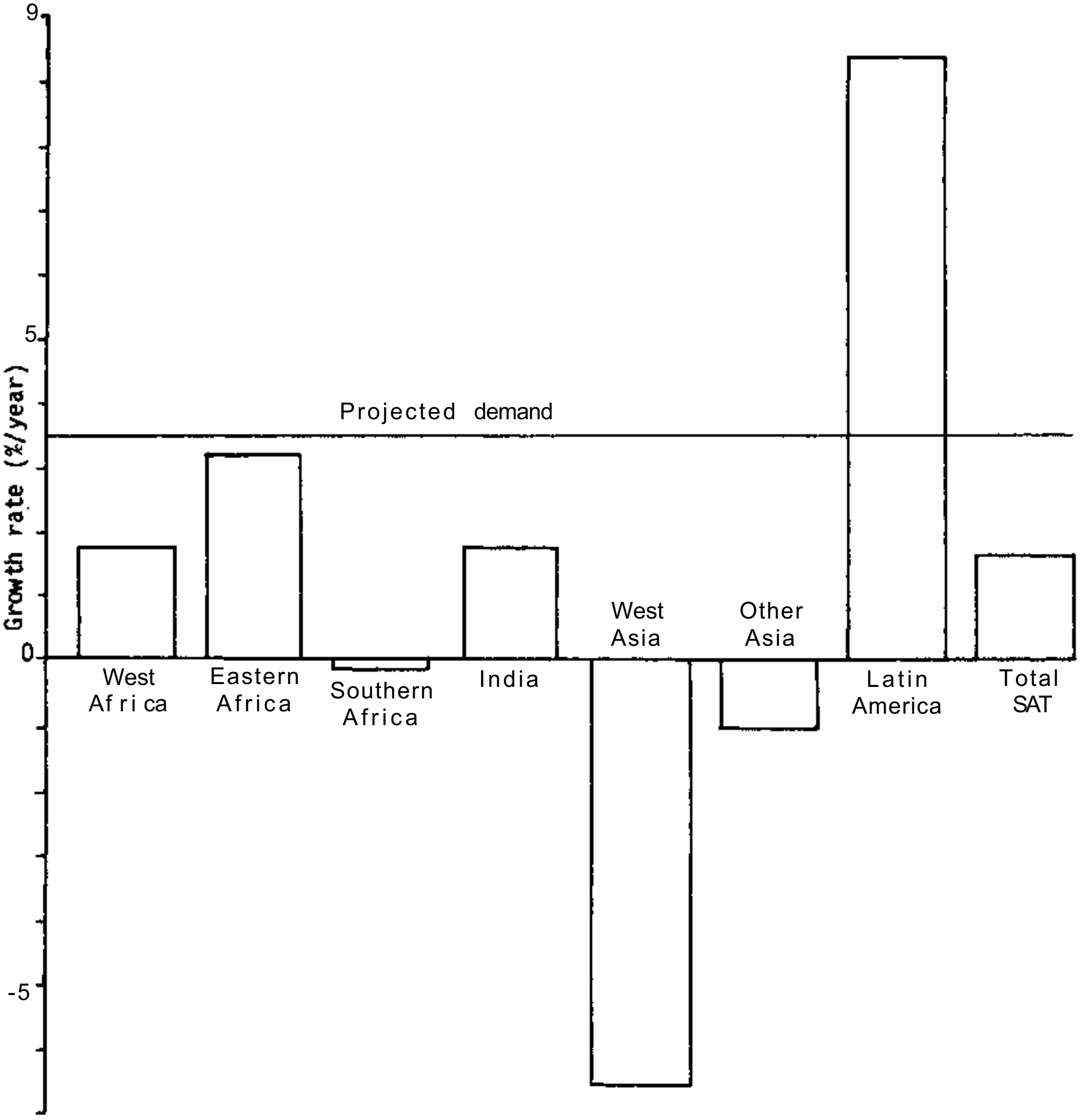


***Figure* 6. Growth in millet production 1968-70 to 1979 and projected demand to the year 2000 (%/year).**

numbers of low-income people with unmet food needs. This will result partly from increasing competition between feed and food uses for the coarse grains in developing countries. Even by 1990 (commercial) food import gaps for sub-Saharan Africa are predicted to range from 9 to 21 million tonnes (USDA 1980). In addition, food grains needed to bring diets up to a minimum calorie consumption level of 2300 kcal/person per day are estimated at between 9 and 13 million tonnes. Hence, in sub-Saharan Africa the food and nutrition problem will involve questions of both production and distribution.

If the developing countries are to address their projected food deficit problems effectively, then greater attention must be paid to agricultural

Table 6. Arable land areas currently and potentially In use in developing countries.[1]

	90 developing countries	Region				Low-income countries	Middle income countries
		Africa	Latin America	East Asia	West Asia		
Potential arable area (million ha)	1843	676	693	335	139	846	997
Arable area in use (% of potential)							
1975	40	30	25	79	63	45	34
2000[2]	50	39	39	87	67	53	47
Arable area (ha) in use per capita of population							
1975	0.37	0.64	0.54	0.23	0.47	0.30	0.48
2000[2]	0.25	0.39	0.45	0.15	0.26	0.20	0.34

1. Source: FAO (1981, p 66).
2. Using FAO's optimistic scenario A

research and development. In this manner their self-sufficiency ratios can be improved and they may even generate exportable surpluses of agricultural products in which they have a comparative advantage (Thompson 1982). This strategy would help finance measures to overcome future cereal deficits and to encourage further development of the countries' economies. The World Bank (1982) specifically refers to the need for increased research in the hitherto neglected areas of rainfed crops, root crops (cassava), and coarse grains (sorghum and millet), so as to boost productivity in humid and semi-arid areas—particularly those in sub-Saharan Africa.

Sources of Future Production Growth

As mentioned earlier, the bulk (60%) of projected crop production increases in developing countries to 2000 is expected to derive from yield increases (Table 1). This will apply especially to the countries of West and East Asia, where population densities are high. Less than 10% of their production growth will be generated from expansion in the arable land area, as they already utilize more than two-thirds of their potentially arable land. The balance will come from increases in cropping intensity, particularly in West Asia. In sub-Saharan Africa, where less than one-third of the potentially arable land is at present cultivated, expansion of arable land is projected to contribute only 27% of future crop production growth. Surprisingly, the FAO (1981) expects yield increases to provide more than half of the future production increases in Africa and cropping intensity 22%. These two figures seem quite high,[4] especially when the share of irrigated land is only 2%. We would expect the relative contribution of area, intensity, and yield in Africa to be about the same as that projected by the FAO for Latin America, namely 55, 14, and 31%, respectively. These projections by the FAO (1981) would imply that more than 60% of the potentially arable land in Africa and Latin America would remain uncultivated (Table 6) in 2000.

Expansion of sorghum and millet production in regions relatively abundant in land, such as sub-Saharan Africa and Latin America, will involve further reduction in forest areas, possibly affecting the agroclimate. In such areas agroclimatologists can play a significant role in monitoring and predicting the likely effects of this on crop production. However, in West and East Asia, where yield and cropping intensity will be the major sources of production growth to the year 2000, the types of questions posed for agroclimatologists will be different, relating more to land-saving types *oi* technological changes rather than the land-using types more relevant in Africa and Latin America. In the words of the World Bank (1982, p.39):

> Many still largely traditional farming systems that were sustainable with a low density of population are becoming increasingly

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[4] From 1961 to 1980, yield and intensity increases together contributed only 50% to production growth in West and eastern Africa (World Bank 1982, p. 57); in India they contributed 87%.

> strained by, and vulnerable to, the pressure of rising population. Spectacular environmental damage exemplifies the consequences of this pressure as land-hungry cultivators push into the tropical forests, up the hillsides, and across drought-prone, semi-arid savannah.

Location-specific technologies are needed to help ensure that production gains are achieved without unacceptably compromising the environment's ability to sustain production and population in the long run. As stated in the World Development Report (World Bank 1982, p.63):

> While irrigation has many advantages, the fact remains that rainfed areas constitute 80 percent of the developing world's cultivated land and support nearly two-thirds of its farmers. Yield increases still depend on the subtle interaction between soil, water, seeds, and sunlight, but the process is not as well understood under rainfed conditions as it is with irrigated land.

Agroclimatologists could render invaluable assistance in the formulation of research and development strategies by mapping zones where sorghum and millets (of various genotypes and phenotypes) could be grown with assurance. These could then be overlaid with maps describing projected population densities and unused arable land to indicate where land-using versus land-saving approaches would be relevant. The FAO's emerging crop suitability classification based on soil and water status in its agroecological study seems to be a step in the right direction (FAO 1979).

Other research areas such as weather forecasting to improve crop planning and yield stability remain important challenges for agroclimatological researchers. In conducting studies and analyses of the SAT, they should be aware of basic agroeconomic differences between regions: in high-potential areas researchers should strive for product-maximizing strategies, while in marginal areas output stability may be more appropriate.

The World Bank (1981) has enunciated a clear policy of selection of agricultural development project sites in sub-Saharan Africa, primarily on the basis of agricultural potential. This translates into those areas with good soil and adequate rainfall. The major challenge facing researchers in the future will be the more marginal areas, especially those in Africa:

> In the less-favored agricultural areas, development efforts had to fall back on traditional or slightly improved varieties of millet and sorghum, cowpeas, and traditional types of maize. The accumulated results of research are limited here. Also, the more marginal the ecological conditions, the more a variety needs to be adapted to the very specific conditions of the zone. Thus, tradeoffs have to be made between yield increases and drought resistance, and agricultural research has not yet succeeded in producing varieties adapted to these special conditions. (World Bank 1981, p.71).

The research strategy in Africa should emphasize measures that increase labor productivity—in particular, the use of farm implements, ox-drawn cultivators, winnowers, threshers, and equipment aimed at reducing women's labor (mills, improved and accessible water supplies). Research aimed at enhancing land productivity should be concentrated especially in those regions where land is becoming a constraint and where potential for yield increases exists.

As yield increases have been the major source of production growth of crops, especially in the more densely populated regions of the developing world, it is instructive to examine yield scenarios used by various agencies concerned with projections of sorghum and millet production. The FAO (1979) projects that yields of millet, sorghum, and other cereals in the developing countries will rise from an average of 740 kg/ha in 1975 to 1200 kg/ha in 2000 (Table 7). This represents a 64% increase. The largest yield growth is projected for East Asia (69%) and the lowest for West Asia (47%). ICRISAT's projection of historical yield trends of a mean of 25 kg/ha per year for the SAT LDMEs (Table 3) gives a yield of more than 1400 kg/ha—well above the 1200 kg figure of the FAO's optimistic scenarios. However, projecting historical yield trends for millets of 4 kg/ha per year amounts to a yield of only 600 kg/ha in 2000.

In a poll we conducted, principal scientists in the cereal programs at ICRISAT, using Delphi techniques, at current levels of funding, projected sorghum and millet yields for India and Africa in farmers' fields in the year 2000 (Table 8).

The scientists were asked to provide their own

Table 7. Yield levels (kg/ha harvested) of sorghum, millets, and other cereals[1] used by FAO in its projections[2] for developing countries.

	Region				
Year	90 developing countries	Africa	Latin America	East Asia	West Asia
1975	740	630	2010	580	890
1990	990	790	2540	800	1090
2000	1210	940	3010	980	1310

1. Except wheat, rice, maize, and barley.
2. Source: FAO (1979).

Table 8. Projected yields (kg/ha) of sorghum and millet in farmers' fields to the year 2000.

	Sorghum		Pearl Millet	
Year	India	Africa	India	Africa
1990	1240	950	770	610
2000	1450	1100	950	770

Source: Results of a poll of principal scientists in the Cereal Programs at ICRISAT.

best estimates but, of course, they might have been influenced in their judgment by other estimates. The results from this poll confirm that yield projections in Table 7 are well within the range of possibility, as seen by cereal breeders at ICRISAT The ICRISAT scientists also believe that yields in on-farm tests of new elite cultivars and practices for sorghum in 2000 could be more than double those being obtained by farmers now, with new genotypes in variety trials yielding more than three times what farmers would be achieving in their fields.

Increases in crop yields and production as a result of research and development may be accompanied by increased variability of production. For example, in non-SAT DMEs with current sorghum yields of over 3400 kg/ha, production variability is more than 80% (Table 3).[5] In contrast, although SAT LDMEs have much lower yields of around 950 kg/ha, they also have a much lower production variability of 13%. The same relationships however do not appear to hold for the millet regions.

In an analysis of the sources of instability in India's foodgrain production, Hazell (1982) found that after the mid-1960s the coefficient of variation of total foodgrain production increased from 4 to 6%. Most of the explanation was the increase in crop yield covariances of different crops in the same and in different states, and an increase in the variability of crop areas sown, which are now more positively associated with yields. About three-quarters of the increase of 2307% in India's pearl millet production variance between the two periods can be attributed to increases in interstate production covariances. Most of the rest is accounted for by variance increases in only three or four states, especially in Rajasthan. Of the 139% increase in the variance of India's sorghum production, 90% is attributable to Maharashtra state, probably largely a result of the disastrous 1972/73 drought.

Hazell postulates that the improved seed and fertilizer technologies have probably had less of a role in this than changes in weather patterns and the more widespread use of irrigation and fertilizers at a time when the supplies of these inputs were less reliable. In such circumstances he doubts the value of research strategies aimed at developing less risky technologies (e.g., disease-, insect-, and drought-resistant cultivars) for individual crops as a means of stabilizing India's total cereal production, as this will not address the covariance problem. Policies to stabilize supplies of fertilizers and electric power for irrigation pumps might be more effective. These conclusions require further research before they are used to formulate policies. Agroclimatologists must play a major role in such studies if the relationships between weather patterns and production are to be quantified.

Conclusion

To the year 2000, it seems that for the world as a whole there will be a balance between the growth in demand and supply of all agricultural products. This also applies to sorghum. But world demand growth for coarse grains is expected to far exceed projected increases in world millet production. Sorghum production in the developing countries of the semi-arid tropics is projected to grow faster than demand, although some regional imbalances will arise; however, major deficits of millet are projected for most regions.

Of the SAT regions, sub-Saharan Africa will

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[5] Production variability is measured here as the dispersion around the linear trend, or 100(1 -R^2), where R^2 is the coefficient of multiple determination of linear trend lines fitted from 1961-65 (average) to 1979.

probably have the largest coarse grain deficits by the end of the century, due primarily to the high population growth rates that will continue up to that time. India should have no difficulty meeting projected sorghum demand growth if the annual sorghum production growth rate of the 1970s (>5%) can be maintained. However, millet production (particularly pearl millet) has been growing more slowly in India of late, and unless this changes there will be large deficits by 2000.

All these scenarios imply that there will be need for a steady increase in research and development on sorghum and millets in the marginal areas in which they are grown in the semi-arid tropics. The World Bank (1981) recognizes this need, which is greatest in sub-Saharan Africa:

> More intensive research should be launched which aims at finding technologies appropriate to these mainly arid and semi-arid regions. Until this technology is discovered, these areas should be provided with basic economic and social infrastructure which will eventually enable the local population to make use of future opportunities. (World Bank 1981, p.52).

In planning this research effort agroclimatologists can play a key role through base-data analysis to delineate zones where breeders, soil scientists, agronomists, and others can develop improved sorghum and millet genotypes, phenotypes, and practices. Such analysis and mapping should involve overlaying present and projected population densities in order to identify where technologies need to be more of the land-saving (labor-using) versus the land-using (labor-saving) type. Mapping of regions by agroclimatologists according to the degree of riskiness of crop production can assist in the design of food security policies. Relating the extent of intercropping practiced by farmers to such measures can also be valuable in designing research strategies in cropping systems.

Yield increases will play a major role in the future growth of sorhgum and millet production in the developing countries, especially in the more densely populated region of Asia. Recent yield trends will have to be substantially improved, particularly for millets in Africa, if major food deficits are to be avoided. Even if increased yields generate greater production instability, this may be an acceptable price to pay for greater general availability of food grains. This danger could be reduced, however, if yield stability could also be improved simultaneously through incorporation of drought, pest, and disease resistance or tolerance; indeed, this may be a prerequisite to adoption of production-increasing technology. However, it may not completely insulate SAT countries from production variability. Measures designed to stabilize consumption through appropriate storage and international trade policies may be more effective in alleviating the consequences of residual instability in food-grain production.

Acknowledgment

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Physical Environment of Sorghum- and Millet-growing Areas in South Asia

M.V.K. Sivakumar, A.K.S. Huda, and S.M. Virmani*

Abstract

In the semi-arid areas of Asia, rainfed farming of sorghum and millet constitutes the main pattern of land use. About 57% of the world's millet and 38% of the sorghum come from Asia; South Asia contributes 60% of the total Asian production of both crops, with India alone producing 96% of the millet and 96% of the sorghum. However, a major constraint to increasing production is drought, resulting from low and variable rainfall and soils with low water-holding capacity. The wide range of variation in other climatic parameters as well—temperature, radiation, and evapotranspiration—in the sorghum- and millet-growing areas is illustrated and discussed. The broad soil regions in semi-arid Asia are described, and measures suggested for improving and stabilizing yields by matching the crop growth cycle with the growing period. The variability in the phenology, growth, and yield of sorghum is illustrated with examples from a 3-year multilocation sorghum-modeling experiment. It is proposed that data banks be set up to collect—via an interagency network—the information on climate, soils, and crops needed to assess the impact of the physical environment on sorghum and millet production in the semi-arid tropics.

Résumé

Le milieu physique des régions productrices de sorgho et de mil dans le sud de l'Asie : Dans les régions semi-arides d'Asie, la culture pluviale du sorgho et du mil constitue la principale forme d'occupation du sol. Environ 57% et 38% de la production mondiale de mil et de sorgho provient de l'Asie; la majeure partie, 60% de la production asiatique, étant cultivée dans le sud de l'Asie, plus particulièrement en Inde (96% du mil et 98% du sorgho). Cependant, une contrainte majeure à l'augmentation de la production est la sécheresse due à une pluviométrie faible et variable et aux sols ayant une faible capacité de rétention d'eau. Cette communication décrit la grande variation d'autres paramètres climatiques, à savoir, la température, le rayonnement et l'évapotranspiration dans les régions de culture de mil et de sorgho. La description des principales régions pédologiques de l'Asie semi-aride est suivie de recommandations pour l'amélioration et la stabilisation des rendements par le callage de la période végétative des cultures avec la période climatique de croissance. La variabilité de la phénologie, de la croissance et du rendement est illustrée par des exemples pris sur trois ans d'essais multilocaux de modélisation pour le sorgho. Les auteurs proposent l'établissement de banques de données pour collecter, par l'intermédiaire d'un réseau d'agences, de l'information sur le climat, les sols et les cultures, afin de mieux évaluer l'influence du milieu physique sur la production du sorgho et du mil dans les zones tropicales semi-arides.

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Asia, with 58% of the world's population, has only 20% of the world's arable land, *77%* of which is already cultivated (Kanwar 1982). It is imperative that the primary strategy for increasing food production in Asia be to improve crop yields on a unit-area basis. This is only possible through an effective understanding and management of available resources, both physical and biological.

In the semi-arid areas of Asia, rainfed farming of sorghum and millet constitutes the main pattern of land use. About 38% of the sorghum and 57% of the millet produced in the world comes from Asia. Burma, India, Pakistan, and Sri Lanka in South Asia cover 79% of the total area and account for 60% of the total production in Asia for both crops. According to the FAO (1981), India contributed 96% of the sorghum and millet produced in South Asia during 1980 (Table 1), but per hectare yields in India are 25% below the Asian average yields. Careful consideration of the physical environment will show, however, that considerable potential exists for raising the yields of these crops far above current averages. For example, research conducted at 15 locations of the All India Coordinated Research Project on Dryland Agriculture (AICRPDA) suggests that across a wide range of rainfall regimes, cereal crop yields could be improved as much as 400% over the yields obtained by the farmers (Fig. 1). The regression coefficients for the relationship between seasonal rainfall and yields of maize, sorghum, and millet suggest that with every 100 mm increase in seasonal rainfall, yields can be increased by 387 kg/ha at the research station, but in the farmers' fields, the expected increase is only 82 kg/ha. This difference could be due to the composite effect of biological and technological innovations adopted at the research stations.

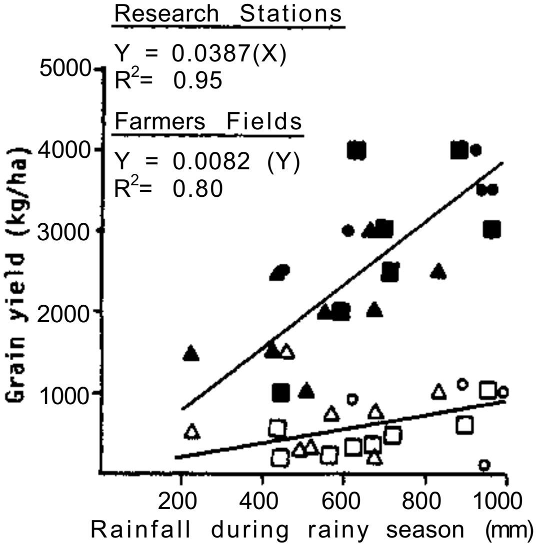


Figure 1. Relationship between rainfall during the rainy season and yield of maize (•), sorghum (■) and millet(▲) grown at research stations (filled-in symbols) and farmers' fields (open symbols) at 15 dryland locations in India.

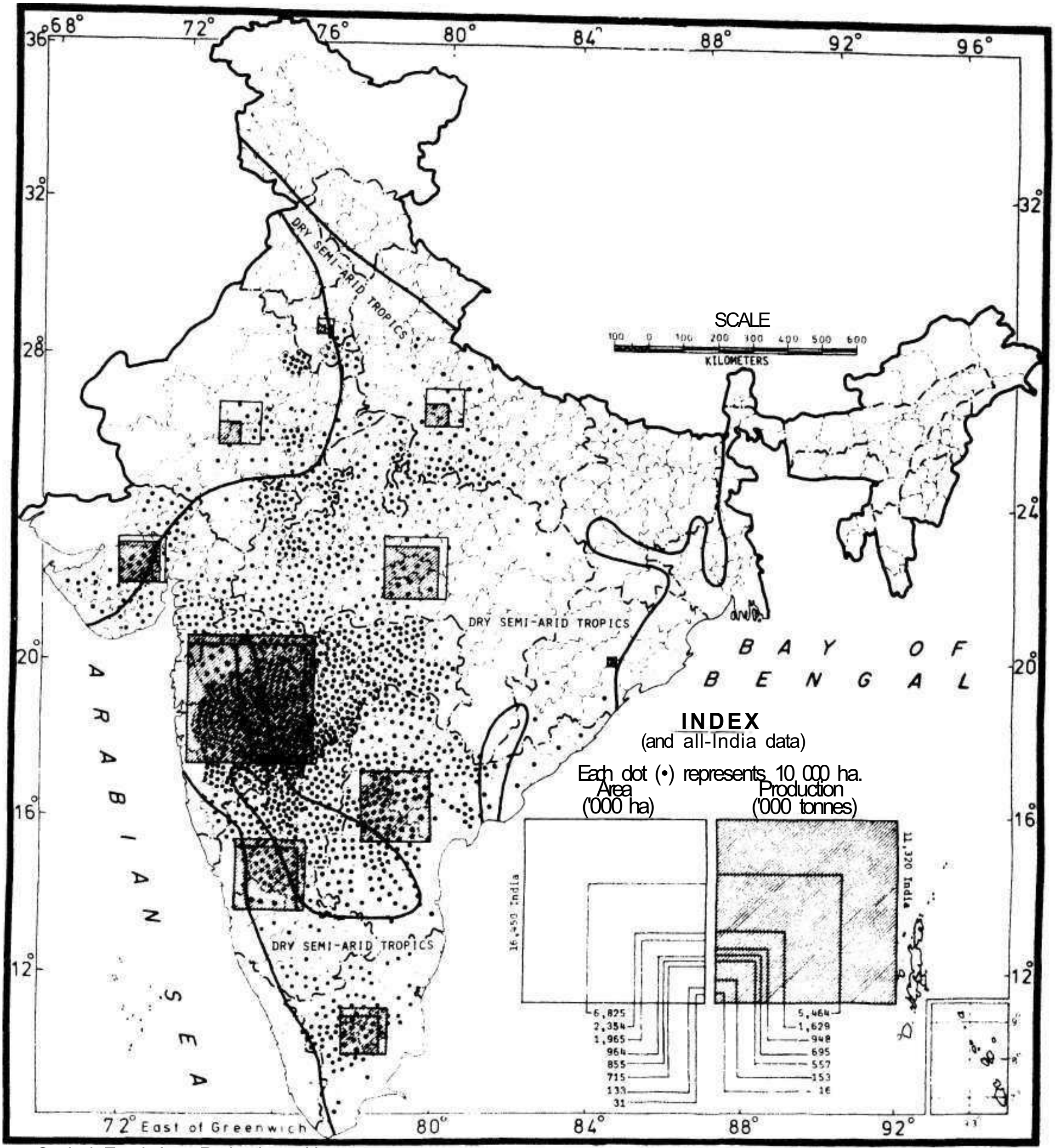
Sorghum- and Millet-growing Regions in South Asia

As shown in Table 1, India contributes about 96% of the sorghum and millet produced in South Asia. Based on data available by district on area and production for 1979/80, maps showing distribution, area, and production of sorghum and millet in India (Figs. 2 and 3) have been prepared (Bose 1981).

Table 1. Sorghum and millet production statistics in South Asia.

	Sorghum			Millet		
Country	Total area (000 ha)	Total production (000 tonnes)	Average yield (kg/ha)	Total area (000 ha)	Total production (000 tonnes)	Average yield (kg/ha)
India	17000	12800	758	17500	9500	543
Burma				180	60	333
Pakistan	480	583	280	641	330	515
Sri Lanka	2	3	1190	35	20	571
Asia	22085	22201	1005	23176	16506	712

Source: FAO (1981).

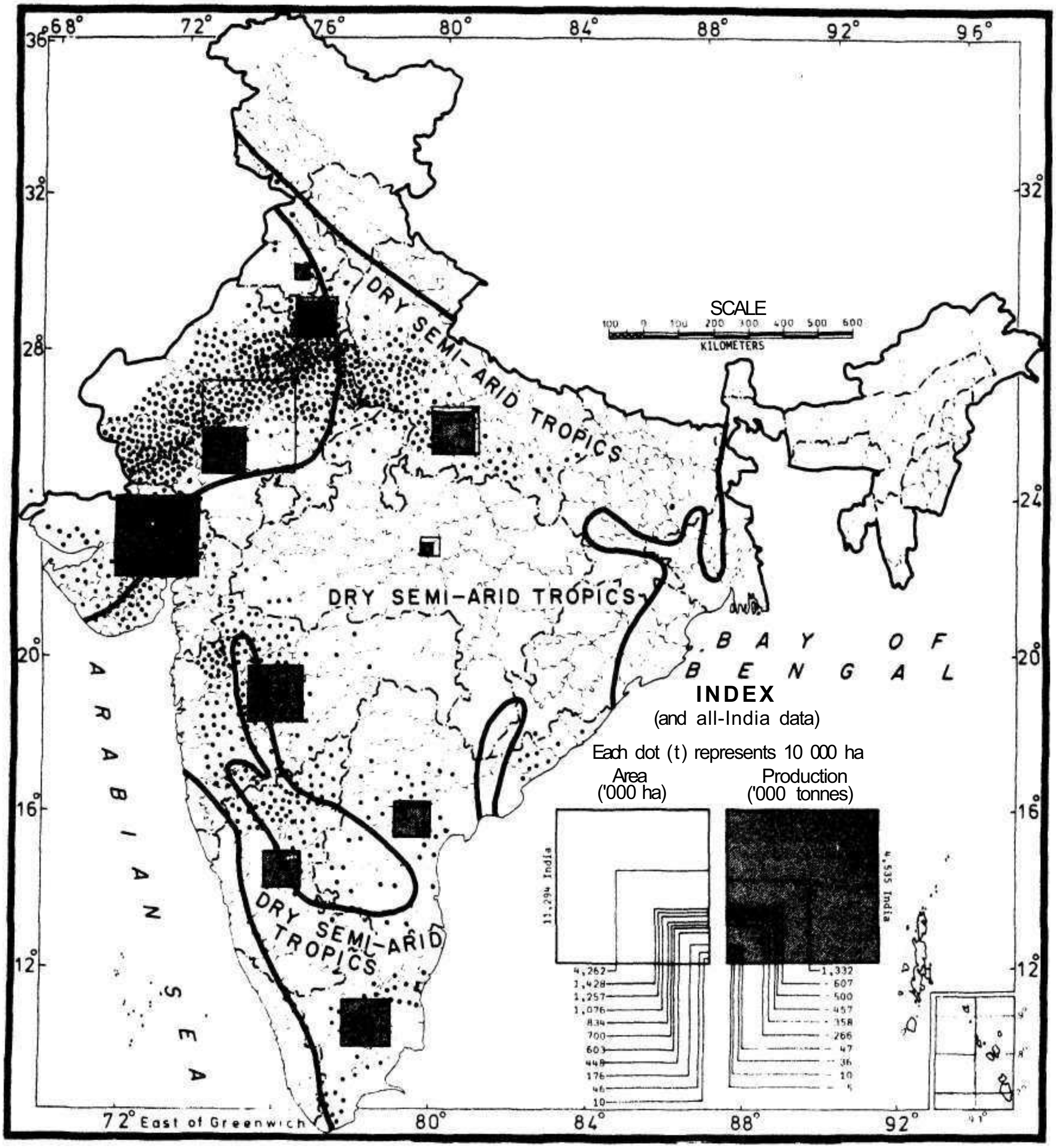


Conical Equal Area Projection with two Standard Parallels

Sources: Agricultural situation in India (June 1981).
ICRISAT Agroclimatology Subprogram Progress report 5 (1980-81).

Figure 2. Distribution, area, and production of sorghum in India (1979/80).

Maharashtra, Karnataka, and Andhra Pradesh contribute 77% of all the sorghum produced in India; Madhya Pradesh, Tamil Nadu, Gujarat, Uttar Pradesh, and Rajasthan together contribute 22%. In all these states, except Rajasthan and Uttar Pradesh, sorghum is grown during both the rainy and postrainy seasons. About 66% of the total sorghum produced in the country is harvested during the rainy season and the rest during the postrainy season; hence it is important to examine the physical environment of sorghum in India in this context. Other major sorghum-producing countries in South



Conical Equal Area Projection with two Standard Parallels

Sources: Agricultural situation in India (June 1981).
ICRISAT Agroclimatology Subprogram progress report 5 (1960-81).

Figure 3. Distribution, area, and production of pearl millet in India (1979/80).

Asia are Pakistan and Sri Lanka. Sorghum production data are not available by region for these countries.

As with sorghum, about 71% of the total millet crop produced in India is contributed by only four states—Gujarat, Rajasthan, Maharashtra, and Uttar Pradesh. Haryana, Andhra Pradesh, Tamil Nadu, Karnataka, Madhya Pradesh, and Punjab are the other prominent states, producing 28% of the total. Unlike sorghum, however, all the millet crop in

India is produced during the rainy season. Pakistan, Burma, and Sri Lanka together produce 4% of the millet crop in South Asia.

Physical Environment of Sorghum- and Millet-growing Regions in South Asia

The physical environment of South Asia is primarily discussed in terms of atmospheric circulation, climatic elements, and soils, keeping in viewthe pertinent features of sorghum and millet crops that are so important to the region.

General Atmospheric Circulation

Rainfall is the most significant climatic element affecting sorghum and millet production in South Asia. Rainfall, temperature, and wind patterns in the region are determined largely by the atmospheric circulation.

The size of the land mass in South Asia—which includes the very high mountains in the north, the plains below them, the peninsula in the south, hill ranges in the northwest and northeast, and a lower range along the west coast—is an important factor in determining the climate of the region. The Himalayas in the north, which form an unbroken range of lofty mountains, block the cold winds from the north and the monsoon winds from the south. By checking the winds from the north, they help the monsoons reach more northerly latitudes than would be possible otherwise. Rao (1981) provided a good description of the atmospheric circulation over South Asia.

In the summer months, March to May, intense heating of the land mass in South Asia leads to increased temperatures and low atmospheric pressure. The heating of land is especially marked over northwestern India and adjoining rainless areas of West Pakistan and a low-pressure zone is well established in the area. The early trade winds change direction on crossing the equator and become southwesterlies and westerlies. After entering the Arabian Sea and the Bay of Bengal, they appear in South Asia as southwest monsoons. On the west coast of Sri Lanka the Arabian Sea branch of the monsoon brings heavy rainfall; it then hits the Western Ghats of India and advances eastward in southern and central India, resulting in moderate rainfall. The Bay of Bengal branch of the monsoon causes heavy precipitation in coastal areas of Burma and parts of northeastern India. These two branches of the monsoon meet north of the low-pressure area and then advance westwards, bringing considerable rainfall to the submontane tract of the Himalayas. Depending on the position and frequency of eastern depressions in northern and central India, the occurrence of rainfall in central and northwestern areas of India varies, which could cause droughts of varying durations and intensities. Rajasthan, southern Punjab, and the Sind plains of Pakistan remain out of the path of the monsoon and get little rain.

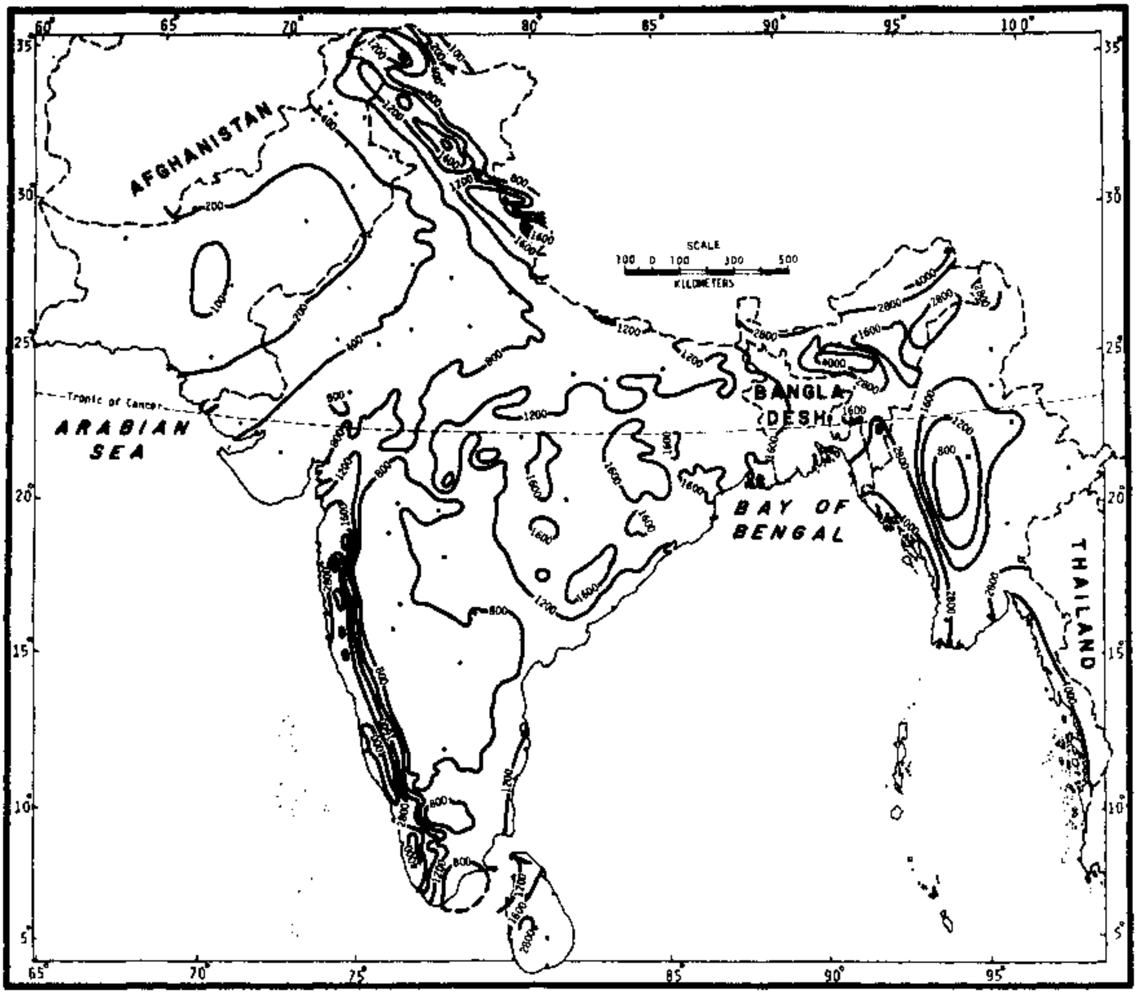
As the southwest monsoon withdraws in September, the northeasterly air currents dominate the area and bring the northeast monsoon rains to Sri Lanka and southeastern and southern India from November to January; they also bring some rain to northern India. Formation of cyclones in the Bay of Bengal and the Arabian Sea also could bring heavy rains inland during October to December. Cyclones over the Atlantic or over regions of the Mediterranean area also bring rain in northwestern Pakistan and India.

Because of these features in the general atmospheric circulation, northeastern India, the west coasts of India and Sri Lanka, coastal Burma, and submontane areas of the Himalayas receive considerable rainfall. The general decrease in rainfall is from east to west and north to south.

Rainfall

Since both sorghum and millet are rainfed, the optimum time of sowing, establishment, and survival of these crops in South Asia depend to a large extent on the fluctuations in the onset of the southwest monsoon, the duration of its influence over South Asia, and its subsequent withdrawal from the area. Isochrones of the onset of the monsoon have been published by the India Meteorological Department (IMD 1978). The normal date of onset of the southwest monsoon is 25 May in Sri Lanka and Burma, 5 June over the southern peninsula, and 1 July in the major millet-growing areas in northwestern India. The monsoon reaches Pakistan around 15 July. The withdrawal also commences in Pakistan by 1 September and progresses steadily into north and central India; by 15 October it withdraws from the upper half of the southern peninsula and Burma.

Mean annual rainfall over South Asia is shown in Figure 4. The orography in the region causes signif-



Conical Orthomorphic Projection. Origin $27^1/_2$° N.
Standard Parallels 16° & 38°

SOURCE: World Survey of Climatology Volume 9, 1981.

Figure 4. Mean annual rainfall (mm) over South Asia—Pakistan, India, Burma, and Sri Lanka.

icant differences in the rainfall received over the whole area. The highest annual rainfall, exceeding 1500 mm, is recorded on the southern slopes of the Khasi-Jaintia Hills in West Bengal, on the slopes of the Western Ghats, in the sub-Himalayan region, over the hill ranges of Tripura, Manipur, Nagaland, and the Mizo Hills, on the western coast of Burma, and on the Colombo-Jaffna belt on the west coast of Sri Lanka. From the east coast rainfall decreases inland up to the eastern side of the Western Ghats in the peninsula, south of 17°N. To the east of the Western Ghats, between 14 and 18°N, is a region of low rainfall (less than 700 mm) covering parts of Andhra Pradesh, Karnataka, and Maharashtra, where a significant quantity of sorghum and millet are produced. North of 24°N, the rainfall decreases from east to west, from 1500 mm in Uttar Pradesh to less than 100 mm in the Thar desert of Pakistan.

When the rainfall isohyets shown in Figure 4 are superimposed on the distribution, area, and production maps for sorghum and millet (Figs. 2 and 3), reasons for the preferential cultivation of these two crops in certain states become obvious. For example, almost all the millet crop in India is grown in areas where the mean annual rainfall is below 800 mm, most of it under 600 mm. Sorghum-growing areas in India, however, are extended up to the 1200 mm mean annual rainfall isohyet, but the majority of the sorghum-growing regions are located in the annual rainfall isohyet range of 600 to 1000 mm.

It is of interest to note that the rainy-season sorghum-growing areas are located between the 800 and 1000 mm rainfall isohyets. The postrainy-season sorghum areas are located in the belt with low and undependable rainfall areas, with less than 800 mm rain. Based on a moisture index defined as

$$\frac{P - PET \times 100}{PET}$$

where P is the precipitation and PET the potential evapotranspiration, Krishnan (1972) showed that the moisture deficiency during the rainy season is accentuated from east to west. During the post-rainy season, moisture deficiency extends over the entire country, except for a small belt in eastern Tamil Nadu. The deficiency increases from south to north in peninsular India and from east to west in north India.

Over 75% of the mean annual rainfall is received during the southwest monsoon period from June to September, except in the eastern coastal belt of the southern peninsula and most of Sri Lanka in the south, and Kashmir in the north. From October to December, Sri Lanka, the southern peninsula, the east coast, Assam, and parts of Kashmir receive good rain from the northeast monsoon.

Rainfall Variability

Russell (1959) pointed out that even in regions with annual water surplus, water deficiencies could occur in specific localities because of deviation of annual rainfall from average values. To illustrate such variability in rainfall, we chose a sample of 169 locations in the rainfed areas of India from available records of the India Meteorological Department (IMD 1967). The mean annual rainfall at these locations varies from 550 to 1700 mm. Mean monthly rainfall and annual rainfall averaged over all the locations showed a coefficient of variation ranging from 39 to 225% for monthly rainfall and 32% for annual rainfall (Table 2). Minimum variability in the monthly rainfall was recorded during June to October, influenced by the predominant southwest monsoon over India.

Monthly precipitation data for 177 locations in Burma, 85 locations in Sri Lanka, and 123 locations in Pakistan have been published by Wernstedt (1972). Coefficients of variation in the monthly and annual rainfall for Burma, Sri Lanka, and Pakistan, respectively, are shown in Tables 3, 4, and 5. All areas in Burma receive high rainfall—except for a small central zone—and the mean annual rainfall is 2185 mm (Table 3). However, the coefficient of variation in annual rainfall is 66%, because of the wide differences in rainfall received over different regions of Burma, and the wide range between the maximum and minimum rainfall received during the year.

Table 2. Monthly and annual rainfall at 169 locations in rainfed areas of India.

Month	Mean rainfall (mm)	Coefficient of variation (%)	Maximum (mm)	Minimum (mm)	Range (mm)
January	17	115	92	0	92
February	14	92	72	0.2	72
March	15	91	104	0.1	104
April	22	119	166	0	166
May	40	103	249	0.4	249
June	122	53	238	6	332
July	256	47	519	7	512
August	240	47	508	12	496
September	170	39	341	16	325
October	93	74	307	2	305
November	40	181	458	1	457
December	15	225	239	0	239
Annual	1042	32	1689	305	1384

Table 3. Monthly and annual rainfall at 177 locations in rainfed areas of Burma.

Month	Mean rainfall (mm)	Coefficient of variation (%)	Maximum (mm)	Minimum (mm)	Range (mm)
January	2.9	136.0	22.9	0	22.9
February	7.2	174.2	105.4	0	105.4
March	12.4	144.9	129.5	0.2	129.3
April	39.5	74.3	179.3	0	179.3
May	229.7	54.7	645.4	48.8	596.6
June	419.9	76.7	1237.2	87.1	1150.1
July	467.6	87.8	1594.1	42.4	1551.7
August	449.4	78.1	1274.8	59.4	1215.4
September	316.0	60.1	968.5	96.8	871.7
October	170.4	35.4	546.9	47.0	499.9
November	57.7	44.5	171.7	18.8	152.9
December	12.7	82.7	110.5	0	110.5
Annual	2185.4	65.8	5741.2	527.6	5213.6

Table 4. Monthly and annual rainfall at 85 locations in rainfed areas of Sri Lanka.

Month	Mean rainfall (mm)	Coefficient of variation (%)	Maximum (mm)	Minimum (mm)	Range (mm)
January	166.4	56.5	497.1	59.2	437.9
February	111.2	51.0	238.0	25.1	212.8
March	142.3	52.6	312.4	24.6	287.8
April	219.6	42.8	413.3	54.1	359.2
May	242.8	73.2	718.0	25.6	692.4
June	185.5	105.3	910.6	3.6	907.0
July	144.7	94.9	712.7	7.1	705.6
August	150.8	84.4	655.0	7.4	648.5
September	151.5	72.8	535.7	15.2	520.4
October	308.9	41.7	685.0	87.9	597.1
November	322.7	22.2	468.4	185.4	283.0
December	254.3	37.6	557.3	109.7	447.5
Annual	2400.7	43.3	5457.4	967.5	4490.0

Rainfall statistics for Sri Lanka also present a similar picture (Table 4), with a mean annual rainfall of 2401 mm averaged over the 85 locations and a wide range in the monthly and annual rainfall; however, the coefficient of variation (43%) is lower. The predominant influence is that of the northeast monsoon; mean rainfall from October to December exceeds the mean from June to September, and the coefficient of variation in monthly rainfall during the northeast monsoon period is also lower than during the southwest monsoon.

Except for a small region north of 32°N, most of Pakistan is dry, and the rainfall is low. The average annual rainfall over 123 locations is 331 mm (Table 5), with a coefficient of variation of 78%. Maximum annual rainfall recorded over the entire country is 1640 mm; the minimum, 39 mm; and the range, 1601 mm.

Solar Radiation

Direct measurements of global solar radiation have been made in India for 16 stations for periods ranging from 8 to 21 years (Mani and Rangarajan 1982). Daily sums of global and diffuse solar radiation for 145 stations in India have been computed by Anna Mani and Rangarajan (1982) using regression relationships between solar radiation and sunshine.

Table 5. Monthly and annual rainfall at 123 locations in rainfed areas of Pakistan.

Month	Mean rainfall (mm)	Coefficient of variation (%)	Maximum (mm)	Minimum (mm)	Range (mm)
January	25.2	92.8	120.4	0.8	119.6
February	25.8	85.0	111.8	2.5	109.2
March	28.2	107.3	154.9	0.5	154.4
April	19.3	119.1	111.0	0.2	110.7
May	12.9	98.9	64.3	0.2	64.0
June	19.8	92.0	106.7	0	106.7
July	76.5	77.7	362.2	1.3	360.9
August	72.9	93.1	358.1	0	358.1
September	27.7	96.9	134.4	0	134.4
October	5.9	138.3	53.3	0	53.3
November	4.2	104.3	22.3	0.4	22.3
December	12.5	87.8	53.8	0.5	53.3
Annual	330.7	77.5	1640.1	39.4	1600.7

The mean daily global solar radiation on an annual basis over India ranges from 4.6 KWh / m^2 per day in the northeast to 6.4 KWh/m^2 per day in the northwest. During the rainy season, solar radiation per day in northern India decreases from 6.0 to 8.0 KWh/m^2 in June to 5.2 to 6.8 KWh/m^2 in September. In peninsular India, however, the solar radiation shows a slight increase, from 4.4 to 5.8 KWh/m^2 in June to 5.0 to 6.0 KWh/m^2 per day in September.

During the postrainy season, solar radiation per day in sorghum-growing areas ranges from 5.0 to 6.0 KWh/m^2 in October to 5.8 to 6.6 KWh/m^2 in February. The lowest values are recorded in December. In the semi-arid tropics of India, therefore, solar radiation should be quite adequate for sorghum and millet production.

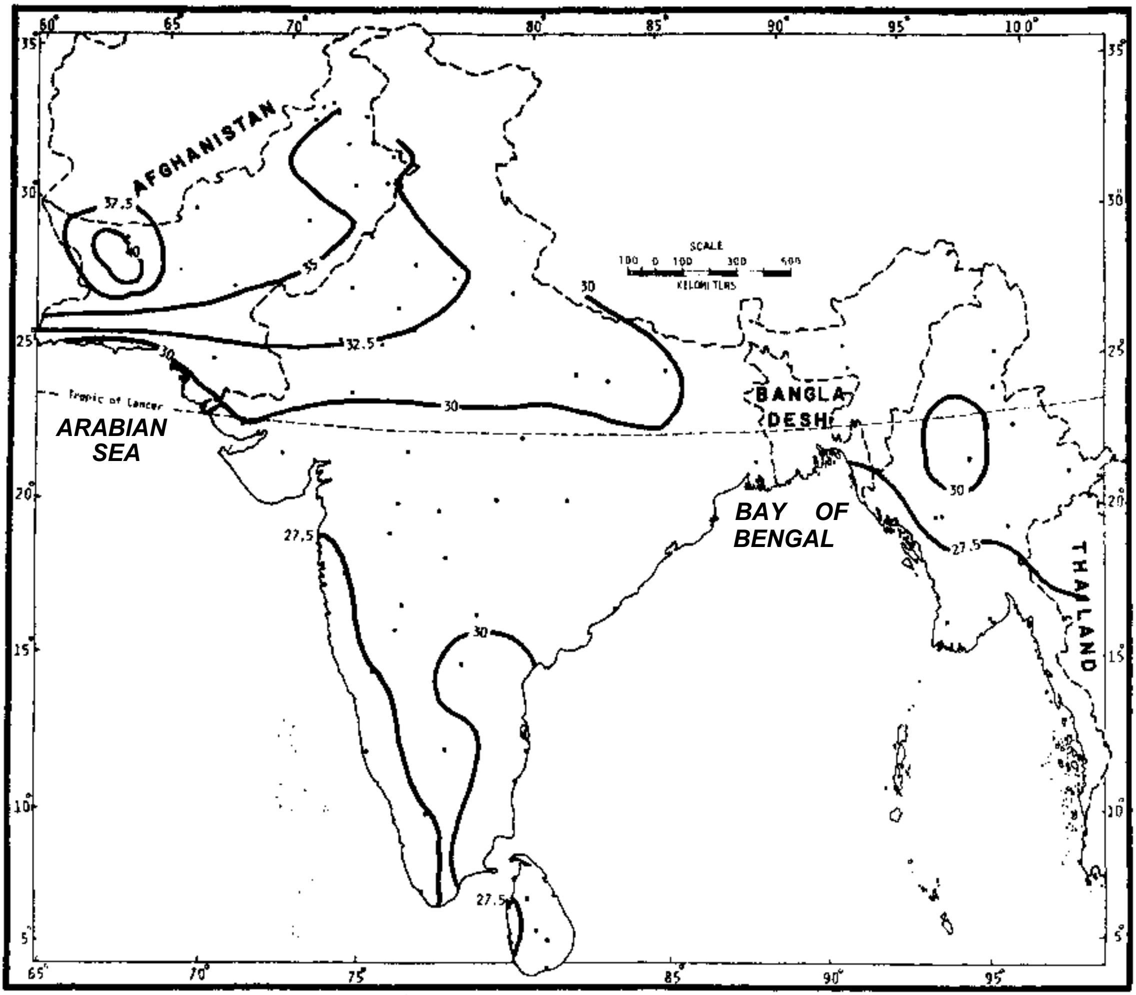
Temperature

In general, temperature determines the rate of crop growth and development. The effects of temperature stress on each critical stage of development of sorghum are discussed by Peacock and Heinrich (these Proceedings) and the response of millet to temperature is described by Ong and Monteith (these Proceedings). We briefly describe here the range of temperatures under which sorghum and millet are grown in South Asia.

Mean daily temperatures (average of the mean daily maximum and the mean daily minimum) over South Asia in July are shown in Figure 5. During July, when both sorghum and millet are usually in the rapid vegetative growth stage over most of India (except in the northwestern regions), the mean daily temperatures range between 28 and 32°C. In Rajasthan and the adjoining areas in Pakistan, the mean daily temperatures exceed 32.5°C; in Baluchistan, they exceed 40°C. In central Burma—which receives the lowest seasonal rainfall in the country—mean daily temperatures exceed 30°C. In southern Burma, July mean temperatures are below 27°C. By October, throughout South Asia the mean daily temperatures generally range from 27 to 29°C. Almost all of the postrainy-season *(rabi)* sorghum in India is grown south of 25°N latitude, where the mean daily temperatures exceed 17.5°C. Figure 6, showing mean daily temperatures for January, indicates the temperatures prevailing in rabi sorghum areas during the postrainy season.

In the major postrainy-season sorghum belt of Maharashtra, Karnataka, and Andhra Pradesh, mean daily temperatures in January exceed 22.5°C.

Average or mean temperatures, however, could be misleading; it is more important to examine the maximum and minimum temperatures. Mean daily maximum temperatures over South Asia in July (Fig. 7) show some interesting features. In the major sorghum-growing regions of India (Fig. 7) the mean maximum temperatures are less than 35°C. However in western Rajasthan, an important millet-growing region, mean maximum temperatures range from 35 to 40°C, and in Pakistan maximum temperatures reach up to 45°C. In the drier regions

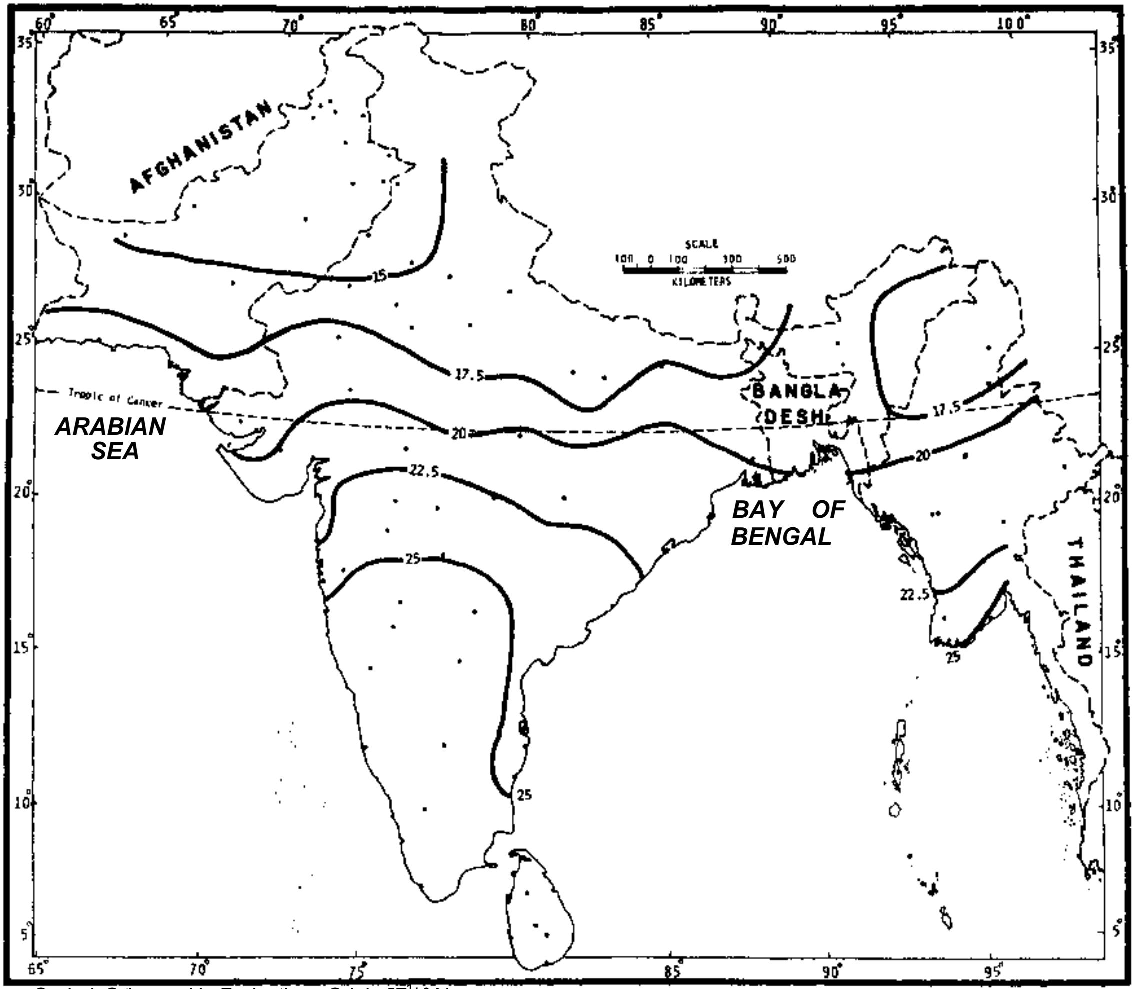


Conical Orthomorphic Projection. Origin $27^{1}/_{2}$° N.
Standard Parallels 16° & 38°

Figure 5. Mean daily temperature (°C) in July over South Asia—Pakistan, India, Burma, and Sri Lanka.

of central Burma, maximum temperatures in July exceed 32.5°C. By October, however, the temperatures in the northwest are lower. The highest temperatures in South Asia are over Baluchistan. Mean maximum air temperatures in January (Fig. 8) exceed 25°C in the postrainy-season sorghum-growing areas, and in the major states of Maharashtra, Karnataka, and Andhra Pradesh, maximum air temperatures are over 30°C.

Mean daily minimum temperatures in July in the sorghum-growing regions of India vary from 25 to 27°C, while in western Rajasthan and Pakistan, minimum temperatures exceed 28°C (Fig. 9). By October in this region, temperatures drop below 20°C, while in central and peninsular India minimum temperatures range from 23 to 25°C. In the postrainy sorghum-growing season, the minimum temperatures are lower and, as shown in Figure 10, in January the mean daily minimum temperatures north of 25°N latitude are lower than 10°C. In central and peninsular India the temperatures range from 12 to 22°C. Minimum temperatures measured at the screen height are often considered to be higher than those actually experienced in the crop canopy. Data published by IMD (1978) show that north of 20°N latitude, the gross minimum temperatures are lower than 7.5°C. Such low air temperatures hamper the growth of sorghum, which is



Conical Orthomorphic Projection. Origin 27½° N.
Standard Parallels 16° & 38°

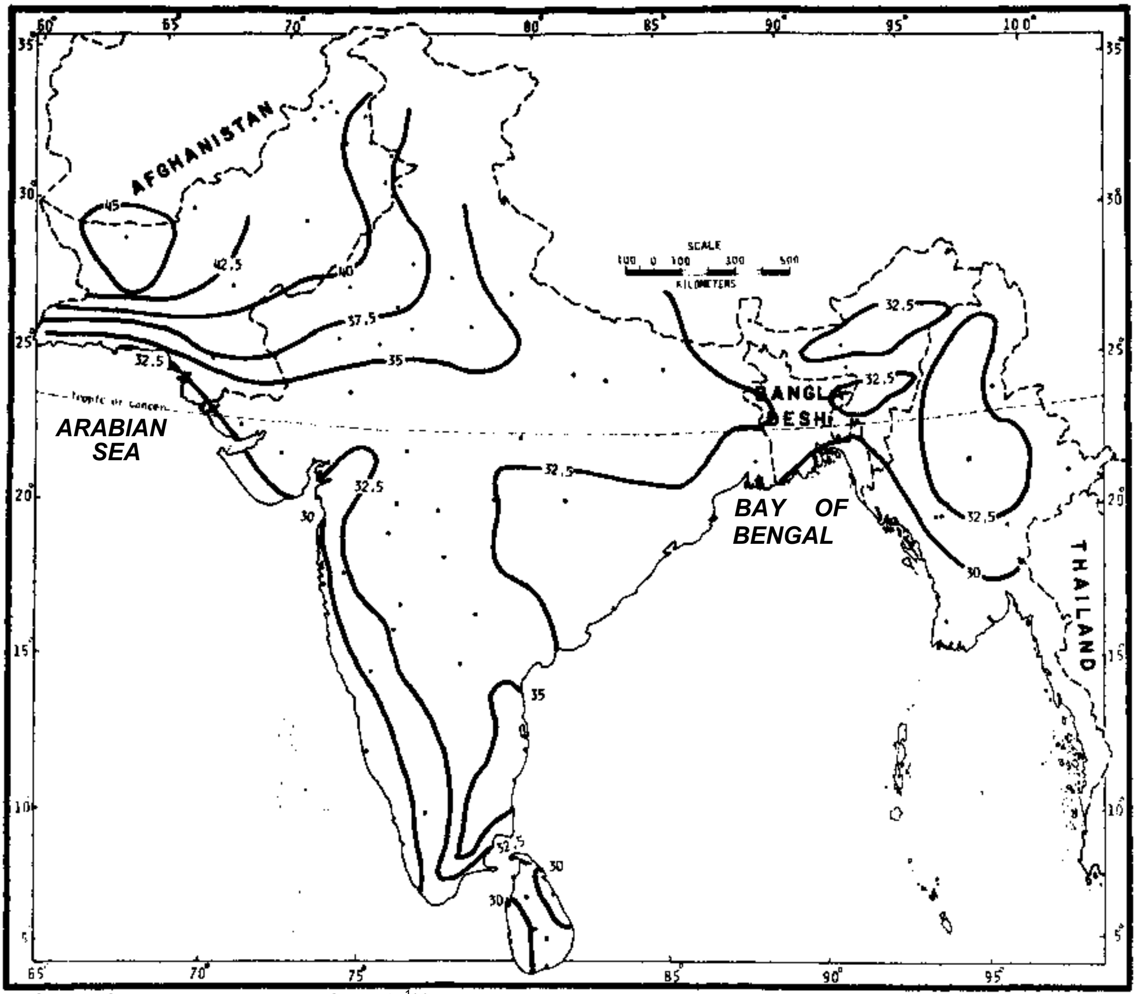
Figure 6. Mean daily temperature (°C) in January over South Asia—Pakistan, India, Burma, and Sri Lanka.

probably why postrainy-season sorghum is primarily limited to peninsular India.

The temperature data discussed above suggest that in more marginal areas suitable for growing millet but not sorghum, the air temperatures are higher by 4 or 5°C. In terms of the relevance of the observed temperatures to the phenology of sorghum grown in the rainy and postrainy seasons, the diurnal range in temperature is small in the rainy season, and the uniformly high temperatures should promote good vegetative growth and grain filling. In the postrainy season, however, the diurnal range in temperature, especially around the time when the sorghum crop reaches flowering, is rather large, and the minimum temperatures are consistently low. The implications of these temperatures are discussed in detail by Peacock and Heinrich (these Proceedings).

Potential Evapotranspiration

Although the rainfall at two locations is similar, if the degree of atmospheric demand for water between the locations is different, it can make a significant difference in the water requirement of the crop. Rao et al. (1971), using a modified Penman's formula, have calculated the potential evapotranspiration (PET) for 300 stations in India, Burma, Pakistan,



Conical Orthomorphic Projection. Origin 27½° N.
Standard Parallels 16° & 38°

Figure 7. Mean daily maximum temperatures (°C) in July over South Asia—Pakistan. India, Burma, and Sri Lanka.

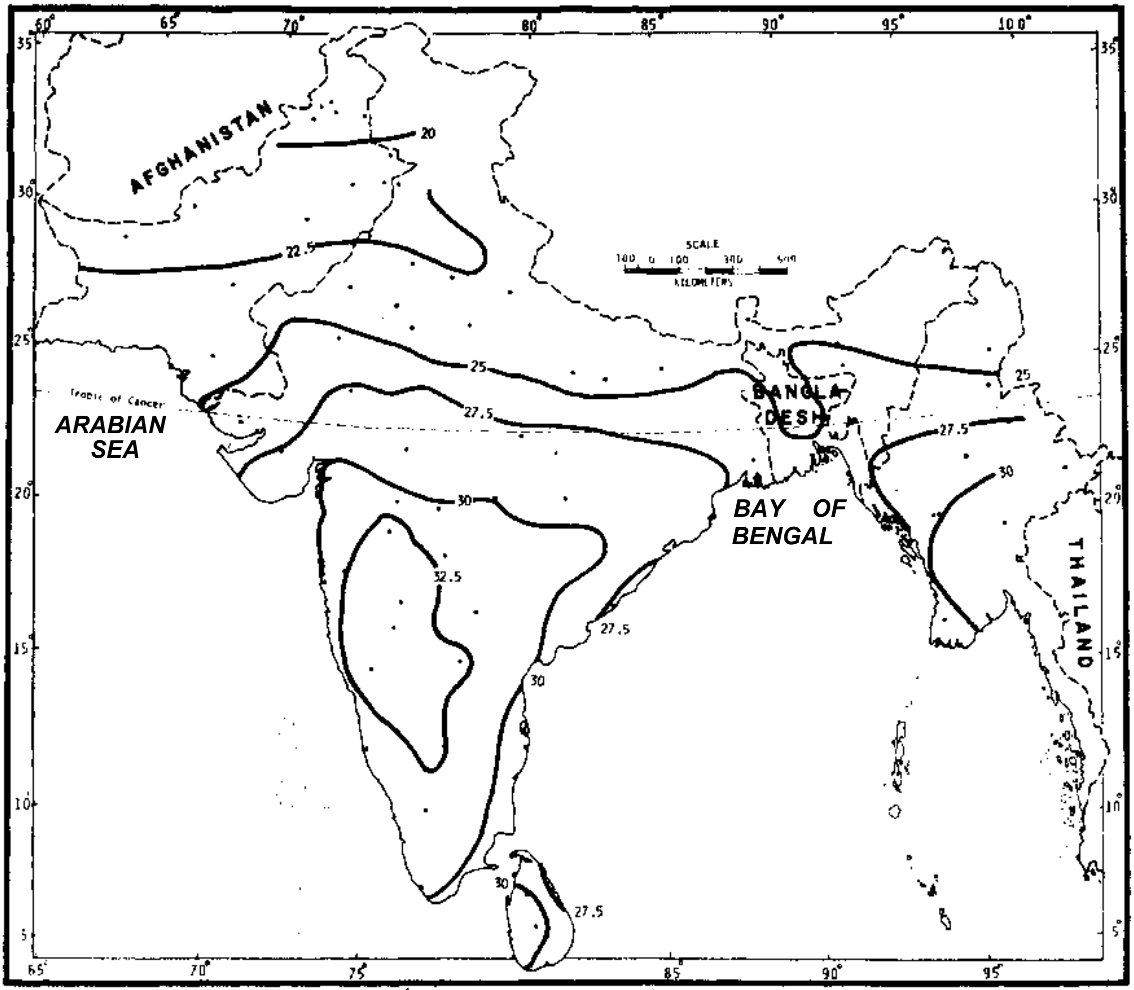
and Sri Lanka from climatological data of temperature, vapor pressure, cloudiness, etc. Mean potential evapotranspiration over South Asia from June to September is shown in Figure 11. In southwestern peninsular India and in Burma, because of the active monsoon and cloudy skies, the PET is low (about 400-500 mm) and in northwestern India and Pakistan, PET exceeds 600 mm. On an annual basis, PET over the sorghum- and millet-growing regions varies from 1400 to 2000 mm, with the higher PET values predominating in the major millet-growing regions of Gujarat and Rajasthan.

During the postrainy season, PET ranges from 80 to 140mm/month in the sorghum-growing areas of Andhra Pradesh, Karnataka, Maharashtra, Tamil Nadu, and Gujarat.

Mean monthly and annual PET, averaged over 169 locations in India (Table 6), show that the variability in PET is much lower than in rainfall and that the atmospheric demand is high.

Moisture Availability

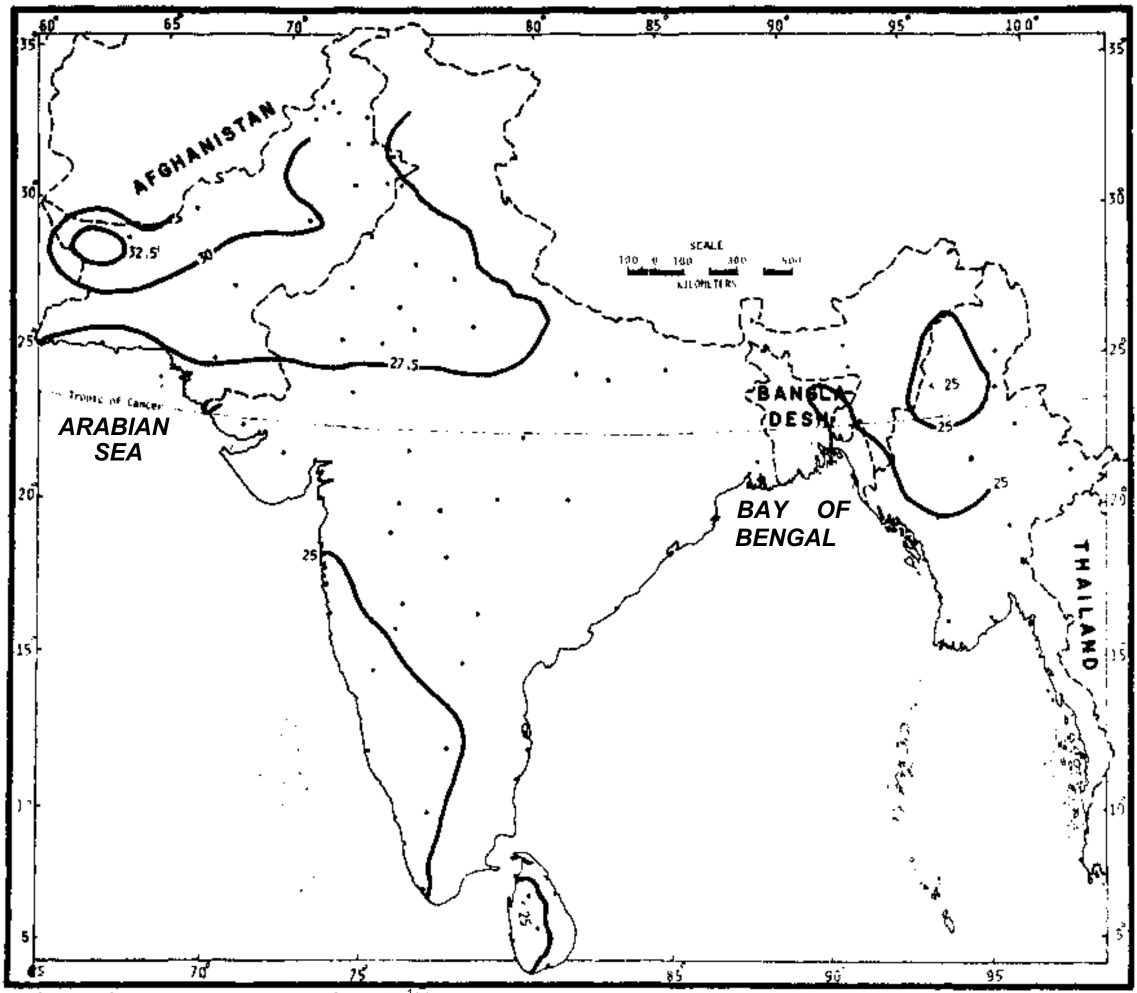
Average rainfall figures do not yield information on the dependability of precipitation. Hargreaves (1975) has defined dependable precipitation (DP) as the amount of rainfall that could be received at



Conical Orthomorphic Projection. Origin $27^{1}/_{2}$° N.
Standard Parallels 16° & 38°

Figure 8. Mean daily maximum temperature (°C) in January over South Asia—Pakistan, India, Burma, and Sri Lanka.

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 rainy season at selected locations in South Asia are shown in Table 7. In Sri Lanka, since the predominant rains occur during the northeast monsoon season, MAI at Hambantota and Mannar from June to October is very low, indicating low potential for sorghum and millet production during this period. In peninsular India, the MAI for Hyderabad, Bangalore, and Pune is indicative of adequate moisture availability for sorghum and millet crop production. In central and northern India, the MAI values show a more favorable moisture environment. In northwestern India, data for Jodhpur and Bikaner indicate that the moisture availability is very low and that both sorghum and millet are likely to suffer from periods of moisture stress during the growing season. In Pakistan, the region around Lahore shows promise for growing millet, and that around Murree shows promise for growing both sorghum and millet. In fact, the high MAI values in July and August suggest the need to provide drainage. Peshawar, however, is very dry, and the rest of Pakistan south of Multan has little or no moisture availability for the growth of sorghum and millet.

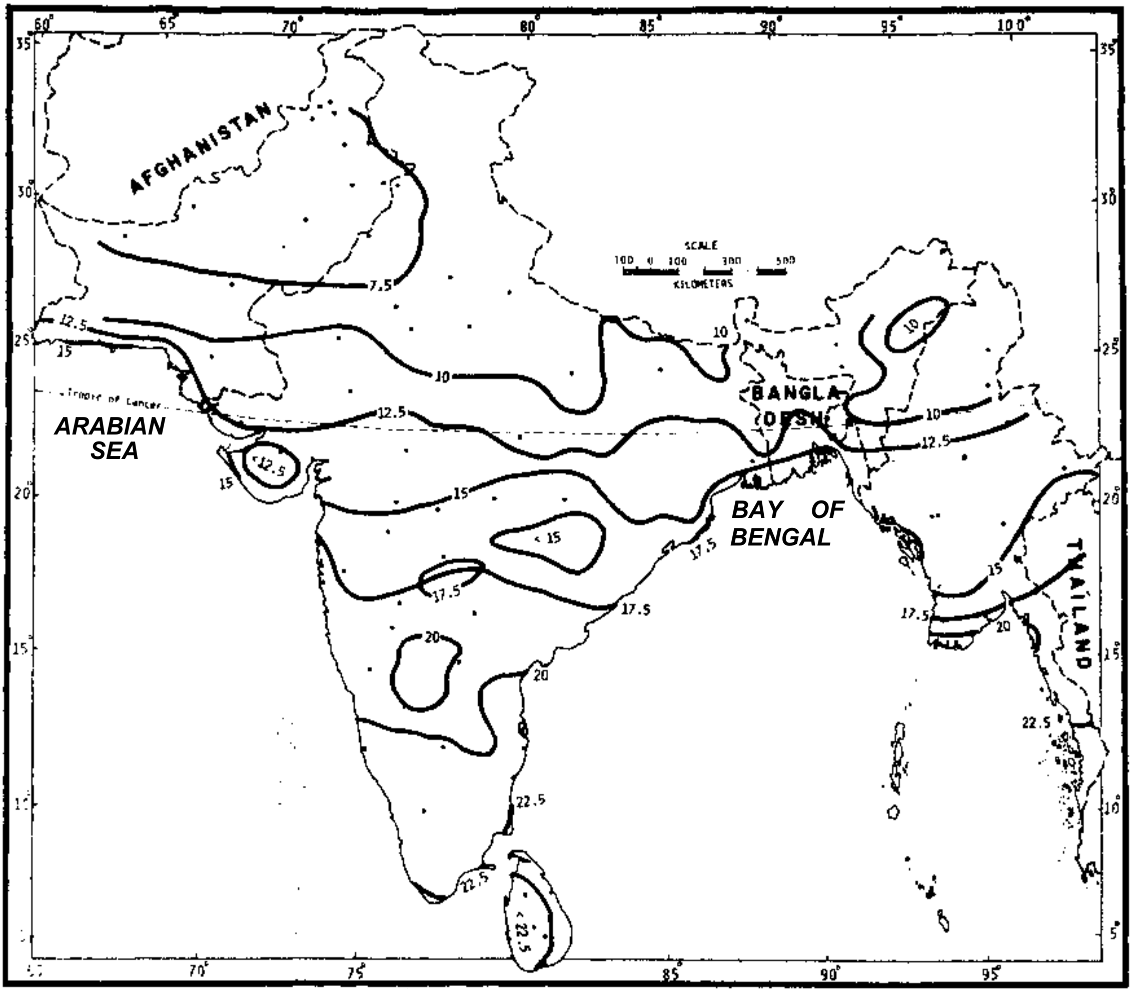


Conical Orthomorphic Projection. Origin $27^1/_2$° N.
Standard Parallels 16° & 38°

Figure 9. Mean daily minimum temperature (°C) in July over South Asia—Pakistan, India, Burma, and Sri Lanka.

Length of the Moisture Availability Period

For rainfed crops like sorghum and millet to be successful, their growth cycles should be of such a length that they are comfortably contained within the moisture availability period. Failure to match these characteristics does not completely exclude the cultivation of the crop, but can result in reduction of yield and quality. Moisture availability period or length of the growing period has been computed by the Agroecological Zones Project of the FAO (see Frere, these Proceedings) for India. 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. Length of the growing period computed for India is shown in Figure 12. For most of the millet-growing areas in India, the length of the growing period extends from 60 to 90 days. It is notable that sorghum-growing areas show a more favorable length of growing period, 90 to 150 days.



Conical Orthomorphic Projection. Origin $27^{1}/_{2}$° N.
Standard Parallels 16° & 38°

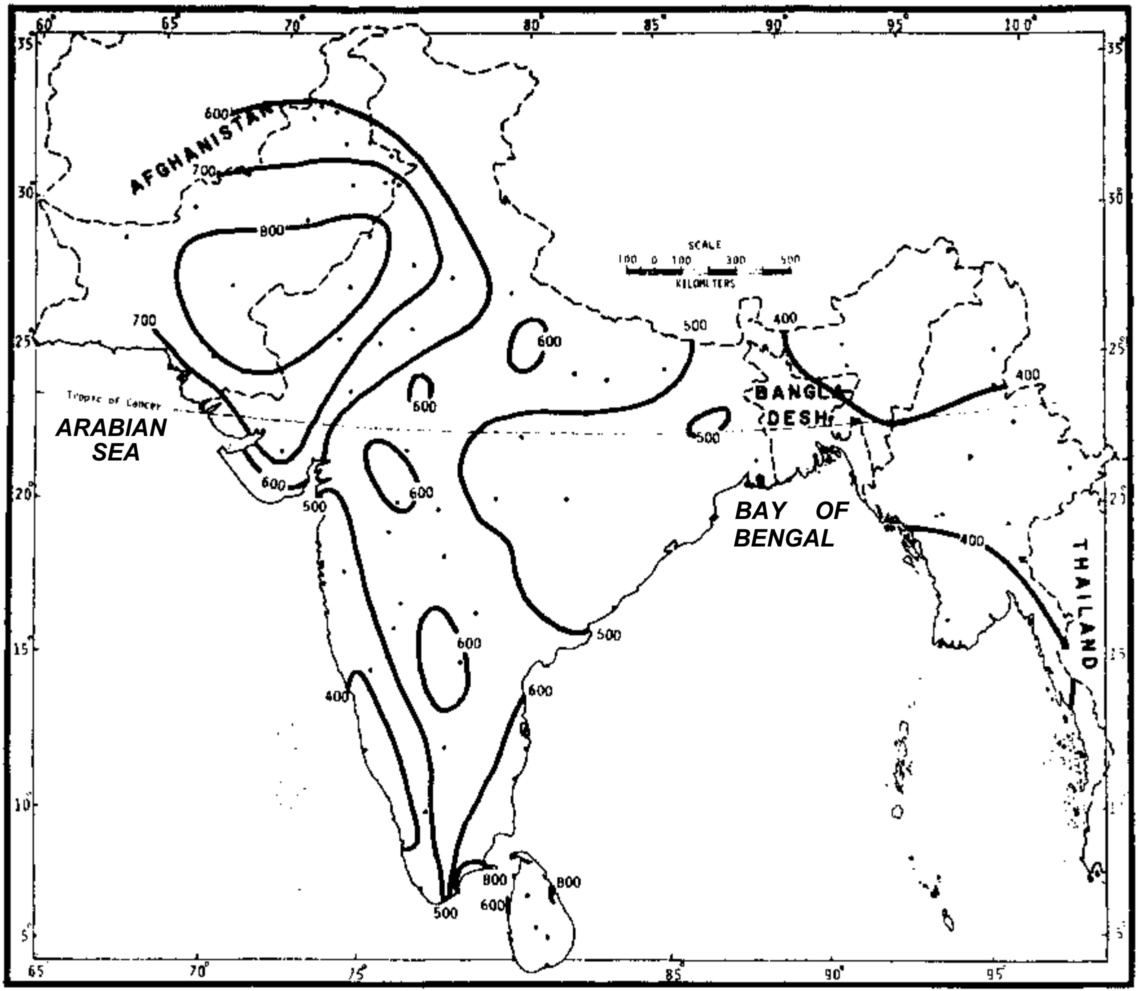
Figure 10. Mean daily minimum temperature (°C) in January over South Asia—Pakistan, India, Burma, and Sri Lanka.

Soils of South Asia

The growing period described above for South Asia takes 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. In the soil map of South Asia published by UNESCO (1977), nine major soil zones were identified in the region covering Sri Lanka, India, Pakistan, and Burma (Fig. 13).

Lithosol-Regosol-Yermosol association in Pakistan. These soils cover the arid parts of Pakistan. The climate is extremely arid, with the mean annual rainfall less than 300 mm, and in most places does not exceed 150 mm. The main soils are Lithosols on hill slopes, stony Regosols on colluvial slopes, and Yermosols on piedmont plains. Lithosols are poor, shallow soils with little potential for improved agricultural production. Regosols are generally poor soils because of low moisture- and nutrient-holding capacity. Yermosols without irrigation are suitable only for grazing; where they are irrigated, drainage and salinity are great problems.

Yermosol-Xerosol association of Pakistan and northwestern India. This soil region covers



Conical Orthomorphic Projection. Origin $27^1/_2$° N.
Standard Parallels 16° & 38°

Figure 11. Mean potential evapotranspiration (mm) during June to September over South Asia.

nearly all of the Indus plains and the semi-arid part of northwestern India. In the Indus plains, because of the strong influence of the regular floods on the soil water regimes, the soils are well developed. In the southeast, Xerosols are formed in alluvium. Low and sporadic rainfall on the Xerosols makes crop production risky. Xerosols are not fertile and need nitrogen and phosphorus application for sustained crop production.

Arenosols and Regosols of the Thar Desert. These are sand dunes and ridges of various shapes and heights. The soils are mainly Cambic Arenosols. Calcaric Regosols occur in the south, where the rainfall is less than 200 mm. The gravelly or stony Arenosols have a low moisture-holding capacity. In the uplands erosion is a problem.

Cambisol-Luvisol association of the northern Indo-Gangetic plains. The main soils in this region at the foot of the Himalayas are the Eutric Cambisols, which developed in calcareous alluvium. Locally there are areas of clayey Gleysols occupying strips of low-lying land. These soils are useful for rainfed cultivation of sorghum and millet. But water erosion is a major problem, and proper soil conservation strategies are essential. They are quite fertile soils and need only nitrogen and phos-

Table 6. **Potential evapotranspiration (PET) for 169 locations in rainfed areas of India.**

	PET			
Month	Mean (mm)	Standard deviation (mm)	Coefficient of variation (%)	Mean rainfall (mm)
January	85	27	32	17
February	103	24	23	14
March	151	23	15	15
April	177	21	14	22
May	207	33	16	40
June	174	34	19	122
July	132	27	20	256
August	122	21	18	240
September	122	18	15	170
October	119	15	12	93
November	90	19	21	40
December	78	25	32	15
Annual	1556	196	13	1042

Table 7. Moisture availability index (MAI) for selected locations in South Asia.

	Moisture availability index (MAI)				
Station	June	July	Aug	Sept	Oct
Hambantota	0.16	0.07	0.09	0.10	0.37
Mannar	0.00	0.00	0.00	0.00	0.56
Hyderabad	0.32	0.75	0.55	0.65	0.21
Indore	0.33	1.59	0.94	0.84	0.03
Jodhpur	0.04	0.24	0.29	0.02	0.00
Lahore	0.03	0.38	0.25	0.04	0.00
Peshawar	0.00	0.02	0.03	0.02	0.00
Quetta	0.00	0.00	0.00	0.00	0.00

phorus to produce high yields. Organic matter is usually sufficient, and soils are easily worked to good tilth.

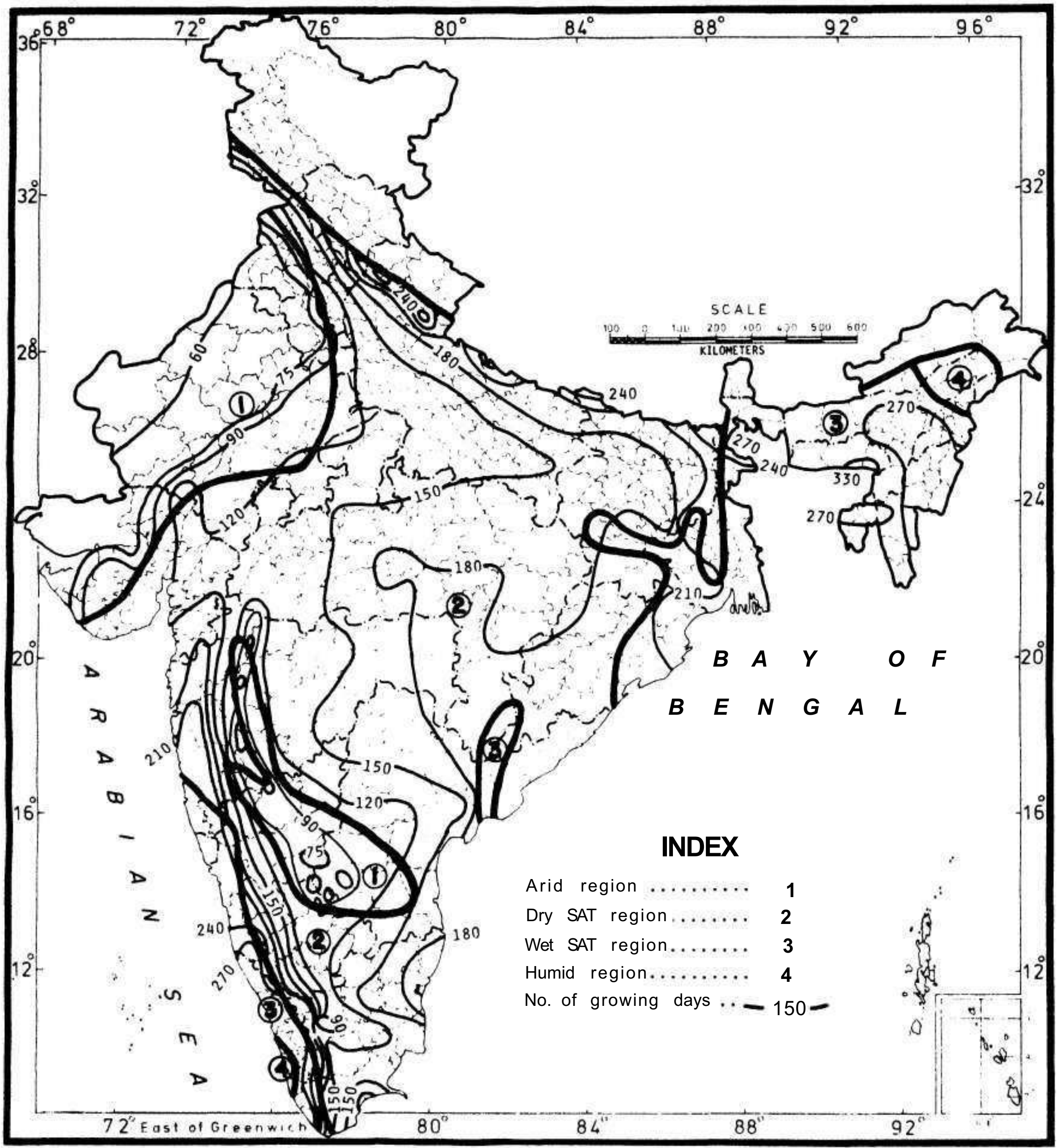
Vertisol-Cambisol association of peninsular India. Covering the northwestern part of peninsular India, this region includes extensive areas of Vertisols intercepted by strips of Cambisols. The soil depth of Vertisols in low-lying areas exceeds 150 cm and in higher terrain it ranges from 100 to 150 cm. Within the nearly continuous Vertisol area are strips of Vertic Cambisols, which occur on high undulating ground. They are slightly to moderately calcareous. Rainfed sorghum and millet can be grown successfully on these soils; however, because they are heavy soils, the drainage is poor, and ridging or making shallow surface drains is essential to provide better drainage. Phosphorus and nitrogen application is essential for higher yields.

Luvisol-Nitosol association of Sri Lanka and peninsular India. These soils cover eastern and southern parts of peninsular India and all of Sri Lanka. Here Chromic Luvisols predominate while Ferric Luvisols are common in the northeast. Nitosols occur in the high-rainfall areas along the west coast, in northeastern India, and in Sri Lanka. Rainfed sorghum and millet are commonly grown on these soils, which are shallow and sometimes on steep slopes, but have a good structure and are easily worked to a good tilth. Intensive soil-conservation measures are needed to protect these soils from erosion on steep slopes. Nitosols on gentle slopes or level areas have no erosion problems; however, low fertility, low available phosphorus, and excessive wetness from low permeability are their limiting factors.

Cambisols of Burma. Humic Cambisols on the higher elevations and Dystric Cambisols on the lower elevations are the major soils. These soils are sandy and are rapidly permeable. Dystric Cambisols in western Burma are subject to erosion and are poor in phosphates and bases. Because the organic matter is sufficient for good physical condition, they respond well to fertilizer and management.

Acrisol-Fluvisol association of the Irrawaddy basin in Burma. Extending from the coast to the center of Burma in the north, this region occupies a 150- to 200-km belt. Acrisols and Luvisols in the undulating to rolling and hilly areas and Eutric Fluvisols in the floodplains of rivers are common. Acrisols, having reached an advanced stage of weathering, are highly acid and low in bases as well as phosphate. Eutric Fluvisols in the floodplains have maintained continuous crop production with low levels of nutrient application. Under good management they respond well to fertilizer use.

Nitosol-Acrisol association of eastern Burma. Dystric and Humic Nitosols and Orthic Acrisols are the common soils here. Excessively drained Orthic Acrisols on high sites in Burma often suffer from drought. The soils have a low natural fertility and



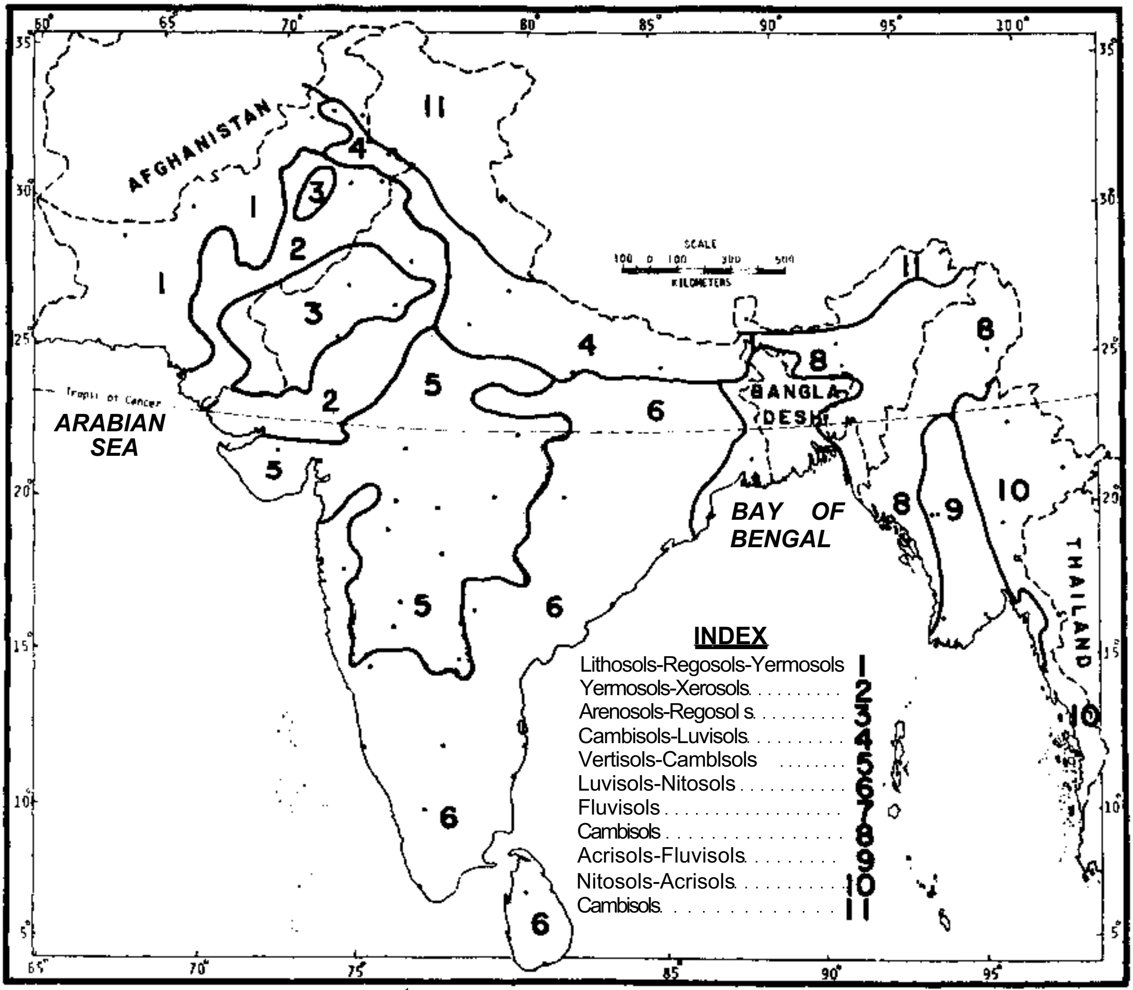
Conical Equal Area Projection with two Standard Parallels

Figure 12. Length of the growing season in India.

are low in phosphate. Dystric and Humic Nitosols with similar low-fertility problems, however, are good deep soils and respond to management. The periodically wet subsoil with the restricted internal drainage may become a restricting factor.

Physical Environment and the Performance of Sorghum

The description of the physical environment in South Asia shows *the* diversity of agroclimatic con-



Conical Orthomorphic Projection. Origin $27\frac{1}{2}$° N.
Standard Parallels 16° & 38°

SOURCE: FAO-Unesco Soil Map of the World Vol. VII-1977.

Figure 13. Broad soil regions in South Asia—Pakistan, India, Burma, and Sri Lanka.

ditions under which sorghum and millet are grown in this region. For improving production of sorghum and millet, it is important to integrate the crop, soil, and climatic information into usable and practicable region-specific recommendations. The growth and development of sorghum over a heterogeneous region such as India always show a lot of variability, depending on the nature of the soil and of the season in which the crop is grown. An example of this variability is available from the data collected on the phenology, growth, and yield of sorghum grown under good management in a collaborative multilocation experiment on sorghum modeling conducted at 10 locations in India over a 3-year period, 1979 to 1981. A detailed report of these experiments is given by Huda et al. (these Proceedings). Observed variability in the phenology, dry matter, and grain yield of sorghum hybrid CSH-6 at 10 locations in India is shown in Table 8.

Table 8. Variability in phenology, dry matter, and grain yield of sorghum hybrid CSH-6 at ten locations in India.

Year	Days to anthesis	Total dry matter (t/ha)	Grain yield (t/ha)
1979	50-62	9.5-17.1	3.4-4.5
1980	49-64	8.2-13.0	2.1-5.6
1981	53-65	8.9-14.0	2.0-6.3

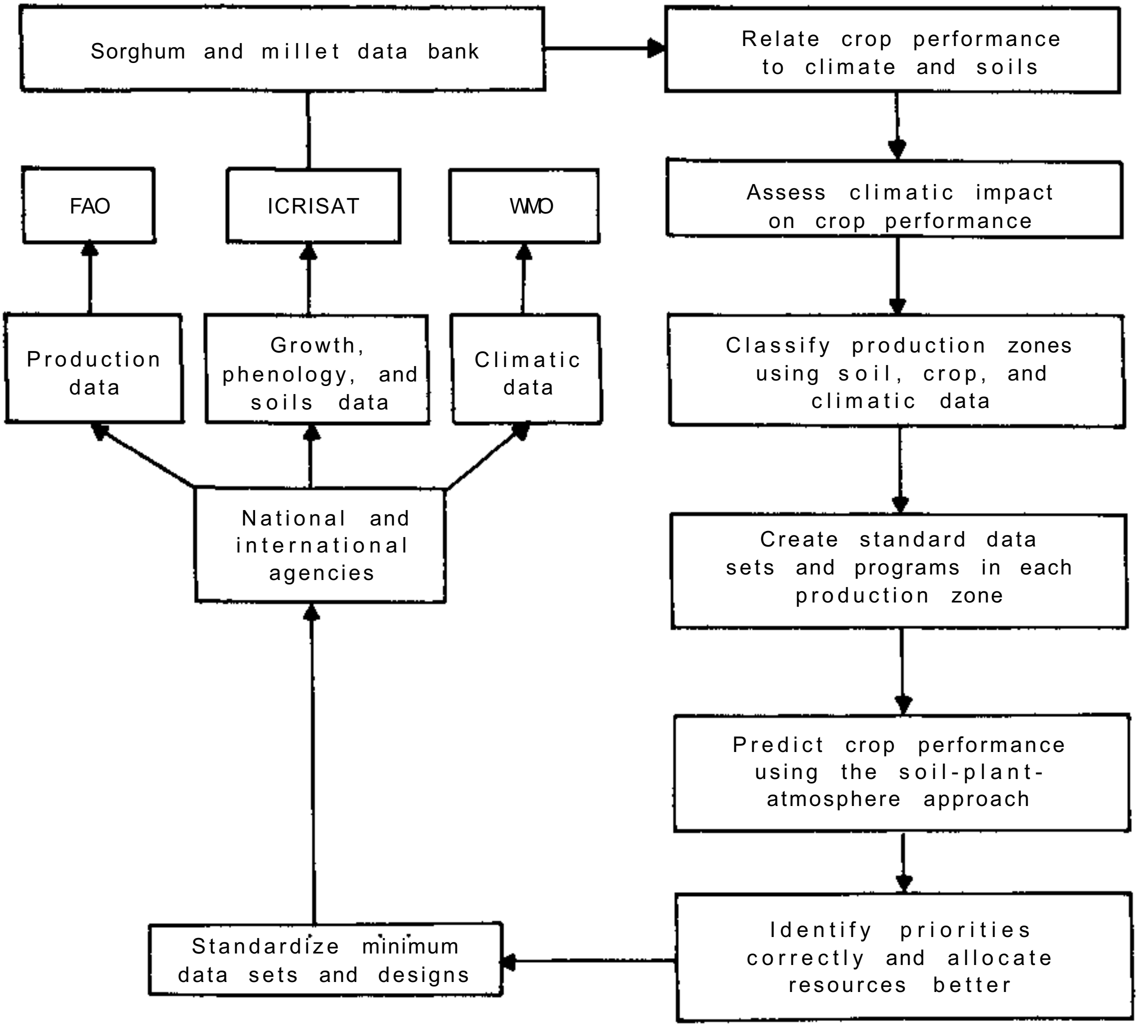


Figure 14. Proposal for an interagency sorghum and millet data bank.

Across the 3-year period, the duration to anthesis varied from 49 to 65 days. Dry-matter production ranged from 8.2 to 17.1 tonnes/ha; grain yields, from 2 to 6.3 tonnes/ha. Because detailed crop, soil, and climatic information was available from these experiments, it was possible to interpret the nature of the sorghum performance at these locations.

However, one difficulty in applying today's results to present problems or relating them to previous experiments is that some or all necessary climate, plant, and soil information is not available. Often experiments involving one or two treatments give excellent single-factor response functions, but with the addition of a few essential variables could give a holistic explanation. It is imperative that a minimum set of data on the site, climate, crop, management, and soils be collected to characterize adequately the sorghum and millet response across diverse environments. Climatic data should include daily maximum and minimum temperatures, on-site precipitation, wind speed, and solar radiation if possible. Crop information should be collected on phenology (sowing, emergence, floral initiation, anthesis, and physiological maturity), plant population, and yield components. The management data should include details on the application of fertilizer, herbicides, and insecticides;

genotype; and irrigation dates and amounts (if applicable). Information on extractable water or available water-holding capacity of soils should also be collected.

Proposal for an Interagency Sorghum and Millet Data Bank

Generation of a suitable crop-production technology for increased and stabilized production of sorghum and millet in the semi-arid tropics-spread over large areas characterized by a variety of agroclimatic conditions—needs a thorough understanding of the soil-plant-atmosphere continuum. Data necessary to generate such understanding are obviously available, but scattered, and very often not published. The research needs of the 1980s call for a much more efficient and concerted effort of the international community of scientists and policy-makers. Hence, a proposal for an interagency sorghum and millet data bank is put forth for the consideration of the participants in this symposium (Fig. 14). We believe that such a bank will serve as a repository of the data on production, growth, phenology, soils, and climate for global sorghum- and millet-growing regions. It is suggested that international agencies such as the FAO, WMO, and ICRISAT, in cooperation with the national and other international agencies, can undertake to collect the necessary minimum data sets. Use of these data should enable the assessment of climatic impact on crop performance and the classification of production zones. For each production zone standard data sets could be made available for predicting the crop performance using the soil-plant-atmosphere approach.

We believe that in the long run such an approach would lead to correct identification of research priorities and better resource allocation. This should enable the national agencies to plan the strategies to improve production of sorghum and millet and, ultimately, to help the farmer.

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Etude le l'environnement avec reference speciale au climat des zones de culture du sorgho et du mil des regions tropicales semi-arides d'Afrique occidentale

M. Konate*

Resumé

Etude de l'environnement avec référence speciale au climat des zones de culture du sorgho et du mil des régions tropicales semi-arides d'Afrique occidentale : Le sorgho et le mil sont deux des principales cultures vivrières des régions tropicales semi-arides et occupent respectivement les quatrième et cinquième rangs parmi les céréales les plus importantes du monde.

Dans ces régions les rendements des cultures sont relativement bas et variables d'année en année, le régime pluviométrique très aléatoire étant principalement responsable de cette situation.

Dans cet article nous étudierons plus particulièrement l'environnement physique des zones de cultures du sorgho et du mil dans les régions semi-arides d'Afrique occidentale. Apres une brève présentation géographique de la zone, un modèle simple de circulation atmosphérique permet d'illustrer les origines de son climat tropical. Il en decoule dans la zone l'existence d'un régime de vents reflétant bien l'alternance des saisons : vent d'Est sec en "hiver" et de Sud-Ouest humide en été apportant l'essentiel des pluies. Le rayonnement solaire reçu sur la zone est relativement abondant toute l'année et la température assez élevée. Ces deux paramètres exercent une influence marquée sur la croissance, le développement et le taux de photosynthèse, et ne constituent pas un facteur limitant la production de sorgho et de mil dans la zone. Par contre la forte variabilite spatio-temporelle de la pluie reste la raison d'une production agricole non stable.

L'obtention d'une production maximale de sorgho et de mil dans la zone d'un point de vue agroclimatologique, passe par le calage convenable de leurs cycles de croissance à l'intérieur des périodes locales de disponibilité en eau. En outre les dates d'épiaison devraient coïncider avec les fins de périodes humides notamment pour les varietes tardives photopériodiques. Ces deux cultures sont pratiquées en régime pluvial, dans la quasi-totalité de la zone, au Sud de l'isohyète 500 mm pour les différentes variétés de sorgho entre les isohyètes 250–500 mm et 1 000 mm en ce qui concerne le mil avec des risques graves de charbon pour cette derniere au delà de 1 000 mm; elles coexistent entre les isohyètes 500 mm et 1 000 mm en fonction du type de sols disponibles, des usages recherchés et des goûts particuliers des utilisateurs.

L'influence du photopériodisme sur le cycle des variétés tardives de sorgho cultivées dans la zone et celle de la longueur du cycle sur le rendement ont été examinées.

Dans le cas du mil, l'effet de certains facteurs agroclimatiques sur le rendement a éte analysé.

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Introduction

Les superficies cultivees en mil et sorgho dans le monde sont vastes (deuxieme rang apres le riz) en raison de leur adaptabilite et leur utilisation pour l'alimentation aussi bien humaine qu'animale.

La caracterisation des climats du sorgho et du mil se limitera dans cet article aux regions tropicales semi-arides d'Afrique occidentale.

La zone de l'Ouest africain, comprise entre la foret equatoriale humide et le desert du Sahara comporte une variete de regions tropicales semi-arides ayant en commun certaines caracteristiques physiques et biologiques.

La vegetation y est essentiellement constituee de steppes ou de formations tropicales buissonnantes sur couvert herbace plus ou moins discontinu avec plus grande frequence de graminees perennes.

La zone semi-aride, objet de l'etude, s'etend sur une bande de territoire longue d'environ 4 000 km de l'Ocean Atlantique a la frontiere entre le Tchad et le Soudan avec une largeur variant entre 300 et 800 km; elle couvre des portions de territoire appartenant a differents pays : Senegal, Mauritanie, Mali, Haute-Volta, Ghana, Togo, Benin, Niger, Nigeria, Tchad et Cameroun. (Fig. 1).

Le sorgho et le mil sont deux des principales cultures vivrieres des regions tropicales semi-arides et les quatrieme et cinquieme cereales les plus importantes du monde.

Le sorgho aurait ete introduit en Afrique occidentale a une date relativement recente, de l'Ethiopie au cours superieur du fleuve Niger en passant par le Soudan. Quant au mil, il serait probablement originaire de la savane ouest-africaine. Ces deux speculations sont essentiellement cultivees pour la consommation humaine et occupent le premier rang dans la ration calorique en Afrique.

L'Afrique de l'Ouest contribue pour 15% a la production total de sorgho dans les zones tropicales semi-arides. Cette production atteint son maximum de concentration au sud de l'isohyete annuelle 500 mm. Les principaux pays de culture dans la zone sont le Ghana, le Niger, le Nigeria et la Haute-Volta. Le mil est cultive. au nord de l'isohyete 1 000 mm, la limite septentrionale de la culture se situant entre les isohyetes 250 et 500 mm, les deux cultures coexistent dans la zone comprise entre les isohyetes 500 mm et 1 000

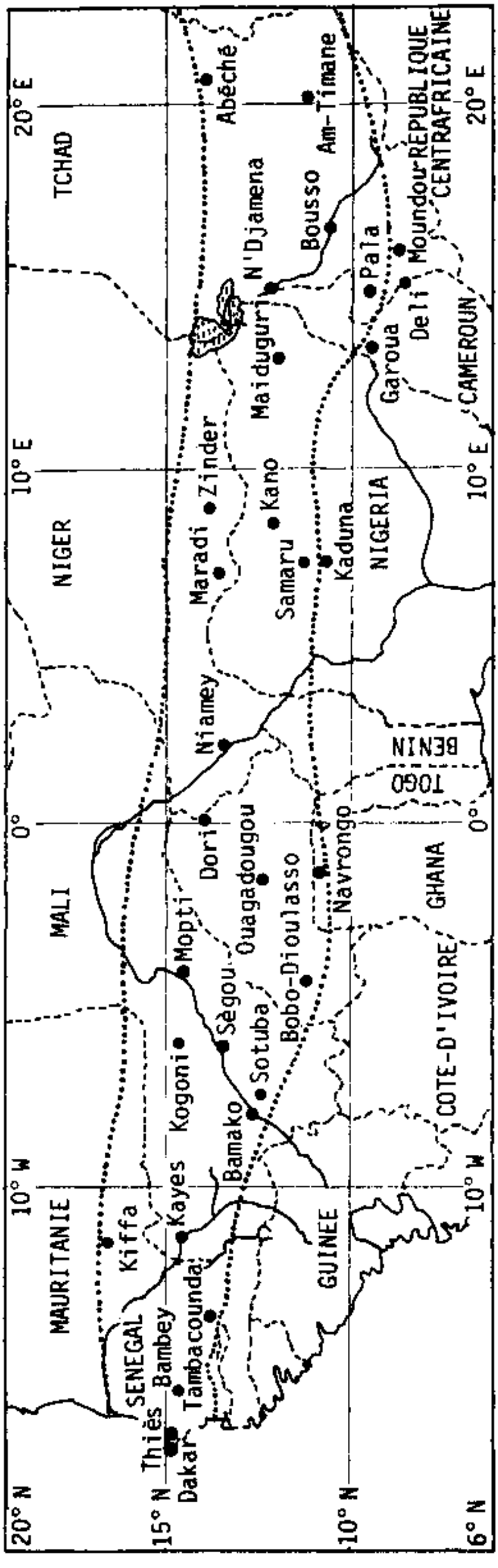

Figure 1. Limites (en pointillé) de la zone.

Source : Cochemé et Franquin (1967).

mm, en fonction des sols disponibles (Tab. 1).

Traits caracteristiques du climat de la zone

Circulation generale et types de temps

Le module de circulation atmospherique sur le continent est essentiellement determine par la rotation de la terre et le gradient de temperature entre les regions tropicales et polaires.

La situation geographique de l'Afrique occidentale lui confere des caracteristiques meteorologiques particulteres differentes de celles qui existent generalement entre les tropiques. L'evolution du temps dans la zone est determinee par l'existence de trois anticyclones subtropicaux: l'anticyclone des Acores, l'anticyclone de Lybie et celui de Sainte-Helene.

Au sein de ces anticyclones, l'air s'accumule lentement en s'affaissant, il est chaud et sec en surface. Sous l'influence de la pression relativement forte, l'air a tendance a s'echapper en partie vers le Nord et en partie vers l'equateur. Du fait de la rotation terrestre, il est devie vers la droite dans l'Hemisphere Nord ou il donne naissance a des vents soufflant du Nord-Est au Sud-Ouest, et vers la gauche dans l'Hemisphere Sud avec des vents soufflant du Sud-Est au Nord-Ouest: ce sont les vents alizes. Les alizes ainsi issus des zones de haute pression des deux hemispheres entrainent des masses d'air de caracteristiques differentes, celles de l'Hemisphere Nord etant chaudes et seches et celles de l'Hemisphere Sud chaudes et humides. La limite entre ces deux types de masses d'air porte le nom de zone de convergence intertropical (ZCIT) ou front intertropical (FIT). Les observations de satellite ont confirme que la ZCIT est une etroite bande de geants cumulus de convection.

Son deplacement, s'effectuant du Nord au Sud suivant les saisons, est fortement influence par les variations de position et de cdte des trois anticyclones. Il suit a peu pres celui du soleil au cours de l'annee mais avec un retard d'environ 6 semaines. Sur l'Afrique occidentale la ZCIT atteint sa position la plus septentrionale en aout entre 20° et 25°N et la plus meridionale vers 5°N en janvier-fevrier (Fig.2).

Dans le premier cas l'ensemble de la zone est soumise a un courant de Sud-Ouest issu de l'anticyclone de Sainte-Helene, qui en passant au-dessus de l'ocean se charge d'humidite; c'est la mousson, generatrice de pluies abondantes; en ce moment la saison des pluies est bien installee

Tableau 1. Repartition des zones de culture du sorgho et du mil compte tenu du climat.

Zone	Cultures			Pluviosite annuelle moyenne (mm)
	Principales		Secondaires	
SUB-ARIDE			Mil C[a]	250
SEMI-ARIDE		Region A		350
	Mil C			
		Region B		550
	Mil M Sorgho C-M		Mil C Sorgho C	
		Region C		800
	Mil M-L Sorgho M-L		Mil Sorgho	
		Region D		1000
	Sorgho L Mil L		Mil C Sorgho C	

Source : Cocheme et Franquin (1967)

a. Le haut du tableau correspond au Nord. Les lettres C, M et L indiquent des cycles de vegetation court, moyen et long.

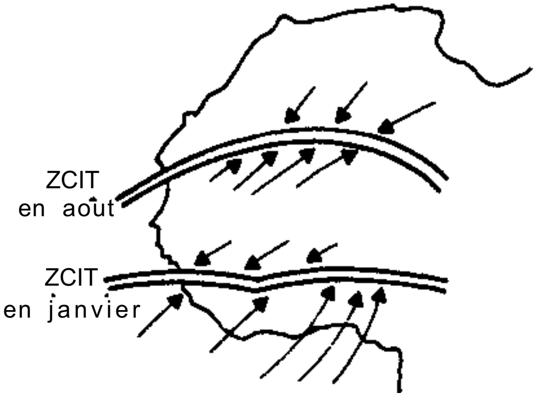

Figure 2. Positions extremes de la zone de convergence intertropicale (ZCIT) sur l'Afrique Occidentale. *Source. Cocheme et Franquin (1967).*

sur toute la zone. Dans le second cas les anticyclones des Acores et de Lybie dirigent sur la zone respectivement des flux de Nord a Nord-Est et Est. Le flux de secteur Est chaud et sec appele harmattan est tres caracteristique de la zone sahelienne de novembre a mai.

Il faut souligner que la pluie ne se produit sur une zone donnee que si elle est suffisamment situee au sud de la ZCIT offrant ainsi des conditions favorables a l'etablissement de la convection.

Les lignes de grains constituent avec la ZCIT, les phenomenes meteorologiques les plus caracteristique de l'Afrique de l'Ouest. Ce sont des perturbations mobiles constituees de bandes de cumulonimbus, axees du Nord au Sud et se deplacant d'Est en Ouest. Elles sont a l'origine d'une grande partie de la pluie tombant sur la zone.

On peut retenir que sur notre aire d'etude, la cause principale des pluies resulte du deplacement vers le Nord de la zone de convergence intertropicale, la ligne de grains etant le phenomene generateur de cette pluie. Le regime des pluies est donc d'une regularite remarquable a grande echelle du fait de l'uniformite geographique de la zone.

Autres facteurs agroclimatologiques

Cette breve description de la circulation atmospherique generate permet de donner des indications sur d'autres facteurs importants pour l'agriculture. L'alternance des saisons est bien refletee par le regime des vents : de Nord-Est dominant en saison seche et de Sud-Ouest en saison des pluies. Mais en debut de saison pluvieuse on peut par moment noter temporairement des retours du regime sec de Nord-Est, ce qui peut affecter serieusement les jeunes cultures. Par ailleurs les temperatures au voisinage de la surface dependent etroitement de la position de la ZCIT et des phenomenes meteorologiques quelle engendre, etant donne que le rayonnement solaire au sommet de l'atmosphere est assez constant.

Elles sont plus basses en atmosphere de mousson et plus elevees dans l'harmattan. De meme l'air de mousson est initialement plus humide, et en surface, cette humidite augmente en raison de l'evaporation.

Environnement climatique des zones de culture du sorgho et du mil

Pluviosite

L'eau est le facteur climatique le plus important de la production de sorgho et de mil dans la zone tant en quantite que par sa repartition dans le temps.

Nous avons vu precedemment que la pluie sur la zone resulte principalement du deplacement vers le Nord de la ZCIT. Cette derniere passe au-dessus de la meme localite deux fois par an; le temps qui separe ces passages successifs determine la duree de la saison pluvieuse a cette localite. C'est ainsi que la longueur de la saison des pluies diminue en gros a mesure que l'on s'eleve en latitude. Il en va d'ailleurs de meme pour la pluviosite annuelle qui varie en moyenne sur la region entre 250 mm et 1 250 mm et est repartie en bandes selon les paralleles geographiques avec cependant quelques irregularites localisees (Fig. 3). Par contre la variabilite d'une annee a l'autre de la pluviosite croit du Sud au Nord; sur la Figure 4 on peut noter une zone centrale de pluviosite superieure a 500 mm ou le coefficient de variabilite est partout inferieur a 20% et de part et d'autre de cette zone centrale, deux regions (partie occidentale du Senegal et Nord du lac Tchad) ou les variations de la pluviosite sont relativement importantes.

D'apres la classification climatique d'Auberville, l'aire d'etude comporte la zone sahelo-

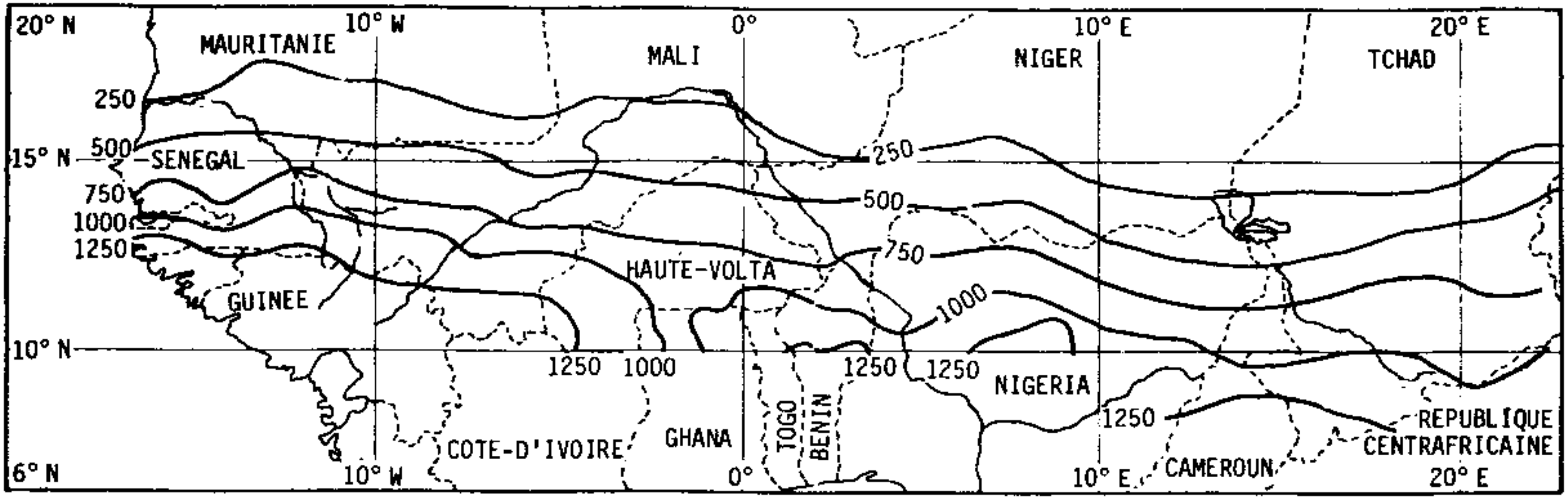

Figure 3. Isohyètes annuelles moyennes de la zone.

Source : Cochemé et Franquin (1967).

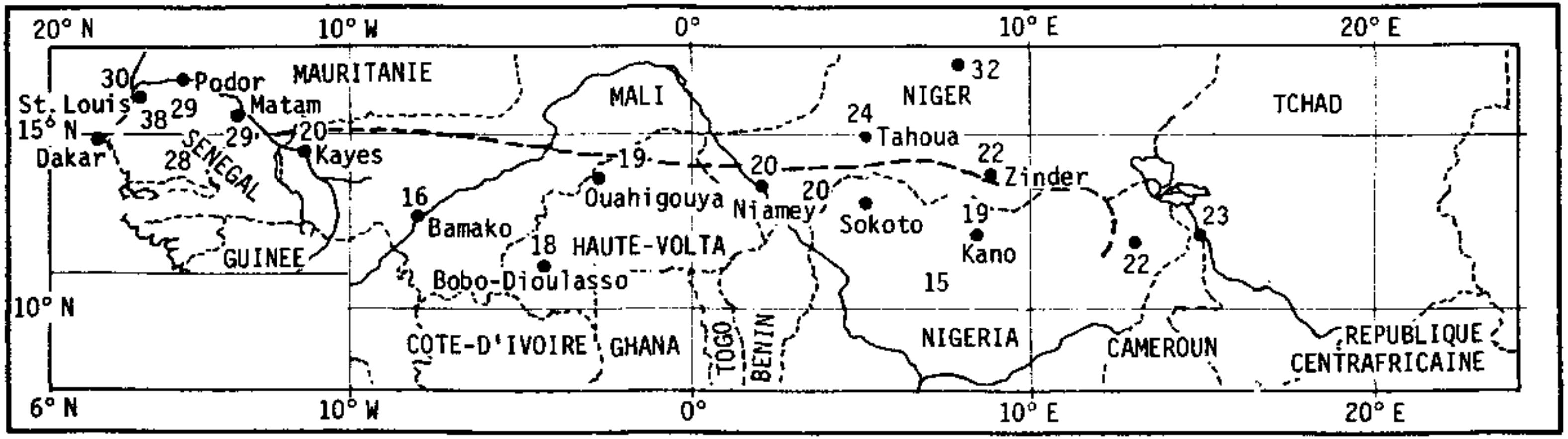

Figure 4. Distribution en surface du coefficient de variation. Les lignes tiretées délimitent la partie de la zone où le co-efficient est inférieur à 20%.

Source : Cochemé et Franquin (1967).

Tableau 2. Indice de l'humidite utilisable (IHU) pendant le cycle vegetatif du sorgho et du mil a des localites selectionnees dans la zone.

Localite	Juin	Juillet	Aout	Sept.	Oct.	Nov.
Bambey (Senegal)	0.05	0.56	1.18	0.93	0.13	0.00
Tambacounda (Senegal)	0.53	1.34	1.95	1.46	0.24	0.00
Bamako (Mali)	070	1.56	2.27	1.32	0.20	0.00
Niono (Mali)	0.20	0.72	1.13	0.55	0.04	0.00
Niamey (Niger)	0.22	0.69	1.16	0.47	0.02	0.00
Pala (Tchad)	1.00	1.69	1.92	1.37	0.22	0.00
N'Djamena (Tchad)	0.19	0.81	1.53	0.52	0.03	0.00
Ouagadougou (Haute-Volta)	0.50	1.03	1.72	0.78	0.06	0.00
Dori (Haute-Volta)	0.18	0.68	1.04	0.45	0.02	0.00
Kano (Nigeria)	0.48	1.07	1.76	0.59	0.00	0.00

saharienne (250-500 mm), la zone sahelo-soudanienne (500-900 mm) et une partie de la zone soudano-guineenne (900-1 250 mm).

Periodes de disponibilite en eau et cycles de croissance

Les valeurs moyennes de hauteur de pluie ne rendent pas compte du caractere stable de la pluviometrie.

La precipitation stable a ete definie par Hargreaves (1975) comme etant la hauteur de pluie a attendre 3 annees sur 4. Ainsi, l'indice de l'humidite utilisable (IHU)*, rapport entre la precipitation stable et l'evapotranspiration potentielle, permet en l'absence d'informations appropriees sur les types de sols, leur profondeur, leur capacite d'emmagasinement de l'eau, etc, de fournir une approximation de la disponibilite de l'eau pour la croissance des cultures. Les valeurs mensuelles de IHU pendant le cycle vegetatif du sorgho et du mil sont presentees dans le Tableau 2. Ces donnees montrent que dans la partie Nord de la zone, le mois de juin est caracterise par de tres faibles indices de l'humidite utilisable. Il en est de meme des mois d'octobre et de novembre dans toute la zone.

L'humidite disponible pour la croissance du sorgho et du mil est par consequent a peu pres suffisante de juillet a septembre dans le Nord de la zone.

Dans le Sud cette humidite est moderement deficitaire en juin et excedentaire de juillet a septembre.

La quantite d'eau disponible ne depend pas uniquement de la pluviosite. L'eau de pluie se repartit en une partie s'evaporant du sol ou des vegetaux (evapotranspiration) et une autre s'ecoulant en surface, soit par infiltration ou drainage. En definitive l'eau disponible pour une culture resulte du bilan entre les gains et les pertes au niveau des racines. Cocheme et Franquin (1967) ont defini a partir des deux termes "purement" climatiques du bilan hydrique (la pluie et l'evapotranspiration potentielle, ETP) des periodes de disponibilite en eau presentant un grand interet pratique sur le plan agronomique (Fig.5).

Dans le Tableau 3 sont rassemblees les dates de debut et de fin et les durees de ces differentes periodes pour 35 stations de l'Afrique au sud du Sahara.

La periode preparatoire

La pluviosite est comprise entre 0.1 ETP et 0.5 ETP; c'est la periode de preparation des sols ou du semis en sec notamment pour le mil. Sa duree dans la zone varie de plus de 50 jours a moins de 20.

La periode franchement humide

La pluviosite est superieure a l'evapotranspiration potentielle; revapotranspiration reelle y atteint les

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*Hargreaves a propose la classification suivante:

IHU: 0 a 0.33	tres deficitaire
IHU: 0.34 a 0.67	moderement deficitaire
IHU: 0.68 a 1.00	legerement deficitaire
IHU: 1.01 a 1.33	adequat
IHU: 1.34 et plus	excedentaire

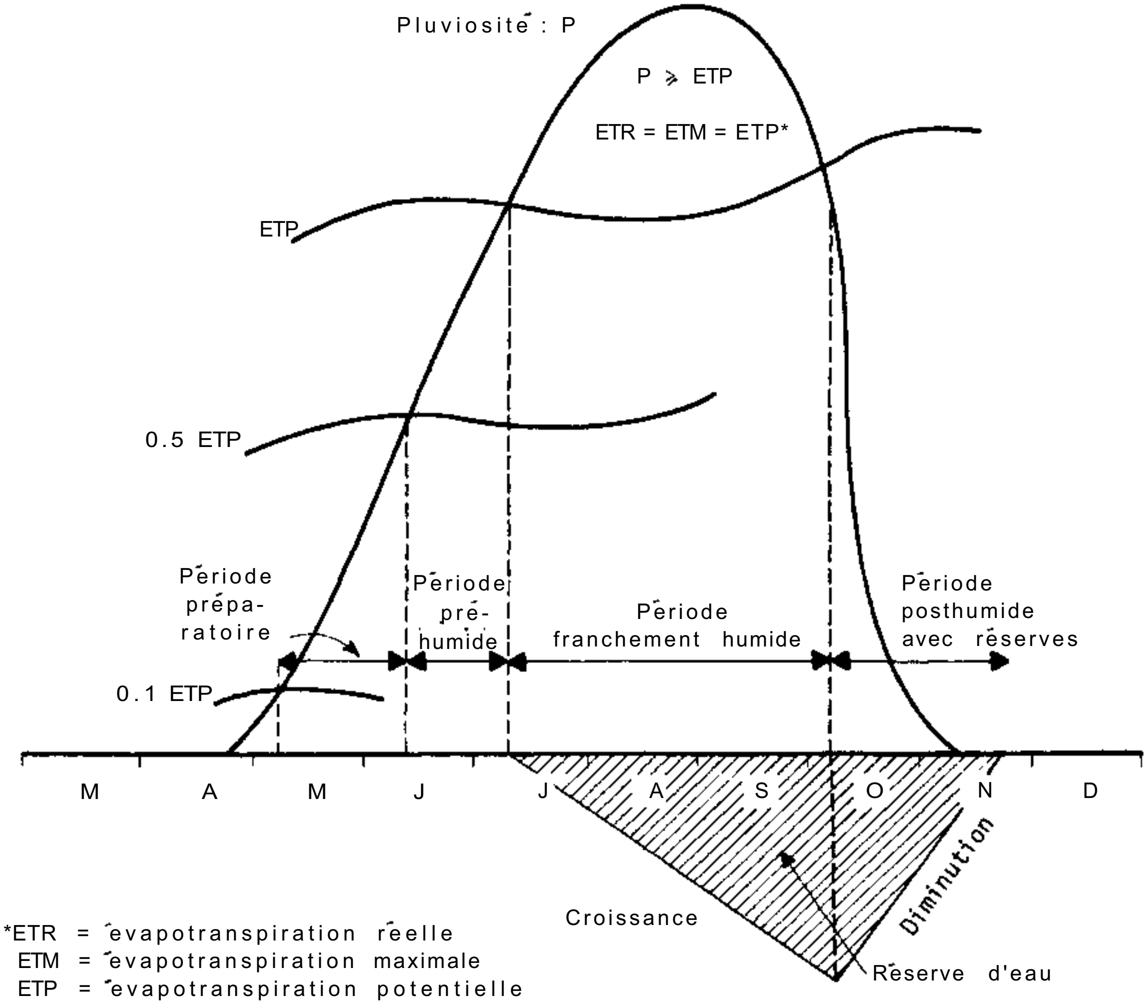

Figure* 5. *Periodes de disponibilite en eau.

Source. *Cocheme et Franquin* (*1967*).

valeurs de ETP. C'est la periode favorable pour la floraison; le sorgho et le mil donnent les meilleurs rendements lorsque la floraison a lieu juste avant la fin de cette periode. La duree de la periode franchement humide varie de 0 au Nord a 140 jours au Sud.

Les periodes intermediaires (periodes prehumide et posthumide)

La pluviosite est superieure ou egale a 0.5 ETP mais inferieure a ETP. C'est pendant ces periodes que les precipitations sont les plus variables. La periode prehumide est celle du semis du sorgho et du mil, la duree du cycle semis-epiaison devant correspondre a l'ensemble des periodes prehumide et franchement humide. La periode posthumide est celle de la maturation, la decroissance des besoins en eau des cultures coincidant avec celle des pluies. Les periodes intermediaires ont en moyenne une duree constante sur la zone.

La period humide

Elle couvre la periode franchement humide et les periodes intermediaires. En prenant en compte l'eau emmagasinee dans le sol qui continue d'etre utilisee par les cultures apres l'arret des pluies, on obtient la periode humide avec

Tableau 3a. Dates moyennes de debut et fin des periodes de disponibilite en eau.

Localite	Date						
	P (mm)	Debut periode prepa-ratoire	Fin periode prepa-ratoire	Debut periode franchement humide	Fin periode franchement humide	Fin periode humide	Fin periode humide + reserves
Agades	164	-	-	-	-	-	_
N'Guigmi	235	20/06	23/07	-	-	3/09	3/09
Gao	261	27/05	2/08	-	-	25/08	25/08
St.-Louis	346	21/06	22/07	7/08	25/08	28/09	2/10
Tahoua	406	26/05	6/07	-	-	8/09	8/09
Abeche	505	9/05	29/06	18/07	4/09	15/09	1/10
Matam	535	4/06	30/06	22/07	9/09	30/09	17/10
Mopti	552	16/05	25/06	15/07	7/09	27/09	8/10
Zinder	548	5/05	25/06	16/07	4/09	15/09	3/10
Dakar Yoff	578	15/06	9/07	25/07	20/09	9/10	29/10
Birni N'Konni	600	4/05	23/06	19/07	8/09	23/09	22/10
Niamey	638	28/04	20/06	10/07	6/09	24/09	16/10
Maradi	642	30/04	22/06	11/07	10/09	27/09	20/10
N'Djamena	648	1/05	20/06	10/07	10/09	26/09	18/10
Maiduguri	659	3/05	17/06	5/07	11/09	29/09	17/10
Thies	694	6/06	30/06	18/07	1/10	13/10	8/11
Segou	724	15/05	13/06	2/07	17/09	30/09	20/10
Sokoto	734	19/04	10/06	5/07	21/09	3/10	20/10
Kayes	821	15/05	11/06	3/07	21/09	11/10	1/11
Maroua	841	19/04	25/05	22/06	25/09	6/10	24/10
Mongo	858	18/04	16/06	28/06	25/09	8/10	29/10
Kano	871	23/04	28/05	25/06	16/09	30/09	19/10
Kaele	878	6/04	24/05	21/06	26/09	8/10	20/10
Ouagadougou	882	15/04	22/05	24/06	22/09	6/10	28/10
Am-Timan	919	10/04	17/05	20/06	24/09	9/10	29/10
Bousso	931	14/04	25/05	18/06	28/09	10/10	2/11
Tambacounda	941	15/05	2/06	19/06	6/10	20/10	12/11
Garoua	1013	1/04	6/05	9/06	1/10	14/10	1/11
Pala	1044	28/03	8/05	5/06	4/10	20/10	9/11
Navrongo	1095	17/03	2/05	13/06	3/10	14/10	2/11
Bamako	1099	19/04	26/05	17/06	2/10	14/10	6/11
F Archambault	1141	23/03	2/05	1/06	8/10	23/10	17/11
Bobo-Dioulasso	1185	14/03	1/05	15/06	3/10	17/10	6/11
Moundou	1228	27/03	27/04	24/05	11/10	27/10	21/11
Kaduna	1298	19/03	22/04	20/05	9/10	21/10	10/11

Source : Cocheme et Franquin (1967)

reserves. C'est cette derniere qui est directement comparable au cycle vegetatif des plantes. Sa duree vane dans la zone de 55 a 200 jours. Par ailleurs le rapport de la pluviosite (exprimee en mm) a la duree en jours de la periode humide avec reserves a une valeur moyenne voisine de 5.5 sur la zone.

Les cycles de croissance du sorgho et du mil varient respectivement de 80 a 250 jours et de 60 a 200 jours (Cocheme et Franquin, 1967). Mais en raison de la tolerance des jeunes plantes de mil a la s6cheresse, des semis precoces peuvent etre effectues pendant la periode preparatoire, ce qui permet un allongement de la periode humide

Tableau 3b. Durees moyennes des periodes de disponibilite en eau.

	Duree (en jours)						
Localite	Periode preparatoire	I_1	Periode franchement humide	I_2	Periode humide	Reserves	Periode humide + reserves
Agades	-	0	0	0	0	0	0
N'Guigmi	33	-	0	-	42	-	(42)
Gao	67	-	0	-	23	-	(23)
St-Louis	31	16	18	34	68	4	72
Tahoua	41	-	0	-	64	-	(64)
Abeche	51	19	48	11	78	16	94
Matam	26	23	49	21	93	17	110
Mopti	40	20	54	20	94	11	105
Zinder	50	21	50	11	82	18	100
Dakar Yoff	24	16	57	19	92	20	112
Birni N'Konni	50	26	51	15	92	29	121
Niamey	53	20	58	18	96	22	118
Maradi	53	19	61	17	97	23	120
N'Djamena	50	20	62	16	98	22	120
Maiduguri	45	18	68	18	104	18	122
Thies	24	18	74	13	105	25	130
Segou	29	19	77	13	109	20	129
Sokoto	52	25	78	12	115	15	130
Kayes	27	22	80	20	122	21	143
Maroua	36	28	95	11	134	18	152
Mongo	59	12	89	13	114	21	135
Kano	35	27	83	14	124	19	143
Kaele	48	27	97	12	136	12	148
Ouagadougou	37	33	90	14	137	22	159
Am-Timan	37	34	96	15	145	20	165
Bousso	41	24	102	12	138	23	161
Tambacounda	18	17	109	14	140	23	163
Garoua	36	34	114	13	161	18	179
Pala	41	28	121	16	165	20	185
Navrongo	46	42	112	11	165	19	184
Bamako	37	22	107	12	141	23	164
F. Archambault	43	27	129	15	171	25	196
Bobo-Dioulasso	48	45	110	14	169	20	189
Moundau	31	27	140	16	183	25	208
Kaduna	34	28	142	12	182	20	202

Note, I_1: periode prehumide et I_2: periode posthumide En cas d'absence de periode franchement humide les chiffres de la derniere colonne sont inscrits entre parentheses

Source : Cocheme et Franquin (1967).

effective; ainsi la periode minimale de disponibilite en eau pour le mil serait de l'ordre de 50 jours. En utilisant la relation precedente entre la pluviosite et la duree de la periode humide avec reserves, l'aire de culture du sorgho aurait pour limites les isohyetes 440 et 1 375 mm et celle du mil les isohyetes 275 et 1 100 mm.

Rayonnement

Il constitue la source de differentes formes d'energie utilisee par les plantes dans les processus metaboliques et la production de matiere seche. Les cultures utilisent seulement 2 a 4% du rayonnement global pour la photosynthese.

Le rayonnement global annuel estime a partir de la duree d'insolation varie sur la zone entre 160 et 180 K cal/cm^2 soit de l'ordre de 440 a 500 cal/cm^2/jour (Cocheme et Franquin 1967). Sa distribution est zonale avec des valeurs croissantes du Sud au Nord. La variation saisonniere est cependant relativement faible: on note un maximum avant et apres les pluies et un maximum en hiver (Fig. 6)

Temperature

L'action de la temperature est examinee aussi bien au niveau qualitatif que quantitatif. Sur le plan qualitatif l'occurrence de certains seuils peut influencer la croissance et le developpement des cultures. Quantitativement, la croissance globale et l'apparition des diverses phases de developpement peuvent etre rapportees aux sommes d'energie que represente la temperature.

Dans la zone, la temperature est elevee avec une variation saisonniere a deux maxima et deux minima.

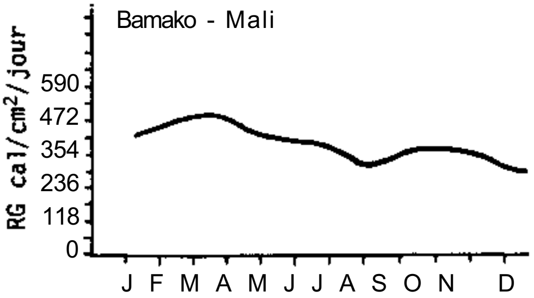

Figure 6. Variation saisonniere (moyennes mensuelles du rayonnement global: RG) dans la zone (cal/cm²/jour). Source: Cocheme et Franquin (1967).

Le Tableau 4 montre que les temperatures maximales varient entre 28°C et 42°C environ. Dans les parties centrale et meridionale de la zone, elles sont en general inferieures a 35°C, voire meme voisines de 30°C sauf en octobre, novembre et quelquefois en juin, alors qu'au Nord elles sont presque toujours superieures a 35°C. Les temperatures minimales, quant a elles, restent comprises entre 15 et 28°C environ.

Tableau 4. Temperatures maxi et mini moyennes de l'air (°C) au cours du cycle vegetatif du sorgho et du mil dans differentes localites de la zone.

Localite	Juin	Juil.	Aout	Sept.	Oct.	Nov.
Bamako (Mali)	34.7 23.3	31.5 22.1	30.2 21.7	31.5 21.6	33.9 21.4	34.9 18.4
Navrongo (Ghana)	32.7 23.2	30.7 22.5	29.6 22.3	30.6 21.9	33.4 21.9	35.9 20.1
Maiduguri (Nigeria)	36.1 23.6	31.8 22.1	30.5 21.7	32.2 21.6	35.4 19.7	35.2 15.4
Ouagadougou (Haute-Volta)	34.5 23.8	31.8 22.5	30.7 21.8	32.2 21.9	34.9 22.4	35.6 18.9
Niamey (Niger)	37.8 25.9	34.0 23.8	32.5 22.8	34.4 23.4	37.0 23.5	35.9 19.0
Dakar (Senegal)	28.6 23.0	29.7 24.4	30.0 25.0	30.3 24.6	30.7 24.4	29.1 21.9
N'Djamena (Tchad)	37.8 24.6	33.8 23.2	31.0 22.1	33.2 22.1	36.5 21.5	36.3 16.8
Kandi (Benin)	31.8 21.3	29.4 20.3	28.5 19.8	28.8 19.4	33.8 21.2	35.0 17.1
Kiffa (Mauritanie)	41.9 28.4	38.8 27.3	36.5 25.5	37.2 25.3	38.5 23.7	34.8 18.6

En outre l'amplitude thermique quotidienne est nettement plus forte en hiver qu'en ete en raison du rayonnement nocturne plus reduit pendant cette derniere periode.

Le zero de germination du sorgho serait compris entre 10 et 15°C et sa temperature serait de l'ordre de 28°C.

Cocheme et Franquin (1967) ont etudie l'occurence de certains seuils de temperature pendant les periodes de disponibilite en eau dans la zone (Tab. 5). Il en ressort que les temperatures minimales inferieures a 15°C ne sont enregistrees que pendant les mois d'hiver, donc en dehors de la periode de vegetation du sorgho et du mil en tant que cultures pluviales. Elles pourraient en revanche, etre affectees par des temperatures elevees. Le Tableau 4 indique l'occurence dans la zone de temperatures maximales superieures a

Tableau 5. Occurence de certains seuils de temperature dans la zone (les chiffres indiques dans la deuxieme rangee representant les mois de l'annee).

	Maximum 40°C				Minimum 15°C		
	3	4	5	6	1	2	12
Agades		0		0	0	0	0
N'Guigmi					0	0	0
Gao		0	0	0	0	0	0
Tahoua		0	+0				
Abeche		0	+0				
Matam		+0	10		0		
Mopti		0	+0		0		
Zinder		0			0		
Dakar Yoff							
Bimi N'Konni		0	+0				
Niamey		+0					
Maradi		+0			0	0	0
N'Djamena		0	10		0		
Maiduguri		0			0	0	0
Thies							
Segou							
Sokoto							
Kayes		0	+ 0				
Maroua							
Mongo	0	+0					
Kano					0	0	0
Ouagadougou							
Am-Timan					0		0
Bousso							
Tambacounda		0					
Garoua							
Pala							
Navrongo							
Bamako							
F. Archambault							
Bobo Dioulasso							
Moundou							
Kaduna							

+ 0 partie de la periode preparatoire

I 0 periode preparatoire

Source : Cocheme et Franquin (1967).

40°C, mais elles ne sont observees, ni au cours de la periode franchement humide, ni meme pendant la periode humide.

Les sols

La determination des periodes de disponibilite en eau et de vegetation effectuee ci-dessus prend seulement en compte l'apport et la demande d'eau a une localitee donnee. Les proprietes du profil d'un sol affectent la retention de l'eau, le ruissellement et le drainage ainsi que les pertes par evaporation et transpiration.

Les sols de la zone se sont developpes en relation avec les conditions climatiques et la topographte et representent d'autre part un heritage des paleoclimats principalement de l'alternance des climats secs et humides aux eres tertiaire et quaternaire.

On y note la presence de sols bruns semi-arides, surtout sableux, au Nord de l'isohyete moyenne annuelle 500 mm ou l'insuffisance des pluies n'a pas permis de migrations appreciables; leur humidite volumique a la capacite au champ varie entre 12 et 15% et au point de fietrissement entre 3 et 4%. Ces sols conviennent particulierement au mil en raison de leur texture grossiere. Entre les isohyetes 500 et 1 000 mm correspondant a la plus grande concentration de production de sorgho on rencontre les sols ferrugineux ou se sont produites une certaine migration et une accumulation de fer et d'argile formant une couche moins permeable a faible profondeur; l'humidite volumique a la capacite au champ est de l'ordre de 17-22% et au point de fietrissement permanent de 7-8%.

A l'extreme Sud on trouve des sols ferralitiques. Enfin, des sols alluviaux, surtout formes d'argile et de limon sont rencontres par endroits notamment dans les bassins des fleuves Niger et Senegal et du lac Tchad.

Quelques aspects des reponses du sorgho au photoperiodisme dans la zone

L'influence de la lumiere sur le sorgho se manifeste sous deux aspects principaux dans la zone : la duree du jour ou photoperiode et l'effet de l'intensite lumineuse associe a la temperature sur la production de matiere seche.

La duree du jour connait une variation saisonniere assez faible dans la zone, avec une amplitude d'environ une heure et demie dans le Nord et d'une demi-heure dans le Sud (Cocheme et Franquin 1967).

La saison vegetative des cultures pluviales couvre la partie de l'annee ou les jours sont les plus longs a toutes les latitudes; la floraison des cultures qui y sont adaptees a lieu au moment ou les jours vont en decroissant.

L'examen des donnees phenologiques moyennes de neuf varietes tardives de sorgho (Tab. 6), permet de noter que pour les semis effectues entre avril et aout, les epiaisons se produisent en octobre alors que les jours raccourcissent, ainsi le cycle de croissancediminue progressivement, ce qui atteste de l'influence du photoperiodisme sur la floraison du sorgho tardif. On constate d'autre part que le nombre d'entre-noeuds et de feuilles fonctionnelles ainsi que le nombre de grains par panicule varient en fonction de la duree de l'intervalle semis-epiaison lorsque les semis sont effectues d'avril a septembre.

A partir de ces constatations, Cocheme et Franquin (1967) ont determine une relation de type parabolique entre la productivite des varietes tardives de sorgho et la somme des temperatures effectuee du semis a *l'*epiaison (Fig.7); elle permet d'obtenir la valeur optimale de la somme des temperatures qui determine la productivite maximale d'une variete donnee et d'en deduire la date de semis optimale connaissant la date d'epiaison de la variete.

Differents auteurs ont etudie l'influence du choix de la date de semis sur le rendement des varietes photoperiodiques locales ou ameliorees de sorgho. Leur epiaison intervenant a la fin des pluies, le rendement depend en grande partie de l'humidite emmagasinee dans le sol. Toutefois si l'epiaison est tardive en raison d'un semis tardif ou bien si un arret precoce des pluies se produit, alors le remplissage des grains se fera de fagon incomplete. A Samaru (Nigeria), une relation lineaire entre la date d'epiaison d'une variete locale de sorgho pendant une saison moyenne et sa date de semis a ete etablie sur une periode de semis de 8 a 10 semaines.

Lorsque le semis etait effectue entre les 12 et 16 mai, repiaison se produisait le 6 octobre, mais a partir de cette date, chaque retard de semis d'une semaine entrainait un retard d'epiaison de 0.9 a 1.3 jours. (Curtis 1968 et Andrews 1973 cites par Kassam 1976).

En cas d'arret precoce des pluies, l'epiaison

Tableau 6. Donnees phenologiques moyennes relatives a 9 varietes tardives de sorgho semees a intervalles d'un mois a Deli (Tchad) a proximite de la limite Sud de la zone.

N°	Avril	Mai	Juin	Juillet	Aout	Sept.	Oct.	Nov.
1	189	163	136	110	92	78	82	94
2	5/10	10/10	13/10	18/10	30/10	16/11	12/12	1/2
3	5095	4295	3515	2815	2355	2070	2205	2455
4	6055	5085	4150	3220	2790	2485	2780	3285
5	4140	3505	2875	2305	1925	1645	1635	1630
6	12.42	12.42	12.39	12.31	12.17	12.00	11.80	11.69
7	25.1	21.3	18.0	14.5	10.6	82	7.6	6.5
8	8.0	64	4.9	4.1	3.3	-	3.2	4.0
9	475	400	350	345	270	-	145	105
10	915	840	680	385	60			

Note : Les semis ont ete faits au debut de chaque mois indique Les nombres mentionnes dans la premiere colonne ont les significations survantes

1. Nombre de jours entre le semis et l'epaison. 2. Date de l'epiaison 3,4 et 5. Sommes des temperatures moyennes, maximales et mimmales cumulees pour la periode semis-epiaison 6. Duree moyenne du jour en heures et centiemes d'heure. 7. Nombre d'entre-noeuds 8 Nombre de feuilles fonctionnelles 9. Surface foliaire en cm^2 10. Nombre de grains par panicule

Source Cocheme et Franquin (1967)

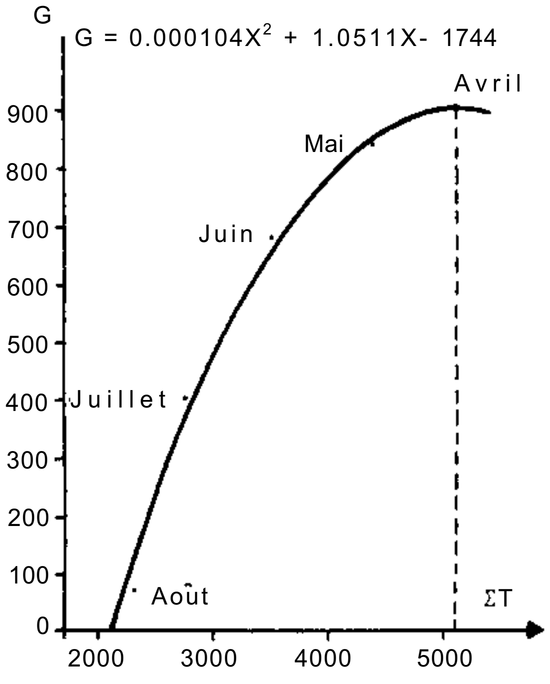

Figure 7. Courbe de productivite (nombre de grains par panicule) d'un sorgho tardif en fonction de la somme de temperatures entre le semis et l'epiaison. Source. Cocheme et Franquin (1967).

retardait de 2 jours par semaine de retard de semis alors que la culture semee le 16 mai epiait encore le 6 octobre; mais apres le 30 mai, tout retard de semis d'une semaine entrainait une diminution progressive de rendement d'environ 200 kg/ha soit a peu pres 12.5% du rendement maximal (Andrews 1973). Le meme auteur a montre que pour chaque semaine de retard de semis apres la date optimale en mai et debut juin, la perte de rendement etait d'environ 300-600 kg/ha (15% environ du rendement maximal).

Par ailleurs Kassam et Andrews (1975) ont montre qu'en semant tardivement un sorgho photoperiodique ameliore de 190 jours approximativement, on reduisait son cycle vegetatif d'environ 6 jours par semaine; de meme le nombre d'epis par plante et le nombre de grains par epi s'en trouvaient reduits.

Influence de certains facteurs agroclimatiques sur le rendement du mil

A partir des donnees de production relevees sur onze annees a Bambey (Senegal), Cocheme et Franquin (1967) ont etudie les relations entre le

Tableau 7. Valours climatiques, hauteurs des precipitations et rendements.

	kg/ha	P (mm)	X_1	X_2	X_3	X_4	X_5	X_6
1950	670	1270	9.5	148	-	896	30	40
1951	790	940	10.0	227	10	470	40	107
1952	1440	885	9.0	101	24	413	25	95
1953	1330	755	9.0	62	5	305	20	82
1954	1230	745	7.5	2	58	360	0	51
1955	1770	780	8.5	15	16	380	10	58
1956	1060	640	6.0	47	54	170	15	155
1957	1100	670	7.0	77	6	284	20	124
1958	1220	820	6.5	39	46	492	5	61
1959	910	460	5.5	-	13	150	5	101
1960	1040	790	8.0	14	14	380	15	73
	1141.8	796	78	66.5	21.5	390.9	16.8	86 1

Source: Cocheme et Franquin (1967).

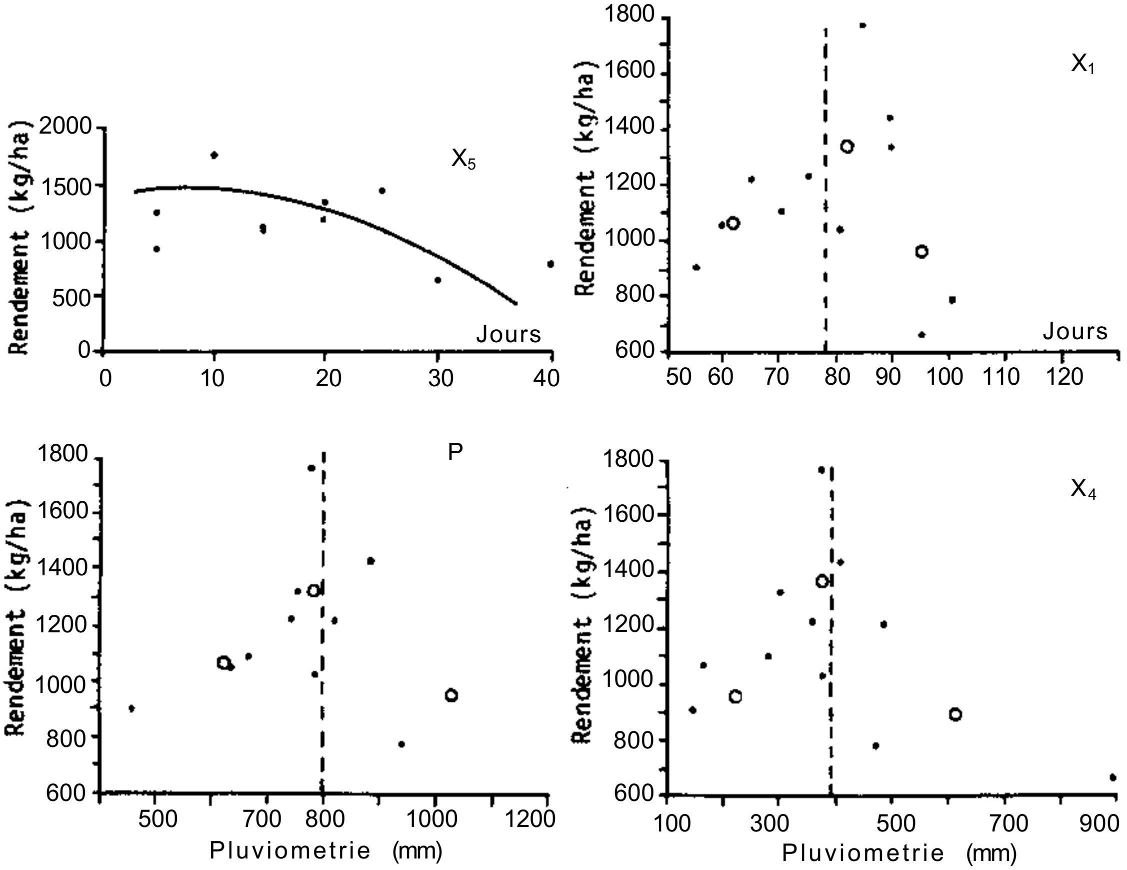

Figure 8. Diagrammes de dispersion du rendement en fonction de P, X_1, X_4 et X_5. Les gros points noirs indiquent les positions moyennes des classes de variables independantes. Source. Cocheme et Franquin (1967).

rendement du mil et certaines variables agroclimatiques: P, precipitations annuelles; X_1, duree de la periode franchement humide; X_2, total des precipitations du mois d'octobre; X_3, total des precipitations de la periode posthumide, X_4, excedent hydrique; X_5, intervalle de temps entre l'epiaison et la fin de la periode franchement humide; X_6, total des precipitations de la periode prehumide. Les donnees sont presentees dans le Tableau 7.

Un examen detaille des relations de chacune des variables P, X_1, X_4, et X_5 avec le rendement a permis de conclure a l'existence d'une liaison curvilineaire. (Fig.8). Ces resultats indiquent qu'en zone semi-aride aussi, des excedents hydriques trop importants ou des periodes humides trop longues peuvent compromettre la production, meme d'une culture adaptee.

Il ressort done que dans le cas de la culture de mil dans la zone, une pluviometrie annuelle superieure a la normale n'entraine pas necessairement une production depassant la moyenne.

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Climate of the Sorghum and Millet Cultivation Zones of the Semi-Arid Tropical Regions of West Africa

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Abstract

Sorghum and millet are the two main food crops of the semi-arid tropics (SAT) and rank fourth and fifth, respectively, among the important cereals in the world. In the SAT, crop yields are relatively low and unstable due to the erratic rainfall pattern,

This paper attempts to study the physical environment of the sorghum- and millet-growing regions of the West A frican SAT. A geographical description of the zone and an explanation of the air circulation pattern will help us understand this tropical climate. Seasonal changes correspond to the wind pattern—a dry easterly wind in "winter" and a wet southwesterly wind in summer that brings most of the rain. Solar radiation over the area is relatively abundant throughout the year and temperatures are quite high. Both these factors have a strong influence on plant growth and development, and the rate of photosynthesis; they are not a limiting factor to sorghum and millet production in the area. The main cause for unstable agricultural production is, however, the high spatial and temporal variation in rainfall.

One way of maximizing yields is to fit the growing period of a crop to that of moisture availability. The heading stage should coincide with the end of the wet period, especially for the late photosensitive varieties. Sorghum and millet are grown as rainfed crops in most of the area; sorghum is cultivated south of the 500-mm isohyet, and millet between the 250- to 500-mm and 1000-mm isohyets, because there is a heavy risk of smut beyond the 1000-mm limit. Both crops are grown between the 500- and 1000-mm isohyets, depending on land availability and consumer requirements and preferences.

The influence of the photoperiod on the duration of late sorghum varieties in the area and that of crop duration on yield are examined. The effect of certain agroclimatic factors is analyzed for millet.

Introduction

Sorghum and millet are grown over large areas throughout the world because of their wide adaptability and their importance as human and animal food. Their cultivated area ranks second after rice. Only climatic characteristics of the sorghum- and millet-cultivating areas of the West African semi-arid tropics (SAT) will be discussed in this paper.

The West African zone lying between the wet equatorial forest and the Sahara desert has a wide range of environments having certain physical and biological characteristics in common.

The area is covered by steppe or tropical bush vegetation over broken tracts of grassland (mainly perennial grasses).

The semi-arid area extends over a large 4000-km belt from the Atlantic Ocean to the Sudan-Chad

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*Agrometeorology Division, National Meteorology Office, Mali.

Note: This is an edited English translation of the original French paper immediately preceding.

International Crops Research Institute for the Semi-Arid Tropics. 1984. Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics: Proceedings of the International Symposium, 15-20 Nov 1982, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

frontier; its width varies between 300 and 800 km. It covers several countries including Senegal, Mauritania, Mali, Upper Volta, Ghana, Togo, Benin, Niger, Nigeria, Chad, and Cameroon (Fig. 1).

Sorghum and millet are the two main food crops of the semi-arid regions and rank fourth and fifth among the most important cereals in the world.

Sorghum was probably introduced into West Africa at a relatively recent date—from Ethiopia through Sudan and down the upper Niger river. Millet probably originated in the West African savanna. These crops are mainly grown for human consumption and constitute the most important source of calories in Africa.

West Africa provides 15% of the total production of sorghum in the SAT. The crop is mainly concentrated in the area south of the 500-mm isohyet. The main producers are Ghana, Niger, Nigeria, and Upper Volta. Millet is grown north of the 1000-mm isohyet; the southern limit lies between the 250- and 500-mm isohyets. Both crops are grown between the 500- and 1000-mm isohyets depending on the availability of land (Table 1).

Climatic Characteristics of the Zone

Air Circulation and Weather Types

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

West Africa's climate differs from that of the tropical regions because of its geographic situation. Weather changes in the area are brought about by three subtropical anticyclones—Azores anticyclone, Lybyan anticyclone, and the Saint Helena anticyclone. The air subsides and accumulates gradually within these cyclones and it is hot and dry at the surface. Due to the relatively high pressure, the air tends to escape partly towards the north and partly towards the equator. Deflected by the earth's rotation, the air is deviated to the right in the northern hemisphere where it gives rise to the trade winds that blow from northeast to southwest; in the southern hemisphere this air is deviated to the left, where the trade winds blow from southeast to northwest. These trade winds from the high-pressure areas of the two hemispheres bring together characteristically different air masses—those from the northern hemisphere are hot and dry

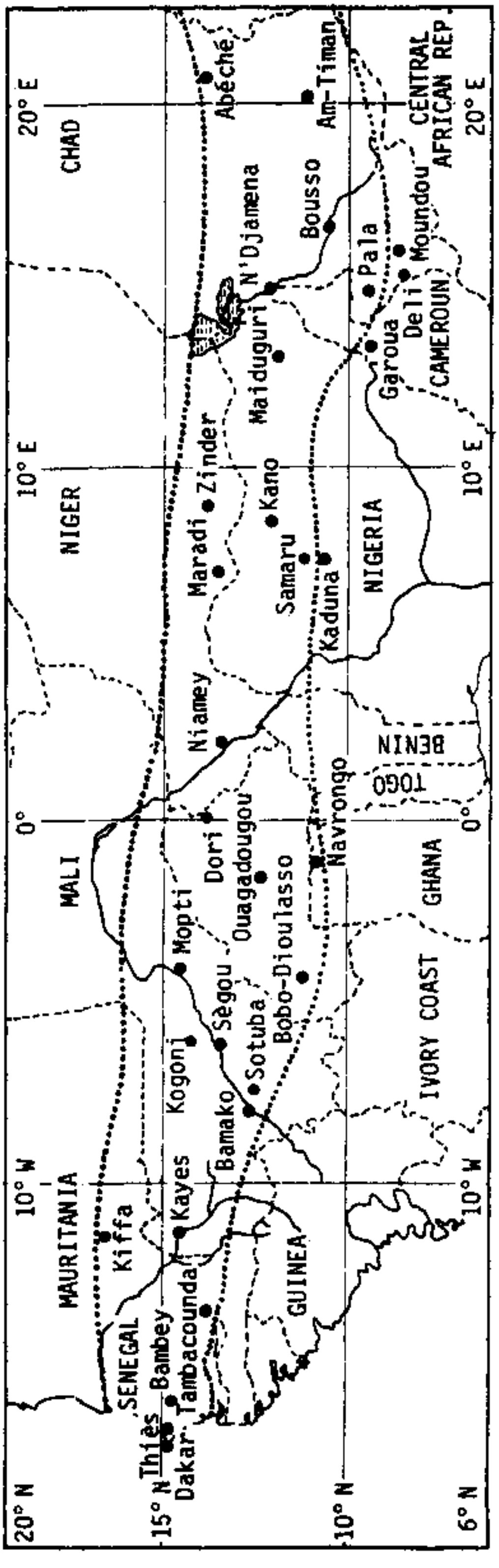

Figure 1. The zone under study (within dotted lines). (Source: Cochemé and Franquin 1967.)

Table 1. Distribution of sorghum and millet cultivation zones according to climate.[1]

	Crop		Average annual rainfall
Zone	Main	Secondary	(mm)
Sub-arid		MilletS[2]	250
Semi-arid	Region A		
	Millet S		350
	Region B		
	Millet M Sorghum S-M	Millet S Sorghum S	550
	Region C		
	Millet M-L Sorghum M-L	Millet Sorghum	800
	Region D		
	Sorghum L Millet L	Millet S Sorghum S	1000

Source: Cocheme and Franquin (1967)

1 The top of the table corresponds to the north

2. S = short-duration; M = medium-duration; L = long-duration

and those from the southern hemisphere are hot and wet. They meet at the intertropical conversion zone (ITCZ) or the intertropical front (ITF). Satellite observations have confirmed that the ITCZ is a narrow band of giant cumulus convection clouds. This front moves from north to south according to the seasons and is influenced by changes in the position and direction of the three anticyclones. It follows approximately the same course as the sun but after a 6-week interval. In West Africa, the ITCZ reaches the northern limit (20-25°N) in August and the southern limit (5°N) in January-February (Fig. 2).

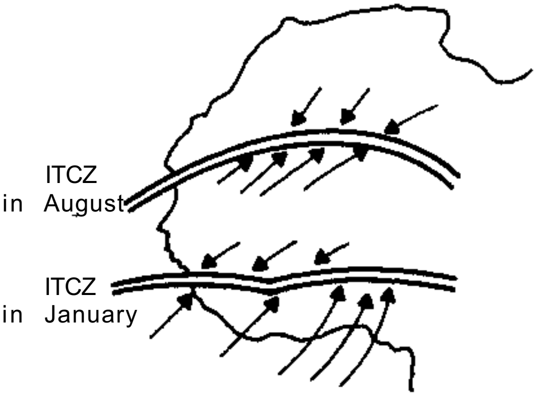

Figure 2. Extreme positions of the Intertropical Convergence Zone (ITCZ) in West Africa.

In the first case, the region is swept by a southwesterly current from the Saint Helena anticyclone, which collects moisture while passing over the ocean. This is the monsoon that brings in heavy rainfall and with its passage the rainy season sets in over the region. In the second case, the Azores and Lybyan anticyclones move towards the area from the north to northeast and the east, respectively. The hot, dry current from the eastern sector is called the *harmattan* and is typical of the Sahelian zone from November to May. Rainfall only occurs in those areas that are situated south of the ITCZ and provide favorable conditions for convection to take place.

The disturbance line and the ITCZ are characteristic meteorological phenomena of West Africa. These are dynamic turbulences made up of longitudinal bands of cumulonimbus clouds that move from east to west, bringing in most of the rain falling in the area.

Rainfall occurs as a result of the northward movement of the ITCZ; the disturbance line is an important source of rainfall. On a large scale the rainfall pattern is very regular because of the geographic uniformity of the region.

Other Agroclimatic Factors

This brief description of the air circulation pattern also explains other important factors related to agriculture. Seasonal changes are represented by the wind pattern—winds from the northeast occur during the dry season and those from the southwest during the rainy season. The dry northeastern regime may sometimes return for a short period at the start of the rainy season, causing serious damage to the young crops. Temperatures close to the surface depend on the position of the ITCZ and related meteorological conditions, since solar radiation at the top of the atmosphere is almost constant.

Temperatures are lower during the monsoon and higher when the harmattan blows. Similarly, the monsoon air is initially more humid and, at the surface, this humidity increases due to evaporation.

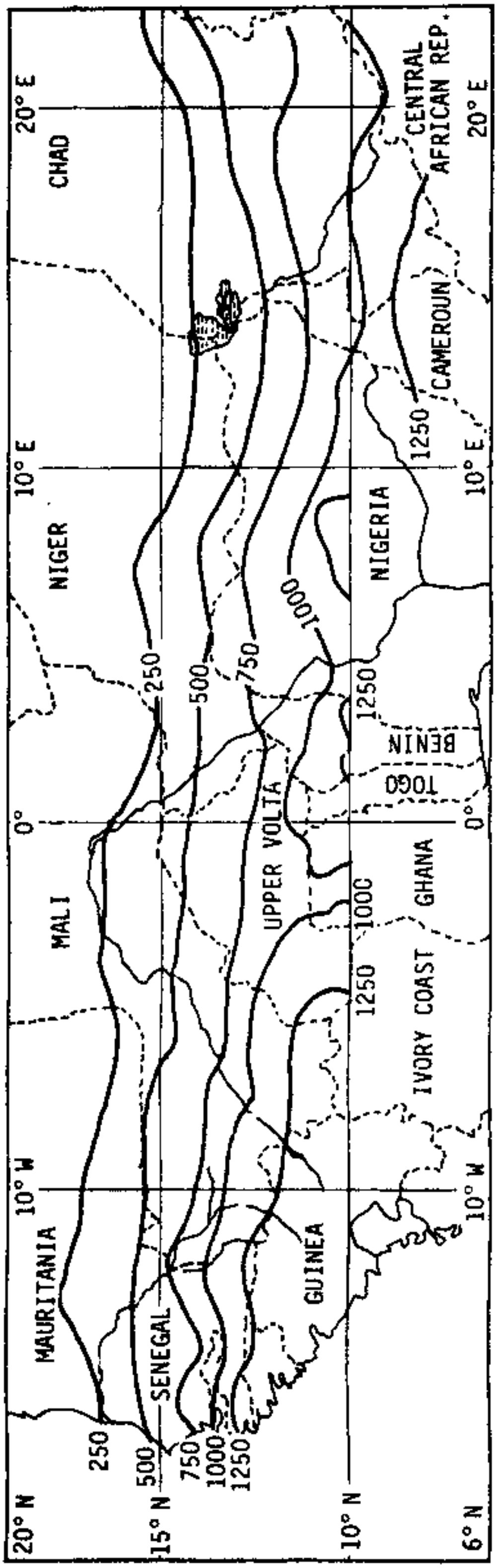

Figure 3. Average annual isohyets of the zone. (Source: Cochemé and Franquin 1967.)

Climatic Environment of Sorghum and Millet Cultivation Zones

Rainfall

Water—its quantity and distribution—is the most important factor for sorghum and millet production in this area.

We have seen earlier that rainfall mainly occurs as a result of the northward movement of the ITCZ, which passes over the same location twice a year. The interval between these two periods determines the rainy season for the location. Generally, the rainy season grows shorter at higher latitudes. Annual rainfall also decreases in the same manner and may vary between 250 mm and 1250 mm; it is distributed in bands running parallel to the equator, with some local variation (Fig. 3). On the other hand, interannual variation in rainfall increases from south to north. Figure 4 shows a central zone where rainfall exceeds 500 mm and the coefficient of variability is less than 20%. In the regions on each side of this central zone (western Senegal and *north* of Lake Chad), variations in rainfall are relatively high.

According to Auberville's climatic classification, the area under study is divided into the Sahelo-Saharan zone (250-500 mm), the Sahelo-Sudanese zone (500-900 mm) and a part of the Sudano-Guinean zone (900-1250 mm).

Water-availability Period and Crop-growing Period

Average rainfall values do not indicate the dependable character of rainfall. Hargreaves (1975) has defined dependable precipitation as the amount of rainfall that may be expected to occur 3 out of 4 years. Thus, in the absence of adequate information on the type, depth, moisture-retention capacity, and other characteristics of the soil, the moisture availability index (MAI)[1] could give an approximate idea of moisture available for crop growth.

The monthly MAI values during the sorghum- and millet-growing period are given in Table 2 The

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[1] Ratio of dependable rainfall to potential evapotranspiration. Classification proposed by Hargreaves (1975): MAI = 0.00 to 0.33 = very deficient; 0.34 to 0.67 = moderately deficient; 0.68 to 1.00 = somewhat deficient; 1.01 to 1.33 = adequate moisture; >1.34 = excess moisture.

MAI values are very low in June in the northern zone and in October and November over the entire region. The moisture available for sorghum and millet crop growth is almost adequate from July to September in the northern zone. In the southern zone, it is moderately deficient in June and excessive from July to September.

The quantity of moisture available does not depend exclusively on rainfall. Part of the moisture from rainfall is lost through evaporation from the soil and transpiration by plants (evapotranspiration), and the rest through infiltration or drainage. Available moisture is therefore a balance between the amount received and lost in the rhizosphere. Using the two purely climatic terms of the water balance—rainfall and potential evapotranspiration—Cocheme and Franquin (1967) have determined the periods of water availability (Fig. 5); this is particularly useful in agricultural planning.

Table 3 presents the dates and duration of the water-availability periods for 35 stations south of the Sahara in Africa.

The preparatory period. Rainfall is between 0.1 PET and 0.5 PET. This is a period for preparing fields or for dry seeding, especially of millet crops. Its duration varies from more than 50 to less than 20 days.

The humid period. Rainfall exceeds potential evapotranspiration, and actual evapotranspiration attains PET values. This period is favorable for flowering; sorghum and millet give the best yields when flowering occurs just before the end of this period. The duration of the humid period varies from 0 days in the north to 140 in the south.

The intermediate periods (pre- and post-humid periods). Rainfall exceeds or is equal to 0.5 PET but remains less than PET. Rainfall is very variable at this time. Sorghum and millet are planted in the pre-humid period and the planting-heading period should correspond to the pre-humid to humid period interval. The crop matures during the post-humid period and the decrease in crop water requirements coincides with that of rainfall. The intermediate periods are generally of constant duration.

The moist period. This covers the humid and intermediate periods. As the water stored in the soil is still being used by the crop even after the rains have receded, this period is considered as the

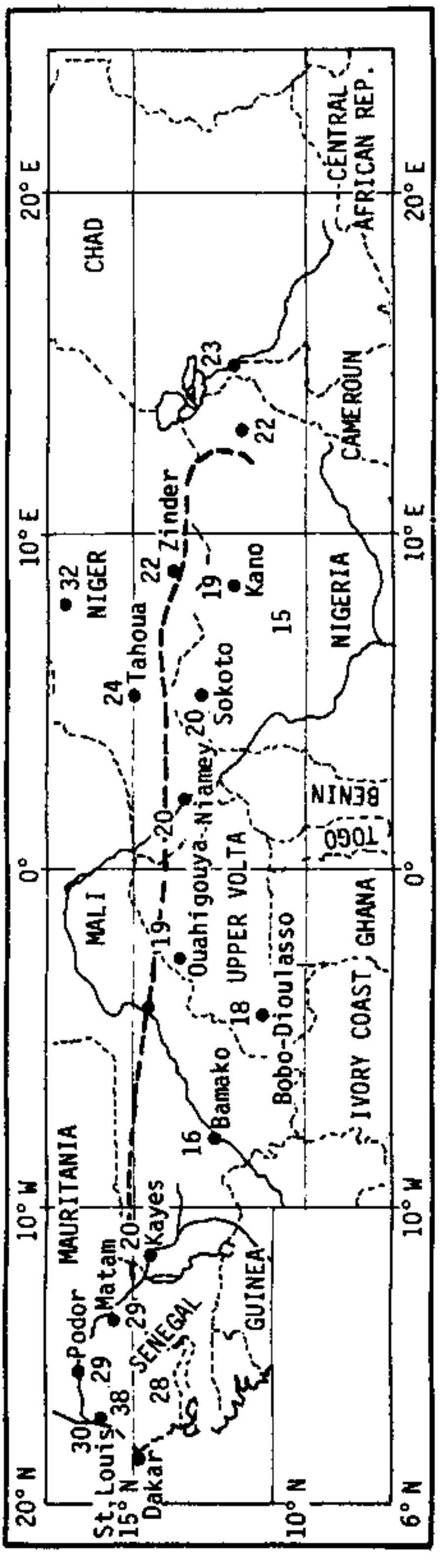
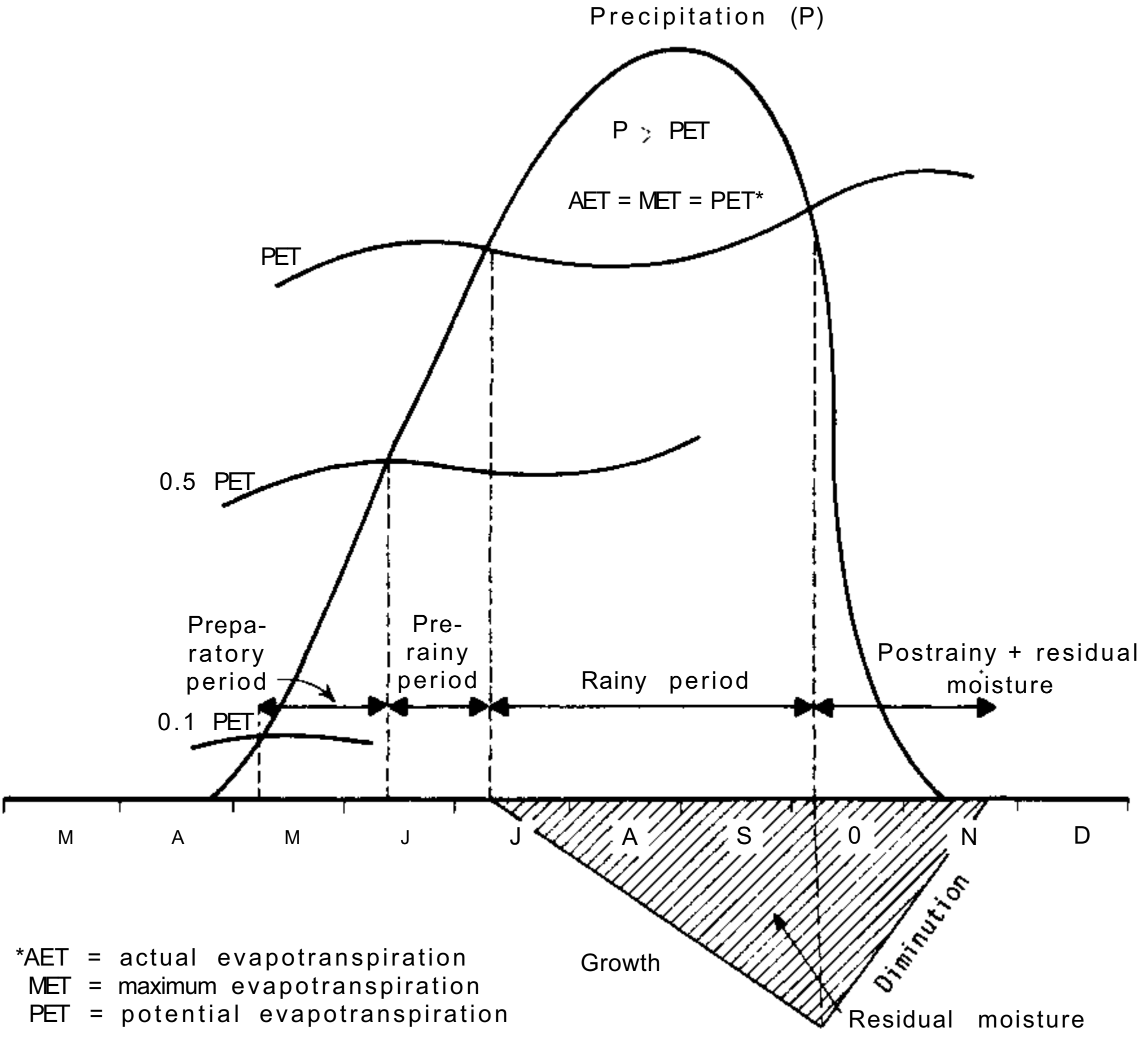


Figure 4. Area distribution of the coefficient of variation of rainfall. The broken lines demarcate the parts of the zone where the coefficient is below 20%. (Source: Cochemé and Franquin 1967.)

Table 2. Moisture availability index (MAI) during the sorghum- and millet-growing period at selected locations.

Location	June	July	Aug	Sept	Oct	Nov
Bambey (Senegal)	0.05	0.56	1.18	0.93	0.13	0.00
Tambacounda (Senegal)	0.53	1.34	1.95	1.46	0.24	0.00
Bamako (Mali)	0.70	1.56	2.27	1.32	0.20	0.00
Niono (Mali)	0.20	0.72	1.13	0.55	0.04	0.00
Niamey (Niger)	022	0.69	1.16	0.47	0.02	0.00
Pala (Chad)	1.00	1.69	1 92	1.37	0.22	0.00
N'Djamena (Chad)	0.19	0.81	1.53	0.52	0.03	0.00
Ouagadougou (Upper Volta)	0.50	1.03	1.72	0.78	0.06	0.00
Dori (Upper Volta)	018	0.68	1.04	0.45	0.02	0.00
Kano (Nigeria)	0.48	1.07	1.76	0.59	0.00	0.00



*AET = actual evapotranspiration
MET = maximum evapotranspiration
PET = potential evapotranspiration

Figure 5. Periods of moisture availability.

Table 3a. Average dates for the beginning and end of the moisture availability period.

		Date					
Location	Rainfall (mm)	Prepa-ratory period begins	Prepa-ratory period ends	Rainy period begins	Rainy period ends	Wet period ends	Wet period + residual moisture ends
Agades	164	-	-	-	-	-	-
N'Guigmi	235	20/06	23/07	-	-	3/09	3/09
Gao	261	27/05	2/08	-	-	25/08	25/08
St.-Louis	346	21/06	22/07	7/08	25/08	28/09	2/10
Tahoua	406	26/05	6/07	-	-	8/09	8/09
Abeche	505	9/05	29/06	18/07	4/09	15/09	1/10
Matam	535	4/06	30/06	22/07	9/09	30/09	17/10
Mopti	552	16/05	25/06	15/07	7/09	27/09	8/10
Zinder	548	5/05	25/06	16/07	4/09	15/09	3/10
Dakar Yoff	578	15/06	9/07	25/07	20/09	9/10	29/10
Birni N'Konni	600	4/05	23/06	19/07	8/09	23/09	22/10
Niamey	638	28/04	20/06	10/07	6/09	24/09	16/10
Maradi	642	30/04	22/06	11/07	10/09	27/09	20/10
N'Djamena	648	1/05	20/06	10/07	10/09	26/09	18/10
Maiduguri	659	3/05	17/06	5/07	11/09	29/09	17/10
Thies	694	6/06	30/06	18/07	1/10	13/10	8/11
Segou	724	15/05	13/06	2/07	17/09	30/09	20/10
Sokoto	734	19/04	10/06	5/07	21/09	3/10	20/10
Kayes	821	15/05	11/06	3/07	21/09	11/10	1/11
Maroua	841	19/04	25/05	22/06	25/09	6/10	24/10
Mongo	858	18/04	16/06	28/06	25/09	8/10	29/10
Kano	871	23/04	28/05	25/06	16/09	30/09	19/10
Kaele	878	6/04	24/05	21/06	26/09	8/10	20/10
Ouagadougou	882	15/04	22/05	24/06	22/09	6/10	28/10
Am-Timan	919	10/04	17/05	20/06	24/09	9/10	29/10
Bousso	931	14/04	25/05	18/06	28/09	10/10	2/11
Tambacounda	941	15/05	2/06	19/06	6/10	20/10	12/11
Garoua	1013	1/04	6/05	9/06	1/10	14/10	1/11
Pala	1044	28/03	8/05	5/06	4/10	20/10	9/11
Navrongo	1095	17/03	2/05	13/06	3/10	14/10	2/11
Bamako	1099	19/04	26/05	17/06	2/10	14/10	6/11
F. Archambault	1141	23/03	2/05	1/06	8/10	23/10	17/11
Bobo-Dioulasso	1185	14/03	1/05	15/06	3/10	17/10	6/11
Moundou	1228	27/03	27/04	24/05	11/10	27/10	21/11
Kaduna	1298	19/03	22/04	20/05	9/10	21/10	10/11

Source: Cocheme and Franquin (1967)

humid period with storage. It should be compared to the crop-growing season. Its duration varies from 55 to 200 days. The ratio between rainfall (mm) and duration (in days) of the humid period with storage has an average value of about 5.5 for the area under study.

The growing season for sorghum and millet crops ranges from 80 to 250 and from 60 to 200 days, respectively (Cocheme and Franquin 1967). Since millet seedlings are drought-tolerant, early plantings can be carried out during the preparatory period, in order to extend the effective moist period. Thus, the minimum water-availability period for a millet crop is about 50 days. On the basis of the earlier ratio between rainfall and duration of the humid period with storage, the sorghum-growing

Table 3b. Average duration of moisture availability periods.

Location	Duration (days) Preparatory period	Prerainy period	Rainy period	Post-rainy period	Wet period	Residual moisture period	Wet+ Residual moisture period
Agades	-	0	0	0	0	0	0
N'Guigmi	33	-	0	-	42	-	(42)[a]
Gao	67	-	0	-	23	-	(23)
St-Louis	31	16	18	34	68	4	72
Tahoua	41	-	0	-	64	-	(64)
Abeche	51	19	48	11	78	16	94
Matam	26	23	49	21	93	17	110
Mopti	40	20	54	20	94	11	105
Zinder	50	21	50	11	82	18	100
Dakar Yoff	24	16	57	19	92	20	112
Birni N'Konni	50	26	51	15	92	29	121
Niamey	53	20	58	18	96	22	118
Maradi	53	19	61	17	97	23	120
N'Djamena	50	20	62	16	98	22	120
Maiduguri	45	18	68	18	104	18	122
Thies	24	18	74	13	105	25	130
Segou	29	19	77	13	109	20	129
Sokoto	52	25	78	12	115	15	130
Kayes	27	22	80	20	122	21	143
Maroua	36	28	95	11	134	18	152
Mongo	59	12	89	13	114	21	135
Kano	35	27	83	14	124	19	143
Kaele	46	27	97	12	136	12	148
Ouagadougou	37	33	90	14	137	22	159
Am-Timan	37	34	96	15	145	20	165
Bousso	41	24	102	12	138	23	161
Tambacounda	18	17	109	14	140	23	163
Garoua	36	34	114	13	161	18	179
Pala	41	28	121	16	165	20	185
Navrongo	46	42	112	11	165	19	184
Bamako	37	22	107	12	141	23	164
F. Archambault	43	27	129	15	171	25	196
Bobo-Dioulasso	48	45	110	14	169	20	189
Moundou	31	27	140	16	183	25	208
Kaduna	34	28	142	12	182	20	202

Source: Cocheme and Franquin (1967)

a. When there is no rainy period, the figures in the last column appear within parentheses.

area would be situated between the 440- and 1375-mm isohyets, and the millet-growing areas between the 275- and 1100-rnm isohyets.

Radiation

Radiation is a source of different forms of energy used by the plants for metabolic processes and dry-matter production. Crops use only 2 to 4% of the global radiation for photosynthesis.

Annual global radiation based on hours of sunshine varies between 160 and 180 Kcal/cm^2, i.e., 440 to 500 cal/cm^2 per day (Cocheme and Franquin 1967). Zonal distribution increases from south to north. Seasonal variation is relatively low, however, with a peak before and after the rains and a maximum in winter (Fig. 6).

Temperature

A qualitative and quantitative analysis of the effect of temperature shows that qualitatively the occurrence of certain threshold temperatures may influence crop development and growth. Quantitatively, overall growth and the various phases of development can be related to the amount of energy represented by temperature.

In the area, temperatures are high, with seasonal variation including two maxima and two minima.

Table 4 shows that the maximum temperatures vary between 28 and 42°C. In the central and southern parts of the zone they are generally less than 35°C and sometimes even around 30°C—except in October, November, and sometimes June—whereas in the north they are almost always higher than 35°C. The minimum temperatures remain between 15 and 28°C. The diurnal range of temperature is much higher in winter than in summer as night radiation losses are much lower in summer.

Base temperature for sorghum germination ranges between 10 and 15°C while the ambient temperature may be 28°C.

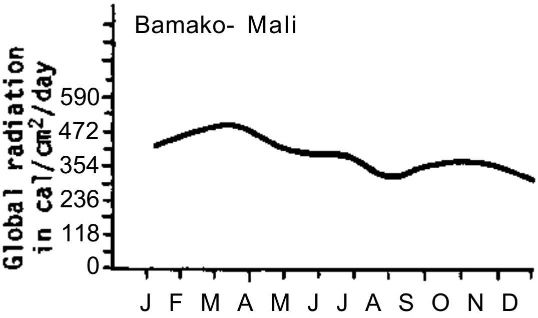


Figure 6. Seasonal variation in the monthly average of global radiation in the zone. (Source: Cocheme and Franquin 1967.)

Cocheme and Franquin (1967) have studied the occurrence of threshold temperatures during the periods of water availability (Table 5). Minimum temperatures falling below 15°C are only recorded in winter but do not occur during the growing periods of sorghum and millet rainfed crops. However, the crop could be affected by very high temperatures. Table 4 shows maximum temperatures exceeding 40°C, but these do not occur during either the humid or the moist period.

Table 4. Maximum and minimum air temperatures (°C) during the sorghum- and millet-growing period at different locations of the zone.

Location	June	July	Aug	Sept	Oct	Nov
Bamako (Mali)	34.7	31.5	30.2	31.5	33.9	34.9
	23.3	22.1	21.7	21.6	21.4	18.4
Navrongo (Ghana)	32.7	30.7	29.6	30.6	33.4	35.9
	23.2	22.5	22.3	21.9	21.9	20.1
Maiduguri (Nigeria)	361	31.8	30.5	32.2	35.4	35.2
	23.6	22.1	21.7	21.6	19.7	15.4
Ouagadougou (Upper Volta)	34.5	31.8	30.7	32.2	34.9	35.6
	23.8	22.5	21.8	21.9	22.4	18.9
Niamey (Niger)	37.8	34.0	32.5	34.4	37.0	35.9
	25.9	23.8	22.8	23.4	23.5	19.0
Dakar (Senegal)	28.6	29.7	30.0	30.3	30.7	29.1
	23.0	24.4	25.0	24.6	24.4	21.9
N'Djamena (Chad)	37.8	33.8	31.0	33.2	36.5	36.3
	24.6	23.2	22.1	22.1	21.5	16.8
Kandi (Benin)	31.8	29.4	28.5	28.8	33.8	35.0
	21.3	20.3	19.8	19.4	21.2	17.1
Kiffa (Mauritania)	41.9	38.8	36.5	37.2	38.5	34.8
	28.4	27.3	25.5	25.3	23.7	18.6

Table 5. Occurrence of certain threshold temperatures In the zone.

	Maximum (40°C)				Minimum (15°C)		
	Mar	Apr	May	June	Jan	Feb	Dec
Agades		0		0	0	0	0
N'Guigmi					0	0	0
Gao		0	0	0	0	0	0
Tahoua		0	-10[a]				
Abeche		0	-10				
Matam		-10	10		0		
Mopti		0	-10		0		
Zinder		0			0		
Dakar Yoff							
Birni N'Konni		0	-10				
Niamey		-10					
Maradi		-10			0	0	0
N'Djamena		0	10		0		
Maiduguri		0			0	0	0
Thies							
Segou							
Sokoto							
Kayes		0	-10				
Maroua							
Mongo	0	-10					
Kano					0	0	0
Ouagadougou							
Am-Timan					0		0
Bousso							
Tambacounda		0					
Garoua							
Pala							
Navrongo							
Bamako							
F. Archambault							
Bobo Dioulasso							
Moundou							
Kaduna							

Source: Cocheme and Franquin (1967)

a. -10 = Part of the preparatory period
10 = Preparatory period

Soils

The water-availability and growing periods calculated above only take into consideration the water supply and demand at a given location. The properties of the soil profile influence moisture retention, runoff, and drainage as well as water loss through evaporation and transpiration.

The soils of the region have evolved according to the climatic conditions and topography of the area and are a result of the paleoclimates, mainly the alternate dry and wet climates of the Tertiary and Quaternary eras.

The brown semi-arid soils are mainly sandy in the area north of the 500-mm average annual isohyet, where there is little migration, because of inadequate rainfall. The volumetric water content of these soils ranges from 12 to 15% at field capacity and from 3 to 4% at wilting point. These soils, because of their coarse texture, are particularly suited to millet crops. In the most important sorghum-growing area lying between the 500- and 1000-mm isohyets, ferruginous soils occur where a certain amount of migration and accumulation of iron and clay form a less permeable and shallow layer. Their volumetric water content varies from 17 to 22% at field capacity and from 7 to 8% at wilting point.

Ferralitic soils occur in the extreme south and alluviums mainly made up of clay and silts are scattered in the basins of the Senegal and Niger rivers and of Lake Chad.

Some Aspects of Photoperiodic Response of Sorghum Crops in the Area

There are two ways in which light influences sorghum crops—through daylength, or photoperiod, and intensity. The intensity of light and the temperature influence dry-matter production.

There is very little seasonal variation in daylength in this area from 1.5h in the north to 0.5 h in the south (Cocheme and Franquin 1967).

The growing period of rainfed crops occurs at a time when the days are longest at all latitudes; flowering of locally adapted crops occurs as the days grow shorter.

Phenological data on nine late varieties of sorghum (Table 6) show that for crops planted between April and August, heading occurred in October when the days are shorter; thus, the growing period is gradually reduced, which proves the influence of photoperiodism on the flowering of late sorghums. When the crops are planted between April and September, the number of internodes, functional leaves, and grains per panicle varies according to the length of the planting to heading period.

Based on these observations, Cocheme and Franquin (1967) determined a parabolic relationship between the productivity of late sorghum va-

Table 6. Mean phenological data on staggered monthly sowings of nine late-maturing sorghum varieties at Deli (Chad) near the southern limit of the zone. Sowing was done at the beginning of each month.

N°	Apr	May	June	July	Aug	Sept	Oct	Nov
1 [a]	189	163	136	110	92	78	82	94
2	5 May	10 Oct	13 Oct	18 Oct	30 Oct	16 Nov	12 Dec	1 Jan
3	5095	4295	3515	2815	2355	2070	2205	2455
4	6055	5085	4150	3220	2790	2485	2780	3285
5	4140	3505	2875	2305	1925	1645	1635	1630
6	12.42	12.42	12.39	12.31	12.17	12.00	11.80	11.69
7	25,1	21 3	18.0	14.5	10 6	8.2	7.6	6.5
8	80	6.4	4.9	4.1	3.3	-	3.2	4.0
9	475	400	350	345	270	-	145	105
10	915	840	680	385	60			

Source Cocheme and Franquin (1967)

a. 1 - Days to heading; 2 = Heading date; 3,4.5 = Sum of average, maximum, and minimum temperatures for the sowing-heading period; 6 = Average duration of daylight (in hours and 1 /100 hour); 7 = Number of internodes; 8 = Number of functional (green) leaves; 9 = Leaf area (cm^2): 10 = Number of grains/panicle

rieties and the sum of temperatures between planting and heading (Fig. 7). This relationship gives the optimum value of the sum of temperatures that determines maximum production of a given variety and also helps to determine the optimum planting date when the heading date of the variety is known.

Several authors have studied the influence of the planting date on yields of local or improved photosensitive varieties of sorghum. Since heading occurs at the end of the rainy season, yields mainly depend on the moisture stored in soil. However, if heading is delayed because of a late planting or an early recession of the rains, grain filling will be incomplete. In an experiment conducted at Samaru, Nigeria, plantings were staggered over 8 to 10 weeks. It was found that there was a linear relationship between the heading and planting dates for a local sorghum variety during a normal season.

When the crop was planted between 12 and 16 May, heading occurred on 6 October, but after this date, for every week of delay in planting, heading was delayed by 0.9 to 1.3 days (Curtis 1968; Andrews 1973, cited by Kassam 1976).

When the rains receded earlier, heading was delayed by 2 days for every week of delay in planting. A crop planted on 16 May still produced heads on 6 October; but after 30 May a 1-week delay in planting reduced yields by about 200 kg/ha, or 12.5% of maximum yield (Andrews 1973). The same author has shown that for each week of delay in planting after the optimum date in May and early June, yield losses were about 300 to 600 kg/ha or about 15% of maximum yield.

Kassam and Andrews (1975) have shown that with an improved highly photosensitive sorghum

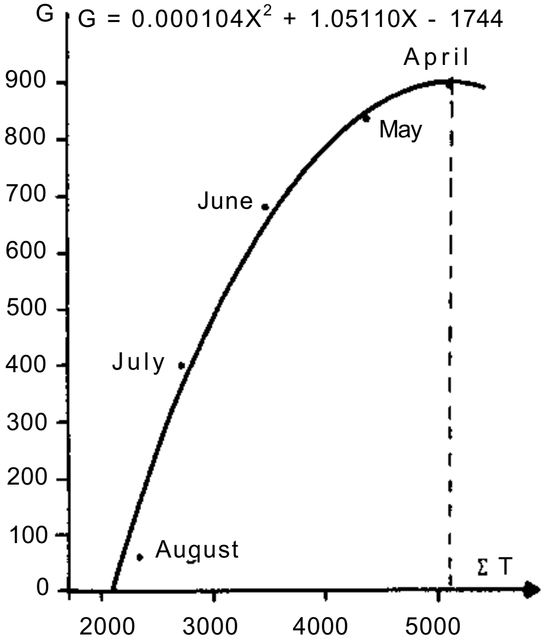


Figure 7. Production curve (number of grains/ panicle) of a late-maturing variety based on the sum of temperatures between planting and heading. (Source: Cocheme and Franquin 1967.)

Table 7. Values of yield, rainfall, and the climatic variables.

Year	Yield (kg/ha)	Rainfall (mm)	X_1	X_2	X_3	X_4	X_5	X_6
1950	670	1270	9.5	148	-	896	30	40
1951	790	940	10.0	227	10	470	40	107
1952	1440	885	9.0	101	24	413	25	95
1953	1330	755	9.0	62	5	305	20	82
1954	1230	745	7.5	2	58	360	0	51
1955	1770	780	8.5	15	16	380	10	58
1956	1060	640	6.0	47	54	170	15	155
1957	1100	670	7.0	77	6	284	20	124
1958	1220	820	6.5	39	46	492	5	61
1959	910	460	5.5	-	13	150	5	101
1960	1040	790	8.0	14	14	380	15	73
Mean	1141.8	796	7.8	66.5	21.5	390.9	16.8	86.1

Source: Cocheme and Franquin (1967)

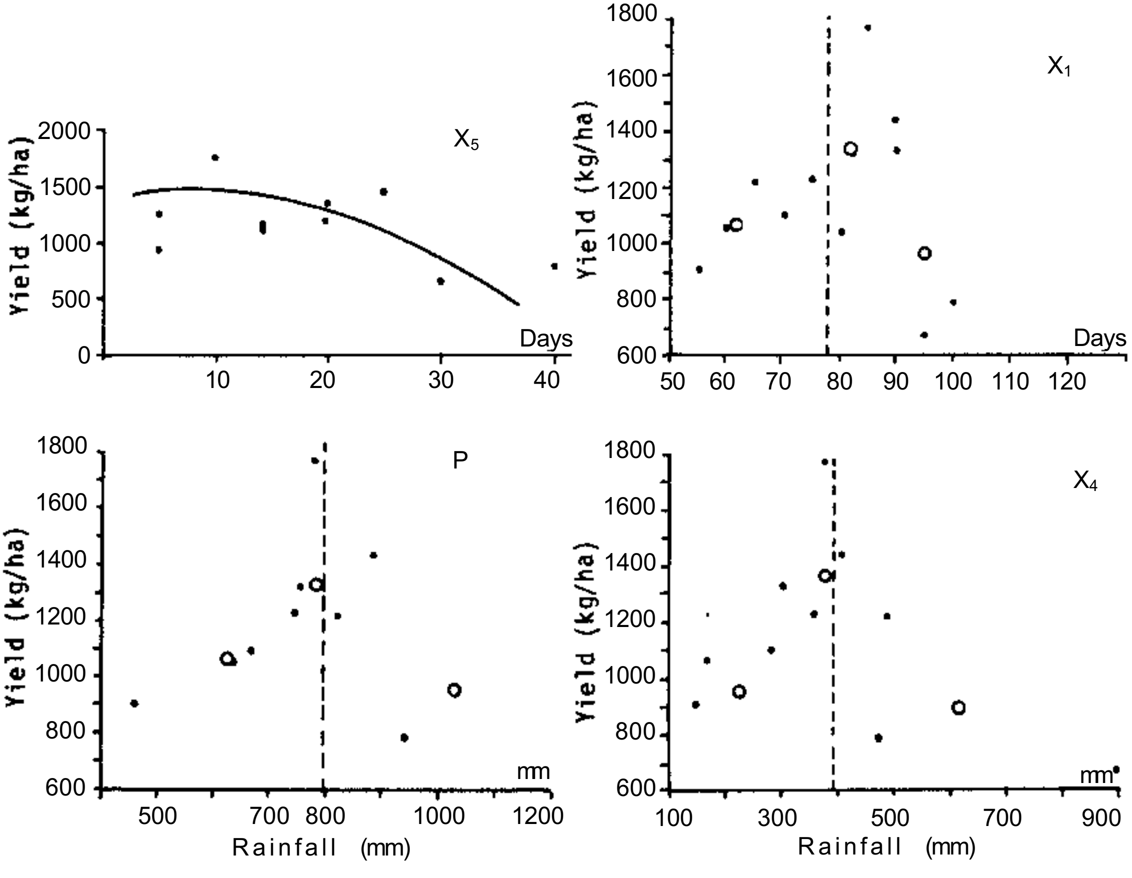


Figure 8. Scatter diagram of yield versus P, X_1, X_4, and X_5. The larger ringed dots show the mean position of classes of the independent variables. (Source: Cocheme and Franquin 1967.)

variety of 190 days, a week's delay in planting could not be fully compensated and even a day's delay in flowering reduced the number of heads per plant and the number of grains per head.

Influence of Certain Climatic Factors on Millet Yields

Using production data collected over 11 years at Bambey, Senegal, Cocheme and Franquin (1967) studied the relationship between millet yields and certain agroclimatic variables—P, annual rainfall; X_1, duration of the humid period; X2, total rainfall for the month of October; X3, total rainfall for the post-humid period; X_4, excess water; X_5, interval between heading and the end of the humid period; X_6, total rainfall for the pre-humid season (Table 7).

There is a curvilinear relationship between each of the variables, P, X_1, X_4, and X_5, and yield (Fig. 8). These results show that even in the semi-arid zones too much water or excessively long wet periods can reduce production even in an adapted variety.

Therefore, millet crop yields in the area are not necessarily more than average even if annual rainfall is above normal.

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Agricultural Climatology of Sorghum—The Americas

R.E. Neild*

Abstract

Nearly 51 million hectares of sorghum, producing 67 million tonnes of grain are harvested in the world each year. Although only 19% *of this area is in the Americas, it yields 48% of the total grain produced. The advent of the new hybrids around the year 1960 has had a dramatic impact on sorghum production in the Americas. This paper describes procedures involving agroclimatic parameters developed from monthly climatic summaries; these were used to compare the phenological responses of sorghum hybrids at different locations in the U.S. Great Plains, the Argentine pampas, and Mexico, which grow 90% of the sorghum in the Americas.*

Résumé

Agroclimatologie du sorgho en Amérique : Les 51 millions d'hectares cultivés en sorgho dans le monde produisent chaque année 67 millions de tonnes de grain. Seulement 19% de ces superficies sont situées en Amérique, mais le rendement représente 48% de la production mondiale. L'introduction de nouveaux hybrides, vers 1960, a eu un effet très significatif sur la production de sorgho. Cette communication décrit comment les paramètres agroclimatiques tirés des relevés climatiques mensuels ont permis de comparer les réactions phénologiques des hybrides de sorgho cultivés aux différents emplacements sur les grandes plaines des Etats-Unis, les pampas d'Argentine et au Mexique, où sont concentrées 90% des cultures de sorgho en Amérique.

Sorghum (*Sorghum bicolor*) and millets (*Pennisetum, Setaria,* and *Panicum* sp) rank third—after wheat (*Triticum vulgare*) and rice (*Oryza sativa*)—among the world's most important food grains. Wheat, rice, maize (*Iea mays*), and soybean (*Glycine max*) are grain commodities in international commerce. These crops are also extensively researched for means to increase yield. But grain sorghum has received much less attention. Except in the USA and other American countries where it is primarily produced for livestock feed, most of the world's sorghum is directly consumed by the poor people who grow it. More information is needed about the requirements of grain sorghum and the locations where it is grown.

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), funded by the Consultative Group on International Agricultural Research (CGIAR) and, more recently, the International Sorghum/Millet Research Program (INTSORMIL), funded by the United States Agency for International Development (USAID), are two major programs, worldwide in scope, that are directed toward improving grain sorghum production. The INTSORMIL program is composed of different projects led by 22 scientists from agricultural experiment stations in 8 states, linked with 26 scientists and/or students in 12 different countries.

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My project with INTSORMIL, the "Agricultural Climatology of Sorghum," has the following objectives:

1. To describe the growing cycle of grain sorghum in terms of climatic requirements.
2. To complete a comparative climatological analysis of sorghum-growing seasons and regions in the USA and other developed countries.
3. To characterize and categorize the climatic conditions in seasons and regions growing sorghum in developing countries throughout the world.
4. To construct crop-weather models to predict the development and yield of grain sorghum.

This paper concerns the agroclimatology of grain sorghum in the Americas. It is based on information obtained in work on objectives 2 and 4.

Figure 1. Sorghum-growing regions in the Americas.

Sorghum-Growing Areas in the Americas

Nearly 51 million ha of sorghum, producing *67* million metric tons (tonnes) of grain, are harvested in the world each year. Although only 19% of this area is in the Americas, it yields 48% of the total grain produced (FAO 1979). Sorghum is grown in 19 of the 29 countries that constitute the Americas (Fig. 1). The USA, Argentina, and Mexico, the principal sorghum countries, produce 89% of the grain.

Sorghum was first domesticated in Africa in the area now called Ethiopia. The mountainous terrain and the diversity of climate in this area resulted in a large number of sorghum genotypes, adapted to a wide variety of environmental conditions. The recently developed high-yielding hybrids now grown in the U.S. Great Plains were derived from a diverse base of African and oriental sorghum strains. Early maturity, insect resistance, high yield potential, and dwarf plants suitable for mechanical harvest are some of the characters developed in these hybrids. Many are considered day-neutral in their photoperiodic response. These hybrids became available in the late 1950s and have had a significant impact on sorghum production in the Americas. An example of this impact can be seen in Table 1, which compares production statistics for sorghum in the state of Nebraska for different 20-year periods before and after hybrid sorghums were introduced during 1957, 1958, and 1959.

During the period 1937 to 1956, the yield of sorghum grain was 1054 kg/ha; during 1960 to 1979 it averaged 3684 kg/ha—a yield increase of 349%. Prior to the development of hybrids, about 100000 ha of sorghum were planted each year. When higher yielding dwarf hybrids became available for mechanical harvest, the area planted to sorghum increased over 7.5 times. With higher yields and more area planted, sorghum production in Nebraska increased about 27 times over the earlier period before the advent of the improved hybrids. These hybrids have displaced maize in a portion of the western subhumid part of the U.S. maize belt and have spread into other sorghum-growing regions of the Americas. Following is a

Table 1. Grain sorghum production in Nebraska before (1937-56) and after (1960-79) the introduction of high-yielding sorghum hybrids.

Period	Yield (kg/ha)	Area (ha)	Total production (tonnes)
1937-1956	1054	99897	105291
1960-1979	3684	764530	2816528
Increase (%)	349	765	2674

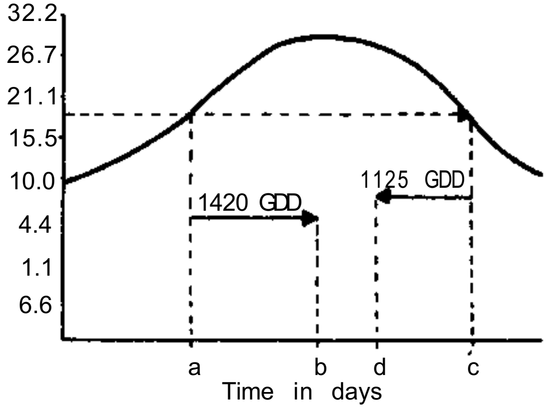
discussion of an agroclimatic procedure used to determine, evaluate, and compare the growing seasons for sorghum at different locations.

Procedures to Determine and Evaluate the Growing Season for Sorghum

Time and Length of Growing Season—Temperate Regions

In temperate regions, where moisture is adequate, the time and length of the sorghum-growing season is dependent on the seasonal temperature curve, the determination of which is similar to procedures developed by Neild and Grieg (1971) and Neild and Richman (1981) for other crops. It begins with and continues as long as the average daily temperature remains above 18.3°C (Logan 1981; Stoffer 1962). A procedure for determining the time and length of planting and growing season is graphically illustrated in Figure 2. The earliest planting date begins at point a. The time between a and c is the length of the sorghum season. The period in days between a and b is the growing season length for a full-season hybrid. The latest planting date, d, is determined by subtracting the growing degree-day (GDD) requirement for the particular sorghum strain from the seasonal accumulated GDD at point c. The time in days from a to d is the length of the planting season.

Summarized in Table 2 are the times of the possible beginning, ending, and length of the planting and harvest seasons for three locations along a north-to-south transect through the sorghum-growing region in the U.S. Great Plains. The temperature curve relative to the requirement for sorghum is such that sorghum can be planted earlier and the seasons are longer as we go south. Sorghum could be planted 8 weeks earlier at Luling, Texas, where the annual temperature averages 20.4°C than at Armour, South Dakota, where temperature averages 8.9°C. The length of the growing season decreases from south to north and is 209 days at Luling, 141 days at McPherson, and 108 days at Armour. The season is so short at Armour, near the northern temperature limit for sorghum, that there is only a brief period of 1 week during which sorghum can be safely planted. A similar relationship exists along a northward transect through the sorghum-growing region of the Argentine pampas.



a=beginning of growing season and earliest planting date
b = maturity date for earliest planting time (full-season hybrid)
c = ending of growing season and maturity date of early hybrid
d= latest planting date (early hybrid)

Figure 2. Procedure for determining growing season in temperate regions.

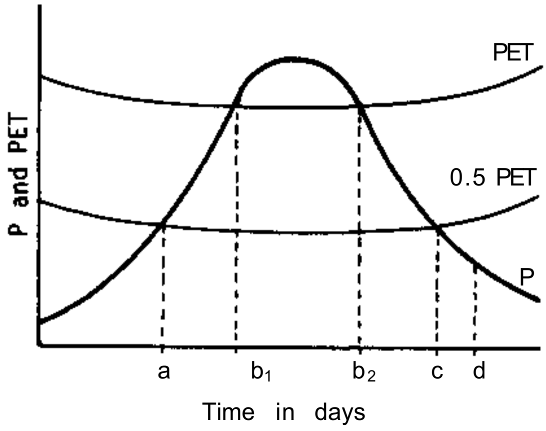
Table 2. Time and length of planting and growing seasons for sorghum in the U.S. Great Plains.

	Planting season				Growing season		
Location	Mean temp. (°C)	Earliest planting	Latest planting	Days	Begins	Ends	Days
Luling, Texas (29°40'N 97°40'W)	20.4	29 Mar	2 Aug	128	29 Mar	29 Oct	209
McPherson, Kansas (38°23'N 98°21'W)	13.4	7 May	2 July	56	7 May	25 Sept	141
Armour, South Dakota (43°19'N98°21'W)	8.9	23 May	30 May	7	23 May	8 Sept	108

Time and Length of Growing Season—Tropical Regions

In tropical regions where low temperature does not limit growth, the time and length of the growing season for sorghum is determined by the seasonal precipitation pattern. Kassam et al. (1978) and Kassam (1979) used precipitation data and computations of potential evapotranspiration (PET) (Thornthwaite 1948) to determine the growing seasons for crops in tropical Africa. This procedure is illustrated in Figure 3 and was used to determine the time and length of growing season for sorghum.

The first day (a) when the normal precipitation becomes equal to or greater than half the normal PET is the beginning of the growing season and earliest planting time. The last day of the growing season (c) is the day when the normal daily precipitation becomes less than half normal PET plus time required to evaporate 100 mm of stored moisture from the period when precipitation exceeds PET. The sorghum-growing seasons for different tropical areas in eastern and western Mexico are shown in Table 3. The growing season at Villahermosa, which receives 1902 mm of rainfall, is 333 days. At Apatzingan (716 mm rainfall), the season is only 125 days. A study by Kassam (1979) shows that a close relationship exists between the amount of annual rainfall and the length of growing season in Africa.



a=beginning of rains and growing period
b_1 and b_2=start and end of humid period, respectively
c = end of rains and rainy season
d = end of growing period
p = precipitation
PET = potential evapotranspiration

Figure 3. Procedure for determining growing season in tropical regions.

Agroclimatic Parameters for Sorghum Hybrids

The most commonly, and often the only, available climatic data for many regions are monthly summaries of temperature and precipitation. These data describe the general characteristics of a region and are useful in comparing one location with another (Nuttonson 1959). However, summaries of weather normals on fixed time periods of 1 month are too long and out of phase with critical stages of crop development, so that their use in agriculture is limited.

Plant growth and development, though time-related in a specific area, are more closely related to the occurrence of critical values in the rise and fall of seasonal patterns of different climatic elements. They are also related to accumulations of temperature and precipitation between phenological stages. A procedure described by Neild et al. (1978). with monthly weather summaries and Julian day number at the midpoint of each month as input data, was used to compute a matrix with 365 rows, with different columns showing temperature, GDD, precipitation, and PET values for each day of the year. These data, called agroclimatic normals,

Table 3. Growing season as related to precipitation at two locations in tropical Mexico.

Location	Rainfall (mm)	Growing season		
		Begins	Ends	Days
Villahermosa (17°59'N 92°55'W)	1902	17 May	15 Apr	333
Apatzingan (19°05'N102°15'W)	716	2 July	4 Nov	125

enable climatic data to be oriented to crop requirements on a daily basis.

Table 4 presents a formula used to calculate daily temperature as a function of Julian day number. The coefficients for this equation were obtained from regression analysis where monthly temperatures (Y) and day number at the midpoint of each month (X) are the variables involved. A comparison between actual average monthly temperatures and calculated temperatures using midpoint day numbers is shown for Lagos, in Jalisco, Mexico. There is close agreement between actual and calculated temperature.

Portions of a matrix computed from monthly temperature and precipitation data from Rafaela, Argentina, and the discussion that follows will be used to describe how monthly weather summaries can be used to determine and evaluate growing seasons for sorghum.

Parameters used to determine the times and precipitation associated with different phenological stages and farming operations for sorghum are presented in Tables 5 and 6. The times of earliest planting are as described in Figures 2 and 3. Critical phenological stages are determined as those times on the seasonal temperature curve when the GDD requirements for specific stages have accumulated. For example, the expected time for seedling establishment of a medium-late hybrid like RS-671 (Table 5) would be 135 GDD after planting. The growing point would be expected to differentiate when 465 GDD have accumulated; boot stage at 783; half bloom at 943; grain filling would be near completion at 1261; and the seed would be physiologically mature when 1420 GDD have accumulated. The GDD required for other hybrids and all development stages from 0 to 9 are also shown in Table 5. These requirements are based on observations by Neild and Seeley (1977) and Logan (1981).

The precipitation during a 15-day period beginning 5 days before and continuing 10 days after

Table 4. Comparison of actual and calculated temperatures at Lagos, Mexico.

		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Actual monthly temperature	(Y)	58	61	66	71	76	76	73	72	70	67	63	59
Julian day number at monthly midpoint	(X)	15	46	74	105	135	166	196	227	258	288	319	349
Calculated temperature at midpoint	$(\tilde{Y})$	58	61	66	72	76	76	74	72	70	67	63	59

$$Y = a + b_1 \mathrm{Cos} \frac{2\pi}{365} X + b_2 \mathrm{Sin} \frac{2\pi}{365} X + b_3 \mathrm{Cos} \frac{4\pi}{365} X + b_4 \mathrm{Sin} \frac{4\pi}{365} X$$

$a = 67.7$; $b_1 = -7.95$; $b_2 = 1.18$; $b_3 = -1.77$; $b_4 = -1.20$.

Table 5. Growing degree-day requirements for various phenological stages of sorghums of different maturities.

		Maturity class					
Phenological stage		Very early	Early	Medium early	Medium	Medium late	Late
Seedling emergence	(0)						
Collar 3rd leaf visible	(1)	135	135	135	135	135	135
Collar 5th leaf visible	(2)	248	275	278	291	306	310
Growing point differentiation	(3)	373	412	419	439	465	474
Flag leaf visible	(4)	499	548	560	587	624	645
Boot	(5)	624	685	700	735	783	816
Half bloom	(6)	750	821	868	883	943	987
Soft kernels	(7)	875	958	980	1030	1102	1158
Hard kernels	(8)	1000	1095	1121	1177	1261	1329
Physiological maturity	(9)	1125	1230	1261	1326	1420	1500

Sources: Neild and Seeley (1977); Logan (1981).

Table 6. Agroclimatic parameters for evaluating sorghum growing seasons.

Farming operation or phenological stage	Parameter
Land preparation and planting	5 days before to 10 days after first spring 18.3°C or date daily precipitation = 0.5 PET.
Planting	Date first spring 18.3°C or date daily precipitation = 0.5 PET
Germination to seedling establishment	Planting to stage 1[a]
Seedling establishment to growing point differentiation	Stage 1 to stage 3
Head formation	Stage 3 to stage 6
Grain filling	Stage 6 to stage 8
Grain maturation	Stage 8 to stage 9
Growing cycle	Planting to stage 9
Harvest	Between 15 and 30 days after stage 9

a. See Table 5 for explanation of stage numbers.

planting was used to evaluate conditions for land preparation and planting operations. Precipitation during a 15-day period between 15 and 30 days after the hybrid has accumulated sufficient GDD for physiological maturity was used to evaluate harvest conditions. Years with above-normal amounts and planting dates or locations with high precipitation during these periods would expect to have difficulties with these operations.

Portions of a daily climatic matrix computed from monthly temperature and precipitation data from Rafaela, Argentina, are presented in Table 7. Shown are those periods when the seasonal temperature curve approaches critical stages. These data will be used to illustrate how the temperature response of hybrid RS-671 may be evaluated at Rafaela.

The average daily temperature at Rafaela rises to 18.3°C and becomes warm enough for germination and seedling growth on 8 October, which is the earliest planting date. The critical phenological stages of seedling establishment, head formation, half bloom, hard kernels, and maturity would be expected to occur on 24 October, 21 November, 26 December, 17 January, and 27 January when 135 (i.e., from accumulated GDD of 33.9 at planting to accumulated GDD of 168.9 at establishment), 465, 943,1261, and 1420 GDD from planting have been accumulated, respectively. These are the dates when the GDD requirements for RS-671 have been met. The precipitation during a growth stage—say between planting and seedling establishment—is calculated by subtracting accumulated precipitation at the beginning of that stage from that at the end. For example, precipitation accumulated between planting and seedling establishment would be 46.1-6.9 = 39.2 mm (see Table 7 for precipitation during other phenological stages). Precipitation for the entire growing cycle is 375.7-6.9 = 368.8 mm. Not shown in this portion but available from the complete matrix are the expected precipitation at land preparation and planting and at harvest, which are 34 and 51 mm, respectively.

These procedures can be used to compare the response of a crop to the temperature and precipitation at different locations, the response to different times of planting at a single location, and the responses of different hybrids to a single location and planting date (Neild and Seeley 1977; Neild and Richman 1979). They may also be used to compare different crops on the basis of their phenological responses to temperature and rainfall (Neild 1982) and the potential of sorghum and other crops in sequence- and relay-cropping systems. Following is a comparison of the climates in the sorghum-growing areas of the USA, Argentina, and Mexico as measured by the phenological response of a medium-late sorghum hybrid, RS-671.

USA

Fifty-three percent of the sorghum area in the

Table 7. Portions of daily climatic matrix showing phenology and precipitation during critical stages for sorghum at Rafaela, Argentina.

Day	Date	Average temp. (°C)	Accumulated GDD	Accumulated precipitation (mm)	Phenological stage	Precipitation (mm) during stage
279	6 Oct	17.8	7.8	2.3		
280	7 Oct	17.8	15.6	4.6		
281	8 Oct	18.3	33.9	6.9	Planting (0)	
295	22 Oct	20.0	148.9	40.5		
296	23 Oct	20.0	158.9	43.3		
297	24 Oct	20.0	168.9	46.1	Seedling establishment (1)	39.2
323	19 Nov	22.8	473.3	121.7		
324	20 Nov	22.8	486.1	125.0		
325	21 Nov	22.8	498.9	128.3	Head formation (3)	82.2
358	24 Dec	24.4	948.1	247.1		
359	25 Dec	24.4	962.5	251.2		
360	26 Dec	24.4	976.9	255.3	Half bloom (6)	127.0
15	15 Jan	24.4	1266.1	330.5		
16	16 Jan	24.4	1280.5	334.3		
17	17 Jan	24.4	1294.9	338.1	Hard kernels (8)	82.8
25	25 Jan	24.4	1425.1	368.1		
26	26 Jan	24.4	1439.5	371.9		
27	27 Jan	24.4	1453.9	375.7	Maturity (9)	37.6
						368.8
				Land preparation and planting		34
				Harvest		51

Americas—about 5.2million ha—is in the USA. The yield averages about 1.8 tonnes/ha. Most of this sorghum is produced in a south-to-north-oriented region between 26 and 43°N latitude and 96 and 104°W longitude that constitutes the southern half of the Great Plains. Precipitation averages 750 mm annually along the eastern border of this region and decreases to 400 mm in the west. The freeze-free season averages 330 days in the south and decreases to 150 days in the north. Most of this region is too hot and too dry for good yield of maize.

Presented in Table 8 are data comparing the climates of Armour, South Dakota; McPherson, Kansas; and Taylor and McCook, Texas, relative to the phenological response of sorghum. These locations are along a north-to-south transect through the Great Plains. The data were developed from matrices of daily parameters computed from monthly climatic summaries as previously described. Except for Armour, where only an early (1125 GDD) sorghum is adapted, the comparisons are based on the response of a standard hybrid, RS-671, that requires 1420 GDD to mature. Shown for each location are the dates of critical phenological stages; the days from planting to these stages; and the precipitation during land preparation and planting, during critical phenological stages, during the growing cycle, and during harvest. The annual precipitation, annual average temperature, and the growing season days above 18.3°C are also shown for each location.

The beginning and duration of the growing season are closely related to the seasonal temperature curve. The temperature first reaches 18.3°C and becomes warm enough for sorghum during the last week of February in the south but not until 3 months later, during the last week of May, in the north. The annual temperatures for McCook, Taylor, McPherson, and Armour are 23.6, 19.7, 13.4, and 8.8°C, respectively. There are 264 days above 18.3°C at McCook and only 108 days at Armour, where only early-maturing sorghum can be safely grown.

The time of planting and consequent phenology of sorghum are delayed from south to north. Sorghum usually is first planted about 10 March in southern Texas but not until about 23 May in the

Table 8. Sorghum phenology and precipitation associated with critical stages for different locations in the U.S. Great Plains.

		Armour, South Dakota		McPherson, Kansas		Taylor, Texas		McCook, Texas	
Latitude		43°19'N		38°03'N		30°34'N		26°30'N	
Longitude		98°21 'W		97°04'W		97°25'W		98°23'W	
Altitude (m)		460		456		174		68	
Annual precipitation (mm)		563		745		825		517	
Annual average temperature (°C)		8.9		13.4		19.7		23.6	
Growing season (days)		108[a]		141[a]		201[a]		264[a]	
		Sorghum Phenology							
		Date	Days	Date	Days	Date	Days	Date	Days
Planted	(0)	23 May	0	15 May	0	3 Apr	0	10 Mar	0
Seedlings established	(1)	7 June	15	28 May	13	18 Apr	15	24 Mar	14
Head forming	(3)	29 June	37	30 June	36	14 May	41	17 Apr	38
Boot	(5)	19 July	57	10 July	56	3 June	61	6 May	57
Half bloom	(6)	29 July	67	20 July	66	13 June	71	16 May	67
Hard kernels	(8)	19 Aug	88	8 Aug	85	30 June	88	3 June	85
Maturity	(9)	1 Sept	101	18 Aug	95	8 July	96	11 June	93
		Precipitation (mm) during critical times and stages							
Sowing		38		33		36		16	
Seedling establishment	(0-1)	40		42		35		13	
Head formation	(3-6)	81		109		89		46	
Grain filling	(6-8)	47		53		47		48	
Maturation	(8-9)	30		25		17		20	
Growing cycle	(0-9)	272		312		267		149	
Harvest		30		41		27		27	

a. Growing season determined by temperature regime.

northern part of the growing region. About 2 weeks are required for germination and seedling establishment at these planting times; 13 days at McPherson and 15 days at Armour and Taylor. The number of days to the half-bloom stage ranged from 66 days at McPherson to 71 days at Taylor. The number of days for head formation (stages 3 to 6) was similar at all locations: 30 days at Armour, McPherson, and Taylor, and 29 days at McCook. The number of days for grain filling (stages 6 to 8) varied more—21,19,17, and 18 for these locations. The number of days for grain maturation were respectively 13, 10, 8, and 8 from north to south. Because of cooler temperatures in the north, the rate of crop development is slower than at other locations, even for an early-maturing hybrid. The early, 1125-GDD hybrid required 101 days to mature at Armour, compared with 93 to 96 days for the late-maturing RS-671 at the other locations.

Precipitation is low in the southern portion of the Great Plains. McCook receives only 149 mm during the growing cycle, so the crop is irrigated. The other locations receive about twice as much rainfall, with amounts varying from 267 mm at Taylor to 312 mm at McPherson. This precipitation is well distributed relative to the phenology of sorghum. Except for McCook, where it is dry, rainfall amounts during sowing and seedling establishment favor land preparation and seed germination but are not so great as to interfere with timely planting.

Over 50% of the growing cycle rainfall occurs during the critical head-formation and grain-filling periods, then decreases during grain maturation. For example, the amounts of rainfall during head formation, grain filling, and maturation at Taylor, Texas, are 89,47, and 17 mm, respectively. Rainfall amounts during the harvest period range from 27 mm at McCook to 41 mm at McPherson.

Mexico

Fifteen percent of the sorghum grown in the Americas—about 1.5 million ha—is grown in Mexico. The yield averages 1.2 tonnes/ha. There are three growing regions: one along the Gulf of Mexico in the east, in the states of Tamaulipas, Vera Cruz, and Tabasco; the second in the northwest, in the states of Sonora and Sinaloa; the third, called El-Bajio, in the highlands of central Mexico in the states of Guanajuato, Jalisco, and Michoacan.

Comparisons of the phenology of the hybrid RS-671 developed from climatic data from Matamoras, Tamaulipas, in the northeast; Villahermosa, Tabasco, in the southwest; Culiacan, Sinaloa, in the northwest; and Lagos, Jalisco, and Apatzingan, Michoacan, in the highlands are presented in Table 9. The length of the sorghum-growing seasons at Matamoras and Lagos is related to temperature. The precipitation pattern determines the growing season at the other locations.

The climate and response of sorghum at Matamoras is similar to McCook in southern Texas. Precipitation and temperature increase southward along the Gulf of Mexico. The daily temperature is

Table 9. Sorghum phenology and precipitation during critical stages for different locations in Mexico.

	Matamoras, Tamaulipas	Villahermosa, Tabasco	Lagos, Jalisco	Apatzingan, Michoacan	Culiacan, Sinaloa
Latitude	25°52'N	17°59'N	21°22'N	19°05'N	27°28'N
Longitude	97°30'W	92°55'W	101°56'W	102°15'W	107°24'W
Altitude (m)	12	10	1878	682	531
Annual precipitation (mm)	747	1902	634	716	603
Annual average temperature (°C)	23.3	26.0	20.0	28.2	24.3
Growing season (days)	278[a]	305[b]	123[a]	125[b]	136[b]

Sorghum Phenology

		Date	Days	Date	Days	Date	Days	Date	Days	Date	Days
Planted	(0)	6 Mar	0	27 Dec	0	16 Jun	0	2 Jul	0	2 Jul	0
Seedlings established	(1)	20 Mar	14	8 Jan	12	26 Jun	10	10 Jul	8	10 Jul	8
Head forming	(3)	14 Apr	39	6 Feb	37	20 Jul	34	27 Jul	25	27 Jul	25
Boot	(5)	6 May	61	26 Feb	57	13 Aug	58	5 Aug	34	4 Aug	33
Half bloom	(6)	16 May	71	9 Mar	72	27 Aug	72	22 Aug	51	22 Aug	51
Hard kernels	(8)	3 Jun	89	29 Mar	92	23 Sep	99	9 Sep	69	8 Sep	68
Maturity	(9)	12 Jun	98	8 Apr	102	8 Oct	114	18 Sep	78	7 Sep	77

Precipitation (mm) during critical times and stages

Sowing		16	91	50	54	27
Seedling establishment	(0-1)	14	73	37	37	24
Head formation	(3-6)	56	123	169	152	137
Grain filling	(6-8)	27	40	105	101	89
Maturation	(8-9)	41	15	51	50	40
Growing cycle	(0-9)	164	370	466	467	363
Harvest		36	28	19	49	39

a. Growing season determined by temperature regime.

b. Growing season determined by precipitation regime.

above 18.3°C all year round at Villahermosa and annual rainfall averages 1902 mm. Excess rainfall rather than inadequate moisture determines the planting schedule for sorghum here. However, March and April are relatively dry and average about 45 mm each month. Hybrid RS-671 can be scheduled so that maturation and harvest coincide with this more favorable dry period if it is planted during the late part of December. This December-to-April sorghum-growing cycle at Villahermosa is similar to the late October to early February season in the northern part of the Argentine pampas and the mid-May to mid-August season in Nebraska and Kansas in the U.S. Great Plains.

The effect of altitude on sorghum phenology can be seen by comparing data from Lagos (1878 m) and Apatzingan (682 m) in central Mexico. The daily temperature becomes suitable for sorghum growth about the middle of May at Lagos. The temperature is cooler than at Apatzingan and the sorghum takes 114 days to mature. The daily temperature is above 18.3°C throughout the year at Apatzingan, but the rainfall regime does not become favorable until 2 July. Although the time of planting is 2 weeks later at Apatzingan, hybrid RS-671 would mature 20 days earlier than at Lagos.

Argentina

Between 2 and 2.5 million ha (about 21% of the Americas) of sorghum are grown in the Argentine pampas. The yield average is about 1.5 tonnes/ha.

Table 10. Sorghum phenology and precipitation associated with critical stages for different locations in the Argentine pampas.

		Rafaela, Santa Fe		Rosario, Santa Fe		Junin, Buenos Aires		Azul, Buenos Aires	
Latitude		31°11'S		32°55'S		34°35'S		36°46'S	
Longitude		63°33'W		60°44'W		60°56'W		59°50'W	
Altitude (m)		9		22		80		105	
Annual precipitation (mm)		941		967		879		823	
Annual average temperature (°C)		17.8		16.8		16.2		13.9	
Growing season (days)		181[a]		165[a]		152[a]		114[a]	
		Sorghum Phenology							
		Date	Days	Date	Days	Date	Days	Date	Days
Planted	(0)	22 Oct	0	1 Nov	0	8 Nov	0	17 Nov	0
Seedlings established	(1)	5 Nov	14	17 Nov	16	22 Nov	14	3 Dec	16
Head forming	(3)	1 Dec	40	13 Dec	42	19 Dec	41	25 Dec	38
Boot	(5)	23 Dec	62	5 Jan	65	12 Jan	65	17 Jan	61
Half bloom	(6)	3 Jan	73	17 Jan	77	24 Jan	*11*	28 Jan	72
Hard kernels	(8)	25 Jan	95	9 Feb	100	17 Feb	102	21 Feb	96
Maturity	0)	5 Feb	106	22 Feb	113	5 Mar	117	6 Mar	109
		Precipitation (mm) during critical times and stages							
Sowing		48		47		43		41	
Seedling establishment	(0-1)	32		51		41		41	
Head formation	(3-6)	126		122		115		74	
Grain filling	(6-8)	81		83		94		60	
Maturation	(8-9)	37		39		53		39	
Growing cycle	(0-9)	361		398		366		274	
Harvest		55		61		49		47	

a. Growing season determined by temperature regime.

This area is west of Buenos Aires between 31 and 36°S latitude. Presented in Table 10 are data comparing the climates of Rafaela, Rosario, Junin, and Azul along a north-to-south transect through this region. Annual precipitation ranges from 823 mm at Azul to 967 mm at Rosario. The annual temperature averages 17.9°C at Rafaela in the north and decreases to 13.9°C at Azul in the south. There are 181 days above 18.3°C at Rafaela but the growing season decreases to 114 days at Azul. Temperatures become favorable for sorghum growth during October in the north but not until the middle of November in the south.

Sorghum phenology at Rafaela, Rosario, and Junin is based on the GDD requirements of hybrid RS-671. Data for Azul—like Armour, South Dakota, in the northern temperature limit for sorghum in the USA—are based on an early-maturing hybrid requiring 1125 GDD. The number of days from planting to maturity for RS-671 increased with cooler temperatures to the south. They were 106, 113, and 117 days for Rafaela, Rosario, and Junin, where the annual temperature averages 17.9,16.8, and 16.2°C, respectively. Much of this difference is associated with slower plant development following the boot stage. The difference in days between the boot and maturity stages for RS-671 at Rafaela, Rosario, and Junin was 44, 48, and 52 days, respectively.

Data in Tables 8 and 10 provide some interesting comparisons between the climate of the pampas and the Great Plains relative to the phenology of sorghum. For example, the annual temperatures at Azul, Argentina, and McPherson, Kansas, are similar and average 13.9 and 13.4°C, respectively. However, the summers are warmer and the growing season for sorghum is longer at McPherson, where there are 141 days above 18.3°C, compared with 114 days at Azul. Hybrid RS-671 is adapted at McPherson but not at Azul. The temperature regime for sorghum at Azul more closely resembles Armour in the Great Plains, even though Armour is 735 km further from the equator.

Precipitation during the sorghum-growing cycle ranges from 280 mm at Azul to 377 mm at Junin. The greatest difference between the precipitation patterns at these locations was during the critical head-formation and grain-filling period. Rainfall ranged between 115 and 126 mm during head formation at Rafaela, Rosario, and Junin, but averaged 74 mm at Azul. During grain-filling the rainfall at Rafaela, Rosario, and Junin was between 81 and 99 mm; it was 60 mm at Azul. The amount of precipitation at sowing, harvest, and different sorghum phenological stages was higher in the Argentine pampas than in the Great Plains of the USA.

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Session 2

Climatic Requirements of Sorghum and Millet

Response of Pearl Millet to Light and Temperature

C.K. Ong and J.L. Monteith*

Abstract

Temperature exerts a major effect on the rate at which crop plants develop and on processes of expansion and extension. Light determines the rate of growth (i.e., dry-matter production) at any stage of development. But there are important interactions: development can be slowed by low light and growth can be retarded when the temperature is too high or too low. We have attempted to quantify some of these relationships in work on millet growing in controlled-environment glasshouses at the University of Nottingham.

The simplest development response is that of germination when light is not a factor. Germination rate increased linearly with temperature from a base of 10 to 12°C to a sharply defined optimum at 33 to 34 °C and declined to zero at about 45 to47°C. Other developmental processes such as leaf and spikelet initiation and tillering responded similarly to temperature. The limited information available suggests that the base temperature at which development stops is different for contrasting varieties: the rate and duration of specific developmental processes also differ.

Rate of leaf extension is also a linear function of temperature up to about 34°C so that the time needed to form a complete canopy decreases with increasing temperature below that limit. However, we found that the amount of dry matter produced per unit of intercepted radiation is conservative at about 2.4 g/MJ (± 10%) for mean air temperatures ranging from 20 to 36°C. The highest yield, both biological and economic, was obtained at 22°C, mainly because the duration of the crop (cv BK-560) was about 30 days longer at 22 than at 31 °C, for example.

The general principles we have tested for temperature and light need to be combined with an appropriate scheme for relating the response of crops to the distribution of rainfall and the storage of soil water. Further work is also needed on the response of plants to damaging temperatures. However, even with the limited evidence now a vailable, a start can be made with problems of pinpointing physiological responses which are mainly responsible for differences in yield of the same variety growing at different sites or in different seasons at the same site. We can also provide breeders with more quantitative guidance in the selection for larger and more uniform yields.

Résumé

Réaction du mil à la lumière et à la température : La température influence considérablement la vitesse de développement des plantes et les processus d'expansion et d'extension. La lumière détermine la vitesse de croissance (c'est-à-dire la production de matière sèche) à tous les stades de développement. Il faut noter certaines interactions : un

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manque de lumière peut ralentir le développement et les températures extrêmes peuvent retarder la croissance. Les auteurs ont tenté de quantifier certaines relations au cours des études sur le mil cultivé en milieu contrôlé dans des serres à l'Université de Nottingham.

La réaction la plus simple, au niveau du développement est celle de la germination où la lumière ne joue aucun rôle. La vitesse de germination augmente linéairement avec la température à partir d'un seuil inférieur de 10 à 12°C, en passant par un optimum précis de 33–34°C, pour devenir nulle vers 45 à 47°C. La température influence de la même manière d'autres processus de développement, tels que l'initiation des feuilles et des épillets et le tallage. Les quelques données dont on dispose donnent à penser que la température à laquelle le développement s'arrête varie chez des variétés différentes; on a également constaté une variation dans la vitesse et la durée de différents processus de developpement.

La vitesse d'extension foliaire est aussi une fonction linéaire de la température jusqu'à environ 34°C; le temps nécessaire à la formation complète du couvert décroît à mesure que la température monte jusqu'à cette limite. Cependant, la quantité de matière sèche produite par unité de rayonnement interceptée se stabilise à environ 2,4 g/MJ (±10%) pour des températures moyennes de l'air de 20 à 36°C. Le rendement maximum sur le plan aussi bien biologique qu'économique a été obtenu à 22°C, surtout parce que le cycle de la plante (cultivar BK-560) se prolonge de 30 jours à 22°C par rapport à 31°C, par exemple.

Les principes généraux liés à la température et à la luminosité devraient être associés aux essais appropriés concernant la réaction des plantes à la répartition des précipitations et aux réserves hydriques dans le sol. D'autres recherches sont nécessaires sur la réaction des plantes à des températures nuisibles. Entre-temps, même avec le peu de renseignements disponibles actuellement, on peut déterminer les réactions physiologiques souvent responsables des différences de rendement chez une même variété cultivée sur des sites différents, ou au même site en différentes saisons. On peut aussi fournir aux phytosélectionneurs plus de données quantitatives qui seront utiles à la sélection de variétés à rendement plus élevé et plus uniforme.

Generalizations

Although many tropical crops are grown in regions where lack of rain is the main restraint on productivity, yields are by no means insensitive to geographical and seasonal differences in other climatic factors. In particular, temperature is the main factor determining the time from sowing to maturity for an annual crop, and the availability of light within the growing season sets an upper limit to the amount of dry matter that the crop can accumulate when water is abundant. Our brief is to review ways in which the growth and yield of pearl millet depend on temperature and on light, setting the scene for later discussions which concentrate on the role of water. We begin with a few generalizations, summarized in Figure 1, to provide a framework for the review of experimental evidence that follows.

All green plants grow and reproduce within a range of temperatures, roughly from 0 to 35°C for species that thrive in temperate climates and from 10 to 45°C for tropical species. The metabolic processes responsible for organized growth cannot function outside these limits. Most processes achieve a maximum rate at a temperature towards the upper end of the range; i.e., at above 25to30°C (temperate) or 30 to 35°C (tropical). Within this range, temperature, sometimes in association with daylength, controls the developmental timetable of plants. Temperature also interacts with light and with water supply to control the assimilation of carbon by green leaves and the rate at which individual organs grow.

When a crop is sown, the time that elapses before the germination and emergence of seedlings is strongly dependent on temperature as well as on moisture in the seedbed. When the mean temperature is close to either end of the physiological range, slow germination is usually associated with poor establishment, because seeds have been attacked by pests or pathogens or simply because the surrounding soil has become too dry. No amount of favorable weather during the growing season can compensate for the small populations of plants so common in the semi-arid tropics,

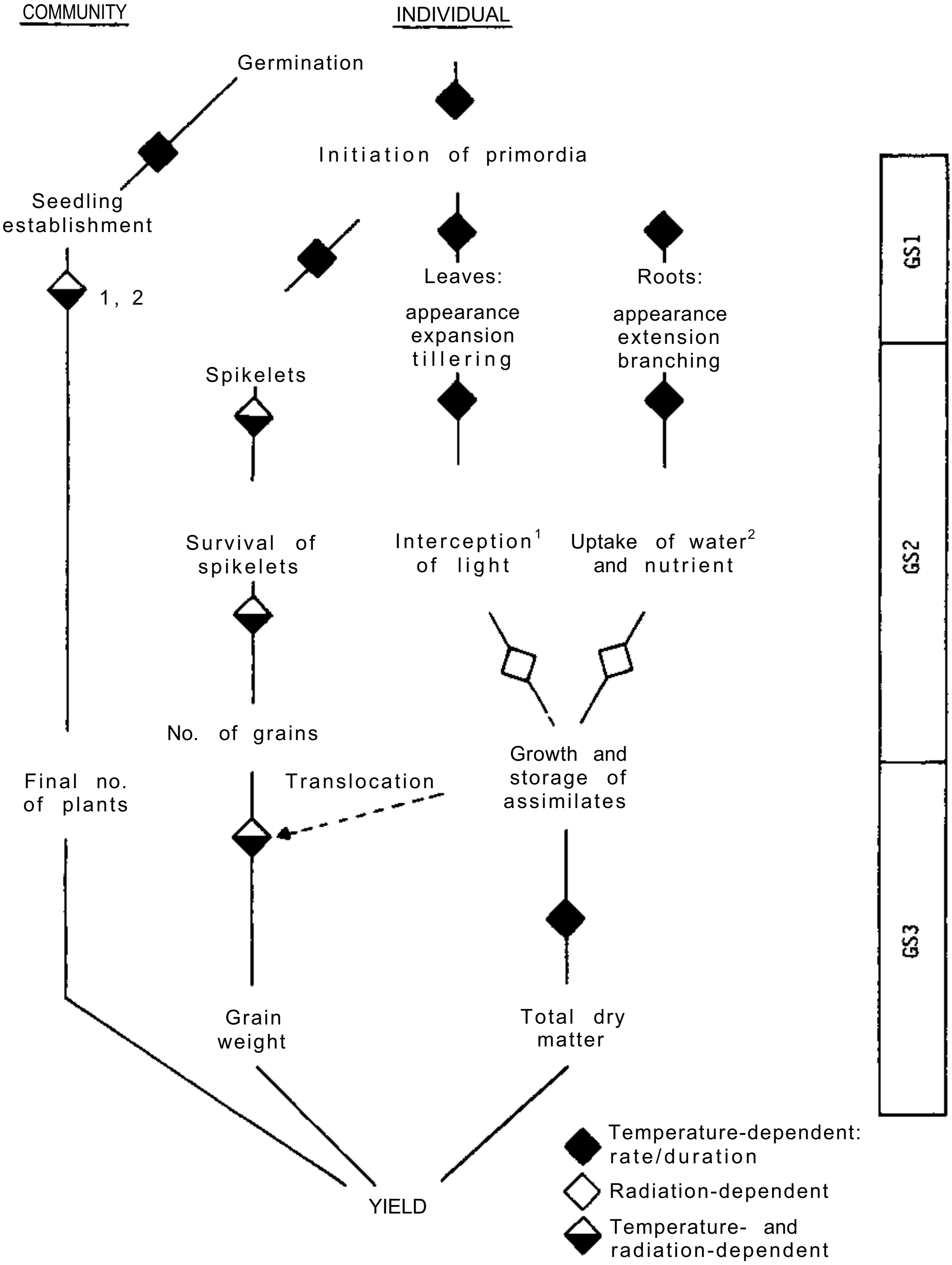

Figure 1. Flow diagram of the stages of plant development that are influenced by light and temperature.

where germination often occurs in rapidly drying soil close to the upper limit of temperature.

In seedlings, the initiation of primordia is the first stage in the development of leaves and roots, sometimes known as "growth stage" 1 (or GS1) although "development stage" would be more appropriate. The rate at which these organs appear, extend, and subdivide depends strongly on the temperature of the appropriate meristem tissue (and on daylength in varieties of some species).

Early in the life of a cereal crop, the switch of primordial initiation from leaves to spikelets appears to be controlled mainly by daylength or vernalization. The second stage of growth (GS2) is marked by the appearance and expansion of successive leaves and by corresponding growth of the root system. In a dense population of plants where roots have access to abundant water and fertilizer, the leaf area index (LAI) usually increases until the foliage forms a canopy intercepting about 95% of the incident lights Thereafter, lower leaves in cereals tend to die as new upper leaves emerge. The amount of foliage needed to achieve this limit ranges from an LAI of about 3 in stands with very horizontal leaves to 10 or more in stands with very vertical leaf disposition. For many cereals, including millet, the range appears to be about 4 to 6. On the other hand, when the population is small, or when the expansion of leaves is restricted by lack of water or nutrients, the interception of light at the end of GS2 may be only a small fraction of the maximum possible figure.

During GS2 the rate of tillering depends on the number of leaves on the main culm, which is governed by temperature and daylength. The duration of tillering is mainly influenced by the supply of assimilates, which is determined, for example, by plant population or timing of reproductive growth.

During GS2, the rate at which spikelets are initiated and the number that survive to become florets depend in a complex way both on light (determining the supply of assimilates) and on temperature (determining the rate of development). For some cereals, including millet, and over a restricted range of temperature, the number of spikelets and grains seems to depend on the supply of assimilate per unit of time as perceived by the reproductive system. The most appropriate way of expressing this quantity appears to be in grams of dry matter per degree day or in megajoules (MJ) per degree day in cases where the rate of dry-matter production is strongly correlated with intercepted radiation.

In the third stage (GS3), growth proceeds at a rate that depends both on light, through the current supply of assimilate, and on temperature, through its control of cellular division and expansion. In many cereals, and particularly in millet, it appears that adverse weather during this stage can be compensated by the translocation to grain of material previously stored in stem tissue. In ideal conditions, grains continue to grow until they reach a maximum size, which is genetically determined, but growth can be curtailed by the premature death of all green tissue and the exhaustion of stored material. In the semi-arid tropics, the length of GS3 is often determined by the amount of water available to the root system at a time when roots, like leaves, are rapidly dying.

Finally, the yield of a crop per unit of field area depends on the product of three factors whose dependence on temperature and light has already been indicated:

1. the number of plants per unit of field area, depending mainly on soil temperature and water after sowing and during GS1;
2. the weight per plant, depending mainly on the interception of light per plant during GS2 and GS3 and on the length of these stages as determined by temperature and water;
3. grain weight as a fraction of total dry weight. This fraction depends mainly on grain number per plant and therefore on light and temperature in GS2. There is usually much less fractional variation in weight per grain except when weather is very unfavorable in GS3.

We now consider the influence of temperature and light on the growth and yield of pearl millet, drawing heavily from experimental work by our own group in glasshouse and laboratory work at the University of Nottingham (Monteith et al. 1983).

Germination and Emergence

Both for germination and for initiation, a rate of development can be specified as the reciprocal of a time t; e.g., the time from sowing seed to the emergence of a radicle of specified length or the time between the successive appearance of primordial cells. For any range of temperature over which the rate of development is a linear function of temperature T, it is convenient to write

$$1/t = (T - T_b)/\theta$$

where T_b is a base temperature (obtained by extrapolation) below which development stops and θ is the "thermal time" for the process, often expressed as an "accumulated temperature" with units of degree days. The equation is valid for development at temperatures between T_b and a well-defined optimum T_o, beyond which the development rate decreases with increasing temperature.

In millet (cv BK-560) germination rate increased linearly with temperature from a base of 10 to 12°C to a sharply defined optimum at 33 to 34°C and declined to zero at about 45 to 47°C (Fig. 2, Garcia-Huidobro et al. 1982). Other developmental processes such as leaf and spikelet initiation and the duration of GS2 respond similarly to temperature (Ong 1983a). Figure 3 shows the relation obtained for the rate of leaf appearance and temperature.

Table 1 summarizes measurements of several processes in cv BK-560. Tb is conservative, but associated with each process is a specific value of θ, which appears to be insensitive to natural variations in irradiance, daylength, or saturation deficit, for example. For some aspects of development, closely related varieties also appear to have similar values of θ . For example, there is little variation in θ for leaf appearance in cvs BK-560, MBH-104 (dwarf), GHB-1399 (dwarf), ICH-190, MBH-110, and ICH-105. For these cultivars it is the duration of specific development phases that differs.

In contrast, recent studies by H. Mohamed on millet varieties adapted to different environments confirm that there is genetic variation, not only in the rate of germination but also in cardinal temperatures. For instance, a heat-tolerant variety, Oasis (P-938) has a low Tb (8.0°C) as well as a high optimum temperature (35.5°C). At a mean soil temperature of 40°C, Oasis would germinate after 1 day compared with 3.3 days for Sanio, a variety from Senegal. This observation confirmed a similar finding at ICRISAT with sorghum that there is a large genetic variation in the ability of seedlings to emerge at high soil temperatures (Wilson et al. 1982). Comparable variation in the rate of emergence exists within seed populations, and in cv BK-560 it has been shown that such variation is largely due to differences in the value of θ. The reason for such variation is unknown. Possible causes under investigation include seed size, degree of seed maturity, and storage conditions. Rapid emergence and establishment are essential to minimize the risk of heat and moisture stress in areas where soil surface temperatures often exceed 40°C.

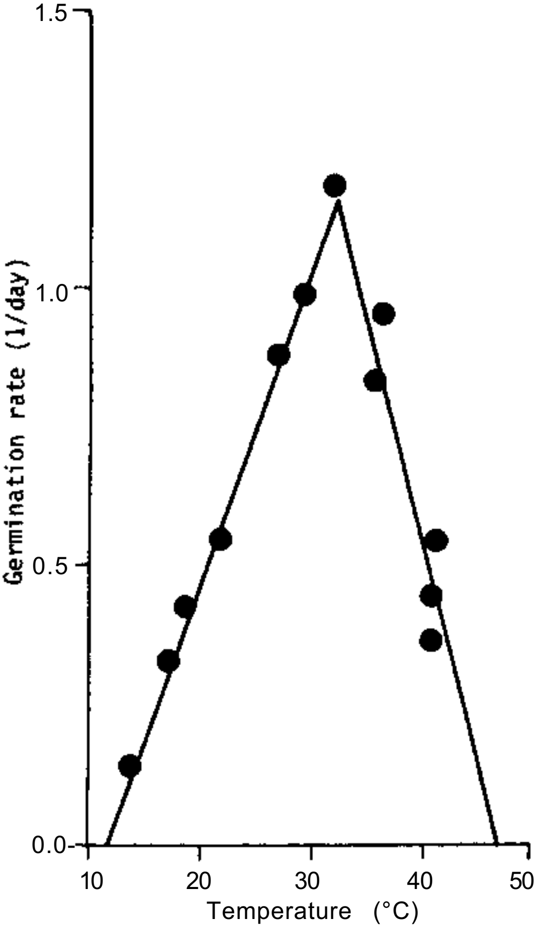

Figure 2. Germination rate of pearl millet (cv BK-560) as a function of temperature. Rate is expressed as the reciprocal of time in days for 50% of the seeds in a batch to germinate (Garcfa-Huidobro et al. 1982).

When seeds were exposed to pairs of alternating temperatures, the rate of germination and the germination percentage were close to values predicted from measurements at constant temperature, provided the maximum temperature did not exceed 42°C during imbibition. Exposure to high temperature during imbibition slowed germination and reduced the number of seeds that germinated. No seeds germinated where the maximum temperature of the cycle exceeded

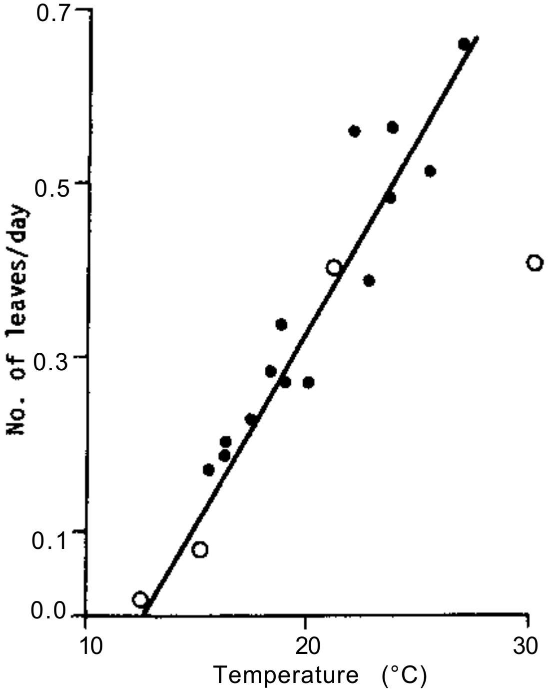

Figure 3. Rate of leaf appearance in millet (cv BK-560) (•), or (cv MX-001) (o) and temperature. Data for MX-001 are from Pearson (1975).

Table 1. Summary of thermal time (θ) and base temperature (T_b)for each process or phase of development in pearl millet.

Process	θ (degree days)	T_b (°C)
Seedling emergence from sowing	Start 28.0±2.6	11.4±1.1
	50% 42.4±1.8	
	90% 60.0±6.1	
	Per leaf	
Leaf initiation	25.6±3.4	11.3±1.8
Leaf appearance	25.0±3.5	12.4±2.0
	24.8±1.7	13.2±3.1
	28.6±1.7	12.0±1.5
Tillering from sowing	Start 140-150 39.5-45.5 per tiller	
Vegetative phase (GS1) 17 days	Independent of meristem temperature	
Early reproductive phase (GS2)	464	10.0
Grain-filling phase (GS3)	300	10.0

47 °C. The adverse effects of heat stress were much less severe when seeds were allowed to imbibe water for 8 h before exposure to high temperature. These laboratory observations by Garcia-Huidobro (1982) are directly relevant to problems of poor germination in the tropics, where the temperature a few centimeters below the surface of bare soil is frequently in the range of 40 to 50°C during the day (Monteith 1979).

Development of Leaf Area and Interception of Radiation

After seedling emergence, both temperature and light influence yield, since dry-matter production is almost proportional to intercepted radiation during the vegetative growth of cereals (Gallagher and Biscoe 1978).

In millet, the maximum number of leaves produced is determined during GS1, the duration of which is largely controlled by daylength (Ong and Everard 1979). During this period, the temperature of the soil surface determines the rate of leaf initiation (Watts 1972), more leaves being produced at high temperatures (Hellmers and Burton 1972; Coligado and Brown 1975 for maize; Ong 1983a).

During the rapid increase in LAI characteristic of GS2, the rate of leaf expansion in cereals increases almost linearly with temperature. Figure 4 demonstrates this response for three stands of millet

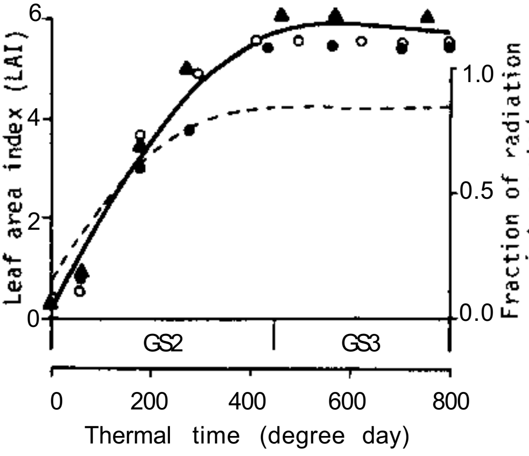

Figure 4. Formation of leaf area and interception of light (----) of millet cv BK-560 at 31 (●), 25 (▲), and 19 (o) °C.

cv BK-560 grown at mean air temperatures of 31,25, and 19°C, with a diurnal cycle of ±5°C. For each temperature regime, maximum LAI was reached at the end of GS2, when θ was approximately 450 degree days, corresponding to a range of durations from 52 days at 19°C to 25 days at 31 °C. These canopies intercepted 70% of the incident radiation when LAI approached 3 to 3.5.

Reduction in the length of GS2 at higher temperatures more than offsets the apparent benefit of warmth in shortening the time taken to achieve maximum light interception. It is clear from the measurements summarized in Table 2 that high temperature can severely reduce yield by shortening the period over which light is intercepted. The implications of this interaction between temperature, intercepted radiation, and the duration of GS2 for grain yield will be explored later.

Little is known about the effects of high temperatures (>32°C) on leaf area development. Evidence from maize (Watts 1972) and sorghum (Peacock 1982) suggests that the rate of leaf extension declines rapidly between 35 and 40°C. Our own measurements suggest an optimum temperature of 32 to 34°C for millet (Fig. 5a). High temperature is usually associated with rapid transpiration, so that the maximum rate of extension is seldom maintained except for brief periods in the morning. The measurements summarized in Figure 4 suggest that the increase of LAI is slightly slower at 31 than at 28°C, probably because of a greater demand for evaporation. In contrast to sorghum (Peacock 1982), pearl millet requires a base temperature nearer 10 than 15.5°C (Fig. 5b). A T_b of 10°C is consistent with the extrapolated values obtained for several developmental processes (Table 1).

Table 2. Duration of GS2 in pearl millet cv BK-560 and the accumulated intercepted radiation at five mean temperatures.

Mean air temperature (°C)	Duration of GS2 (days)	Total intercepted radiation during GS2 (MJ/m^2)
31	25.1	93
28	30.5	133
25	33.1	178
22	41.4	205
19	51.6	238

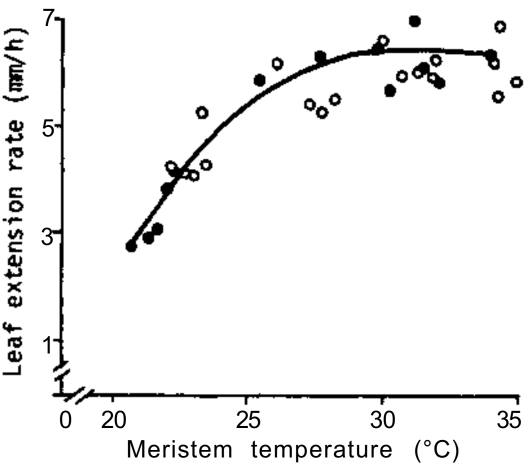

Figure 5a. Hourly extension rate of leaf 9 between 0500 and 1600 h GMT. Measurements were made at 24 (o) and 25 (•) days after sowing when maximum saturation deficit at 1500 h GMT reached 3.5 kPa.

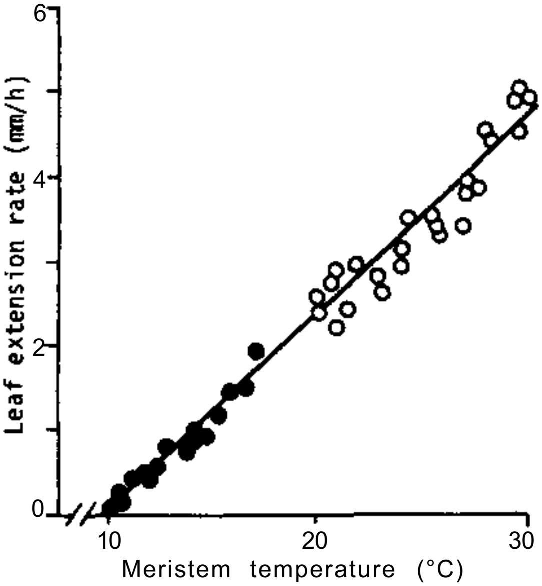

Figure 5b. Rate of leaf extension of millet cv BK-560 as a function of temperature. Hourly extension rate of leaf 7 of potted plants inside (o) and outside (•) the glasshouse was measured on two consecutive days. Both day and night values fell on the same line (fitted by eye).

Roots

The rate of root elongation of millet is also a linear function of temperature with a T_b of about 12°C (Fig. 5c). Similar rate-temperature relationships have been established for the roots of maize (Blacklow 1972) and cotton (Arndt 1945). The elongation of roots is usually measured on young seedlings, as it becomes increasingly difficult to extract all the roots from the soil. The production of root axes in cv BK-560 is closely correlated with the number of leaves produced on the main culm and with the soil temperature at 5 cm depth (P.J. Gregory, personal communication). For this process too, the value of T_b obtained by extrapolation is about 10°C, which is consistent with values established for many developmental processes (Table 1). Root elongation, as recorded experimentally, is a consequence of both cell division and cell expansion.

Tillering

Leaves from tillers can account for 60 to 70% of the total leaf area in a healthy millet crop (Gregory and Squire 1979). Although the photosynthetic efficiency of leaves on tillers may be less than on the main culm (since they are usually shaded) they sometimes make a major contribution to final yield (Egharevba 1977). There is much evidence that tillering in cereals is sensitive to both temperature and light. In general, basal tillers start to emerge after the production of a specific number of leaves, which can be quantified in terms of thermal time. Subsequent tillers are produced at a rate further associated with the number of leaves on the main culm. Varietal differences in tillering have been reported: cv Katherine Pearl tillered after four or five leaves were produced (Begg 1965); cv Ingrid Pearl, after eight or nine leaves (Pearson 1975).

Many workers concluded that T_b and T_o for rate of tillering are both lower than for the production and expansion of leaves (Pearson 1975; Ivory and Whiteman 1978). Our own studies on vegetative and reproductive plants suggest that although differences are small, they may exist when the dominance of the main stem is modified by photoperiod or when the light regime within the canopy is modified by temperature or plant spacing. In long days, for instance, the longer duration of GS1 increased the number of tillers produced, mainly because tillering continues for a longer period (Ong 1983a). When light competition is reduced or delayed by decreasing plant population or by low temperatures, tillering increases dramatically. For millet (BK-560) grown in Niger, a stand with2.9 plants/m^2 had 2.8 times more tillers than a stand with 11.5 plants/m^2 (Azam-Ali et al. unpublished).[1] Fussellet al. (1980) reported even more prolific tillering for the same species: 7.8 times more at 21 than at 30°C.

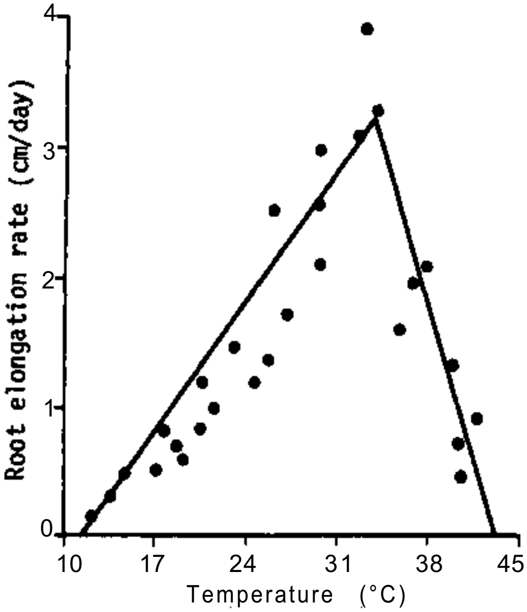

Figure 5c. Rate of root elongation of millet (cv BK-560) as a function of temperature. Lines are fitted by eye. (Source: Garcia-Huidobro et al. 1982.)

The agronomic significance of tillering is most evident in millet/legume intercrops when most of the increase in yield is usually derived from the additional tillers produced (Reddy and Willey 1980).

In pure stands, however, high tillering ability may be disadvantageous in those areas where millet is grown for grain. Although tillers may make up over 60% of the total dry matter of the crop, they repres-

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[1] S.N. Azam-Ali, P.J. Gregory, and J.L. Monteith, 1983, Effects of planting density on water use and productivity of pearl millet (*Pennisetum typhoides)* grown on stored water. Water use, light interception and dry matter production. (In preparation).

ent only about 15% to the grain yield since many fail to produce grains. Egharevba (1977) concluded that, in Nigeria, reducing tillers from 10 to 3 or 5 consistently increased grain yield of millet (cv Ex-Bornu) by 15 to 30%. On the other hand, uniculm plants yield about *20%* less than the high-tillering control.

Photosynthesis, Dry-matter Production, and Light

The photosynthesis of millet leaves has been measured in the laboratory but not in the field, as far as we are aware. McPherson and Slatyer (1973) established light-response curves for the leaves of *P. typhoides* (cv Katherine Pearl) exposed to artificial light with a specific quantum flux density up to 4000 μ E/m^2/s. When the irradiance was less than about 400 μ E/m^2/s (equivalent to about 170 W/ m^2 or one-fifth of full sunlight), the photosynthesis rate increased almost linearly with irradiance at about 6.0 g CO_2 /MJ of total radiation. At an irradiance equivalent to half of full sunlight, the efficiency was about 4.5 g/MJ and in full sunlight it was about 2.7 g/MJ. Assuming arbitrary factors of 60% for the loss of CO_2 by respiration and 30/44 for the relative weight of dry matter and CO_2, corresponding figures for the efficiency of dry-matter production are 2.5,2.0, and 1.1 g/MJ of total radiation for 20, 50, and 100% of full sunlight.

In a crop canopy, the average irradiance of a leaf is usually less than the irradiance as measured on a horizontal surface above the canopy. When the sun is shining, the average irradiance is approximately KI where the extinction coefficient K, depending on the architecture of the canopy and the geometry of the sun, has a value of about 0.5 for millet (Marshall and Willey 1983) during midafternoon. The efficiency of dry-matter production by a canopy would therefore be expected to be in the range 2.0 to 2.5 g/MJ. For comparison with field measurements by our colleagues, by ICRISAT staff, and by Begg (1965), we have calculated the weight of dry matter produced by stands of millet per unit of radiation intercepted by the foliage before anthesis (Table 3). Values for three well-watered crops ranged from 2.15 to 2.37 g/MJ, consistent with prediction. For an unirrigated stand growing mainly on stored water after the monsoon, the value was 2.0 g/MJ, and for a crop growing entirely on stored water on a sandy soil in Niamey it was 1.5 g/MJ. Corresponding values for the period from sowing to harvest were lower by about 30% on average, consistent with the decline in canopy photosynthesis after anthesis in the absence of new leaves.

Table 3. Dry-matter production, insolation, temperature, and conversion rate in pearl millet at three sites.

	Hyderabad, India			Niamey, Niger [c]	
	1977 postrainv season [a]		1978 rainy season [b]	Postrainy season	Katherine, Australia [d]
	Irrigated	Unirrigated			
Total dry matter at maturity (g/m^2)	622	312	810	300	2174
Maturity (days after sowing)	68	68	75	70	112
Mean air temperature (°C)	21.5	21.5	25.8	27.4	28.1
Mean daily insolation (MJ/m^2)					
Whole season	15.2	15.2	17.9	17.0	21.3
Pre-anthesis	14.1	14.1	18.0	19.0	21.0
Total intercepted radiation (MJ/m^2)					
Whole season	448	290	530	256	1576
Pre-anthesis	207	192	170	153	887
Conversion rate (g/MJ)					
Whole season	1.49	1.14	1.38	1.17	1.26
Pre-anthesis	2.35	2.00	2.15	1.50	2.37

References: a. Gregory and Squire (in preparation).
b. Marshall and Willey (1983).
c. Azam-Ali et al. (in preparation).
d..Begg (1965).

When we repeated this type of analysis for crops growing in our glasshouses at mean temperatures between 19 and 31 °C, we obtained mean values of 3.1 g/MJ (to anthesis) and 2.4 g/MJ (whole season). These values were expected to be larger than those for field crops growing in the tropics because the irradiance was only 10 MJ/m^2 per day but the pre-anthesis figure was not expected to exceed the dim-light figure of 2.5 g/MJ which McPherson and Slatyer obtained for single leaves. Either their leaves were stressed—which is unlikely—or our plants were intercepting more light than we calculated, possibly because of lateral illumination in a stand which was 2.0 m high but only 32 m^2 in area. We did not harvest plants growing within 0.3 m of the walls, but this precaution may not have been adequate.

Although the absolute values of efficiency for our glasshouse plants may be somewhat too large because of edge effects, we have no reason to doubt the validity of relative values measured at different temperatures, as shown in Figure6. Above 21°C, the fractional change of efficiency with temperature is small, but there is a broad maximum at about 25°C. The single leaves monitored by McPherson and Slatyer reached a maximum photosynthesis rate at about 35°C (and, very surprisingly, maintained about 60% of the maximum rate even at 50°C). Their measurements and ours can be partly reconciled if our lower maximum reflects the effects of temperature on senescence as well as on the maximum photosynthesis of a young leaf. We were measuring the response of a population of leaves which aged faster with higher temperature.

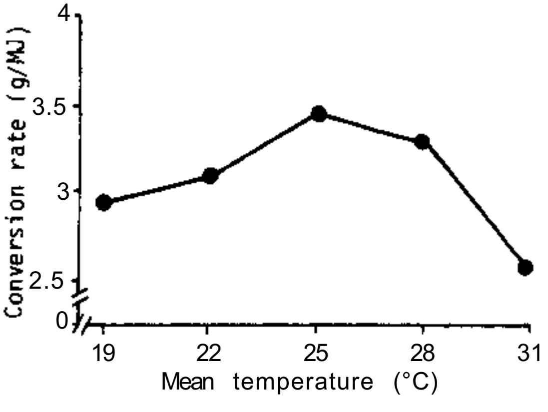

Figure 6. Rate of dry-matter conversion (g/MJ) of millet stands (cv BK-560) at five mean temperatures.

Effect of Temperature and Light on Grain Yield

The damaging effect of extremes of temperature on spikelet survival and the number of grains per panicle is well documented (Fussell et al. 1980; Ong 1983b). Figure 7 shows the relation between the number of grains produced by two millet cultivars as a function of mean air temperature. Both sets of data indicate an optimum temperature of 22 to 25°C, above and below which grain number declines sharply. At low temperatures, grain number is probably reduced by the direct effects of spikelet death, spikelet sterility, and male sterility (cf. Downes and Marshall 1971 for sorghum).

Environmental factors that affect either growth rate per plant or development rate, through temper-

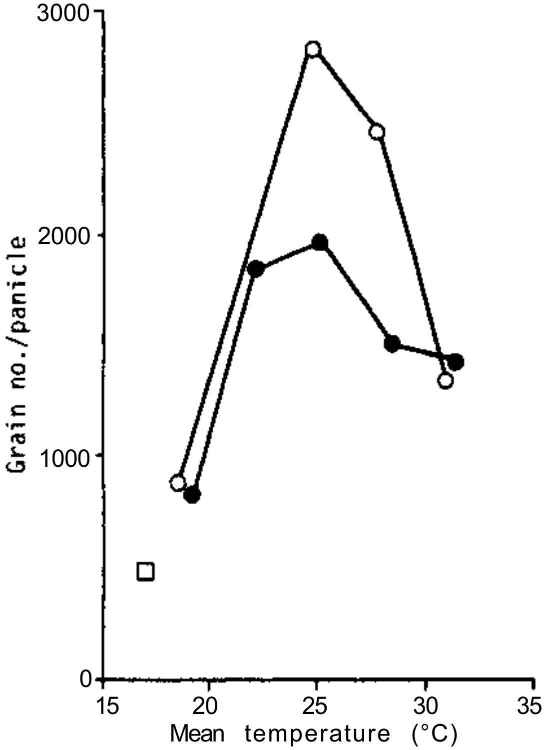

Figure 7. Final number of grains per panicle as a function of mean temperature. Data for cv BK-560 (●) and cv Tift (○) (Fussell et al. 1980) were obtained from glasshouse experiments and field data (□) from Pearson (1978).

ature, have a clear influence on grain number at final harvest (Fig. 8). For example, the difference between the 22 and 28/29°C treatments in two consecutive years was caused by the amount of radiation intercepted. On the other hand, differences between temperature treatments in 1979 were strictly due to the rate of development. The Hyderabad data confirmed the finding that post-anthesis growth rate had negligible influence on grain number since the unirrigated stand stopped growing after anthesis (44 days after sowing) while the irrigated stand grew for another 26 days. Final plant weight reached 10.9 and 22 g respectively.

Even more conclusive evidence for the importance of the duration of GS2 is reported by Fussell et al. (1980). They showed that when plants were transfered from one temperature regime to another at various stages of development, the greatest response of grain number to temperature was during GS2. Transfer to different temperature regimes after anthesis had little effect on the number of grains produced. Temperature after anthesis appeared to determine the *duration* of grain growth when water was not limiting but had relatively little influence on the *rate* of grain filling. Thus the production of larger grains at low temperatures is explained by the longer duration of grain growth. An increase in grain weight was also observed when grain number was reduced during GS2. However, such compensatory growth was seldom large enough to increase the harvest index, even when growing conditions improved after anthesis.

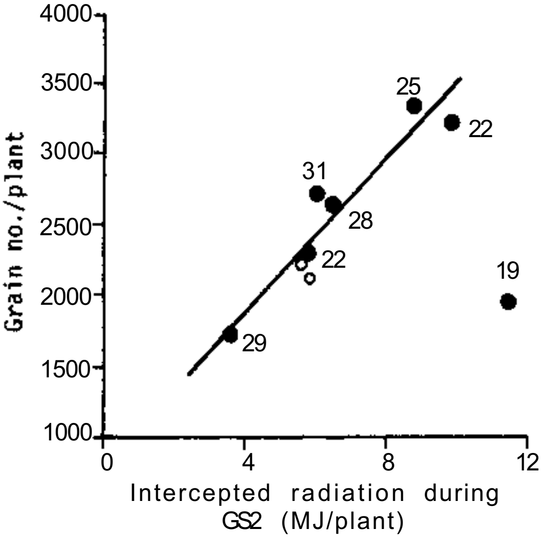

Figure 8. Final grain number per panicle as a function of radiation intercepted during GS2 (cv BK-560). Mean temperatures are indicated on glasshouse data (•). Data from ICRISAT experiment (Gregory and Squire 1979) are represented by open symbols (o).

Harvest Index

A comparison of harvest index and plant size for cv BK-560, grown at different irrigation, spacing, and temperature regimes, supports the hypothesis that the final number of grains produced is determined early in the life of the crop, and the large differences in plant size after anthesis have a relatively small effect on the final harvest index, unless tiller mortality is substantial (Fig. 9). From a spacing experiment in Niamey and an intercrop experiment in Hyderabad, harvest index was conservative—in the range 0.34 to 0.45, despite a four- to five-fold difference in plant size. During GS2 there is unlikely to be a large difference between plants sown on the same date at the same location, in terms of water extraction and/or radiation interception. Furthermore, the number of grains on fertile tillers is also determined early. The highest harvest index of this set was recorded in a postrainy-season crop

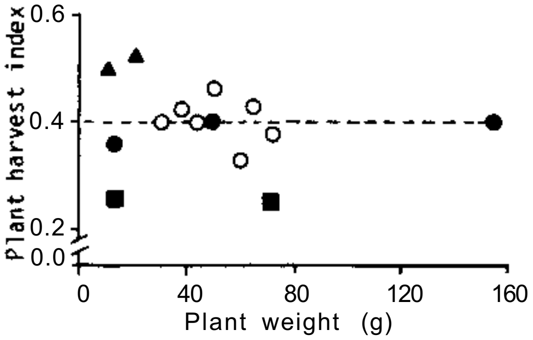

Figure 9. Harvest index of pearl millet cv BK-560 and plant weight (g).

Glasshouse crops	○
Niamey crop	
(Azam-Ali et al. in press)	●
Hyderabad crops	
Postrainy season 1977	▲
Rainy Season 1978	■
(Reddy and Willey 1980)	

(1977) with few vegetative tillers. We cannot explain the low harvest index in the rainy-season crop (1978). Low temperature (19°C) in GS2 also reduces the harvest index because of fewer grains and proportionally more vegetative tillers.

Conclusions

In millet, and presumably in most cereals, developmental processes sensitive to temperature can be divided into two categories. The first category includes the initiation and appearance of leaves and the duration of GS2 and GS3—processes that are independent of light and therefore of growth rate, at least when plants are exposed to normal sunlight in the field. The second category includes reproductive processes, which determine yield potential as expressed by the number of spikelets or grains produced by an ear. Both in the field and in controlled environments, the final number of reproductive units depends on the growth rate of the whole plant (and therefore usually on irradiance) as well as on temperature. The relation between irradiance and thermal time suggested by Nix (1976) was a first step towards the combination of light and temperature in a physiologically appropriate form.

Examples of the first category are relatively well documented for many cereals. We have been able to reconcile measurements on cv BK-560 grown in our glasshouses and at two contrasting sites, Niamey and Hyderabad. Both final leaf number and time to anthesis were close to the prediction derived from the thermal time of the duration of the GS1 and GS2 phases.

In contrast, the second category is less well defined, although its agronomic significance is obvious. The concept of a "thermal growth rate" that incorporates growth rate per unit rate of development is central to our understanding of how yield components are determined, not only in millet, but in all crop plants. A successful attempt has been made to use this concept to explain spikelet survival and grain number in millet (Ong and Squire, in preparation), in maize (Hawkins and Cooper 1981), and in wheat (Rawson and Bagga 1979).

In this review, we were able to draw a number of general conclusions from our experience with a single cultivar, BK-560, but we are aware of many gaps in our understanding of how the growth and development of millet respond to environmental factors. The following list summarizes priorities for research.

1. *Germination.* The rate-temperature relationship established on a thermal gradient plate needs to be tested in farmers' fields. ICRISAT has already taken a lead in this respect. The value of T_b for contrasting varieties needs to be confirmed for other processes and phases of development as in cv BK-560 (Table 1).
2. *Daylength.* The influence of day length on the duration of GS1, GS2, and GS3, is still obscure. Most existing information fails to distinguish GS1 from GS2 and therefore has limited application. Regular apical dissection is necessary in experiments involving daylength treatments. In addition, there is virtually no information on how daylength influences the rate of leaf appearance, tillering, and growth. Ong and Everard (1979) indicated how morphology and partitioning in millet are particularly sensitive to daylength regimes.
3. *Grain number.* This is the major component of grain yield, yet our understanding of the mechanisms controlling this process is so poor that no clear concept has been applied to explain variation from year to year and from site to site. The concept of a thermally adjusted growth rate is a promising first step in the analysis of field experiments.
4. *Survival of spikelets and tillers.* The relation between survival and environment has not been studied systematically, although it is widely recognized that the adaptability of millets is associated with tiller production and survival. Development is usually monitored so infrequently that it is difficult to understand the influence of ontogeny and phenology, let alone the physiological basis for tiller survival.
5. *Genotypic differences.* Large differences in T_b and T_o have been established for the germination of contrasting varieties, but the biochemical and genetic basis for these differences is still unknown.

Until research in these areas makes substantial progress, it will be unsafe to generalize to other seasons and other sites measurements made over a restricted number of seasons and sites. We do not believe, however, that a better understanding of physiological processes will necessarily make models of crop growth even more complex. On the contrary, we have found that a search for conservative quantities in biological, as in physical, systerns can greatly simplify their analysis and mathematical description. The possibility that base temperature is nearly constant for a wide range of developmental processes in millet cv BK-560 is a good demonstration of this principle.

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Light and Temperature Responses in Sorghum

J.M. Peacock* and G.M. Heinrich**

Abstract

Sorghum (Sorghum bicolor) *has achieved importance as a well-adapted crop of the arid and semi-arid tropics, where water, temperature, and nutrients invariably limit yield but where radiation* (light) *levels are often high. The effects of light on sorghum growth are dealt with briefly but considerable emphasis is placed on the effects of temperature. The literature has been thoroughly re viewed and relationships are summarized for each critical stage of development: germination and establishment, leaf area development, panicle initiation and development, and grain filling.*

It is emphasized that physiologists need to develop simple methods capable of screening large numbers of germplasm and breeders lines in order to identify and quantify genetic variability that will be useful in matching sorghum to specific temperature situations. Some simple methods are described, and the role of the agroclimatologist is also stressed in obtaining a clearer picture of temperature conditions in sorghum-growing areas of the world, and the probabilities of stress-inducing temperatures occurring during the growing season. It is clearly established that temperatures at all stages of crop development are a crucial environmental factor determining sorghum growth and development.

Résumé

Réaction du sorgho à la lumière et à la température : Le sorgho (Sorghum bicolor) *a pris de l'importance comme culture bien adaptée aux régions tropicales arides et semi-arides où les problèmes liés à l'eau, les températures et les éléments nutritifs limitent les rendements. Dans ces régions les niveaux de rayonnement sont souvent élevés. Cette communication traite plutôt des effets de la température sur la croissance du sorgho; les effets de la lumière sont présentés brièvement. A partir de la documentation, les auteurs ont fait une synthèse des relations pour chaque stade de développement : germination et établissement de la culture, développement de la surface foliaire, initiation et développement des panicules, remplissage des grains.*

On souligne la nécessité pour les physiologistes de concevoir des méthodes simples permettant de cribler un grand nombre de lignées de matériel génétique et de sélection pour déterminer et quantifier la variabilité génétique. Ceci facilitera le choix du type de sorgho le mieux adapté à des conditions de température données. Quelques méthodes simples sont décrites. L'agroclimatologiste devrait contribuer à une meilleure com-

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préhension des conditions de température régnant dans les régions productrices de sorgho et des probabilités de températures critiques pendant la période de croissance étant donné que la température joue un rôle capital dans la croissance et le développement du sorgho.

Sorghum (*Sorghum bicolor* L Moench) has achieved its importance in the world as a well-adapted crop of the arid and semi-arid tropics where light (radiation) levels are invariably high and nonlimiting, but where water, temperature, and nutrients invariably limit yield. Although the title of our paper is "Light and temperature responses in sorghum," the authors recognize that the central theme given to this session is the response of sorghum and millet to environmental stress. For this reason our paper is largely confined to the effects of temperature on sorghum growth, and the authors make no apology for the brief section on light, which deals with environments where water and nutrients are not limiting. Indeed it is our aim to point out that research on leaf photosynthetic rates and light utilization per se may be of limited use compared with research on the effects of temperature, particularly in those areas where drought is a major limiting factor.

In this paper we hope to make four points. First, that temperature stress is a major factor limiting sorghum production in the semi-arid tropics (SAT); therefore, there is an urgent 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. Second, that if we know when these temperature-stress conditions are likely to occur, we may be able to adjust our management of the crop to reduce these effects. Third, that sources of resistance to temperature extremes do exist in the germplasm, which may enable us to overcome some of the effects of such extremes. Fourth, that simple, inexpensive techniques capable of screening large numbers of germplasm and breeders lines can be developed.

We propose to examine the effects of temperature on each critical stage of development, from the newly sown seed to physiological maturity of the grain. Consideration will be given to what is currently known about the response and adaptation of sorghum plants to low and high temperatures and the temperature x growth-process interaction at critical stages of development (in this context we refer you to a recent review by Peacock 1982). We will also consider available screening methods capable of identifying sources of resistance to temperature stress.

Growth and Development

Light

Photosynthesis

Sorghum has the potentially high rates of dry-weight production of any C_4 crop. However, the rate of growth of the canopy is largely determined by the net photosynthetic rate of the leaves and panicle. Under nonstress conditions, photosynthesis is affected by the amount of incident photosynthetically active radiation (PAR), the proportion of this light intercepted by the canopy structure, and the distribution of it down the canopy.

Leaf photosynthetic rates have been measured by a number of workers (Eastin I968; Turner and Incoll 1971; McCree and Keener 1974; Rawson et al. 1978).

Genetic variation has been shown to exist (Kreig 1982), with values ranging from 23 to 72 mg CO_2/dm^2 per hour. As in many cereals, there is significant photosynthesis by the inflorescence. Fischer and Wilson (1976) observed in the field that 15% of total canopy photosynthesis during a 3-week period after anthesis was accounted for by the panicle. Eastin (1968) measured over 40% light interception (PAR) by panicles in some varieties.

Light Interception and Canopy Structure

Light distribution patterns in sorghum have been described by Goldsworthy (1970), Witt et al. (1972), Kanemasu and Arkin (1974), Clegg et al. (1974), Fischer and Wilson (1975), and Kanemasu and Owonubi (1978). Light extinction coefficients (K) and the fraction of light not intercepted by unit leaf area index (S) (Monteith 1965) have been calculated from these numerous studies. Values of K range from 0.29 to 0.69 and of S from 0.46 to 0.79. It was observed (Goldsworthy 1970) that S values generally increased with increasing population density and were affected by cultivar. This was attributed mainly to differences in leaf inclination. Fischer and Wilson (1975,1976) observed higher net photosynthetic and crop growth rates associated with (the theoretically advantageous) higher leaf inclination, more uniform leaf dispersion, smaller leaves, greater canopy depths, and lower K values. Hoshino et al. (1978) provide additional evidence of the advantage of plant height.

Crop Growth Rate

The highest crop growth rate reported for sorghum is 43.6g/m^2 per day (Fischer and Wilson 1975), the average rate for the whole crop cycle from emergence being 31 g/ m^2 per day. This was achieved at a plant population of 646000 plants/ha and average shortwave radiation of 26.5 MJ/m^2 per day for the whole period.

Clearly, at the higher irradiance levels (mean annual 17-25 MJ/m^2 per day) experienced in the SAT (Sivakumar and Virmani 1982), potential dry-matter accumulation for sorghum is high. It is also evident that such accumulation levels depend on the crop canopies intercepting nearly all the incoming radiation. However, in most areas in the SAT where sorghum is grown, this does not happen: poor crop establishment, low fertility, and drought result in very poor crop stands, poor growth, and low levels of light interception.

It is therefore unlikely that light per se is the major limiting factor to grain yields in the SAT; other environmental factors, such as water and temperature, may impose more serious restrictions on crop growth. The subject of water use in sorghum is covered in detail by others in these proceedings (Seetharama et al.; Kanemasu et al.; Forest and Lidon) and by Dancette and Forest (C. Dancette and M. Forest, 1982, Recent work on water requirements of millet and sorghum, unpublished). Thus the rest of this paper deals with the response of sorghum to temperature only.

Temperature

In the semi-arid tropics where sorghum is grown, air temperatures often exceed 40°C and leaf temperatures of 55°C have been measured (Peacock 1982). At the soil surface even higher temperatures (>60°C) may be experienced by the emerging sorghum plumule (Peacock and Ntshole 1976) and temperatures as high as 68°C have been reported (Peacock 1977). It should be noted that to interpret the effects of temperature per se on plant growth in the field is often difficult, because temperatures in a crop canopy vary both with time and space. It is perhaps also worth considering, in view of the main theme of this symposium, that high-temperature stress is often accompanied by water 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 these stresses separately. This has been done in Nebraska and Texas, USA, and currently is a major research area at Patancheru, India (ICRISAT 1981). Heat stress is also easier to induce experimentally than water stress, and 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 Andrews 1969).

In addition, sorghum is also subjected to cool temperatures and is known to be particularly sensitive to chilling (Bagnall 1979). However, some grain sorghums are known to possess varying degrees of cold tolerance (Singh 1977) and a substantial number of these are grown in the highlands of Ethiopia, Uganda, Yemen Arab Republic, and—to a limited extent—in the highlands of Kenya, Zaire, Cameroon, and 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).

Germination and Establishment

The ability of a sorghum seedling to emerge and establish rapidly is essential to the success of any new cultivar. However, this has been largely ignored by crop-improvement programs throughout the world. Although many promising sorghum cultivars have resistance across geographic regions to pests and diseases, what is their use if under field conditions they fail to emerge and establish? it has long been recognized that sorghums germinate best at relatively high temperatures, and the optimum temperature observed by Martin et al. (1935) was between 30 and 35°C. But a review of the literature (Peacock 1982) (Table 1) shows that the best germination occurs at soil temperatures ranging from 21 to 35°C. Moreover, it would appear that the supposedly lethal temperature for germination ranges from 40 to 48°C (Table 1). These two ranges suggest that there is genetic variation, not only in the optimum temperature required for highest germination, but in the maximum temperature at which plumules can survive.

Table 1. Summary of literature showing the range of optimum temperatures and the upper limits of temperature for germination in *Sorghum bicolor.*

Temperature (°C)	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)

Recent studies at ICRISAT (Soman 1981; Wilson et al. 1982) have confirmed that there is genetic variation in the ability of sorghum to emerge at high soil temperatures, and that some lines have the ability to emerge even when soil surface temperatures are as high as 55°C.

The effect of temperature on the rate of plumule extension was also examined (Soman 1981). It is argued that the sooner the plumule reaches the surface, the better its chance of emerging before a surface crust develops. Plumule extension rates were shown to vary among genotypes; e.g., at 41 °C growth rates ranged from 0.5 to 1.3 mm/h (Peacock 1982). The development of the plumule in the soil is being examined more closely, and some visual observations indicate that on reaching the surface (in many instances where there is no crust), the plumule bends over, apparently as a result of the high surface temperature.

It is worth noting that throughout this series of experiments on factors affecting crop establishment (temperature, water, and crusting effects) the varieties performed significantly better than these particular hybrids. This is perhaps significant, because numerous reports have been received this year about poor crop establishment of hybrids, notably CSH-5 and CSH-6, in both central India and West Africa. Until now the dominance of sorghum hybrids in both nonstress and stress conditions has gone unchallenged.

At low temperatures, large-scale screening of the germplasm has not been carried out, although 600 lines were recently examined in Texas (F. Miller and J. Mann, personal communication), and a joint ICRISAT/INTSORMIL project has now been initiated to examine germination at low temperatures in a wide range of germplasm of different taxonomic groups from different elevations. A recent review of the literature (Peacock 1982), summarized in Table 2, shows clearly that genetic differences occur.

When temperatures drop below 0°C, sorghum seedlings are often killed, although some have been reported to withstand a slight frost (Martin 1941). Seed 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 percentages (30-35%) subsequent germination is markedly affected (Carlson and Atkins 1960; Rosenow et al. 1962; Kantor and Webster 1967).

At present it would seem that there have been few attempts to select for improved establishment at cold temperatures, but the problems of crop establishment in sorghum at both low and high temperatures cannot be overemphasized.

Table 2. Summary of literature showing the range of minimum temperatures for germination and the lower limit for seedling survival in *Sorghum bicolor.*

	Temperature (°C)	Reference
Minimum germination temperature	7-10	Quinby et al. (1958) Pinthus and Rosenblum (1961)
	5-17	Thomas and Miller (1982)
55% seedling emergence	15	Singh and Dhaliwal (1972)
Seedlings killed	<0	Martin (1941)

Leaf Area Development, Stem Growth, and Tillering

In sorghum, as in any crop plant, the rate of dry-matter production is strongly affected by leaf area, especially between emergence and panicle initiation (GS1), when the canopy is developing (McCree and Davis 1974). The factors influencing leaf area development include the time to panicle initiation (through its effect on leaf number); the rates of leaf appearance, leaf expansion, and leaf senescence; and the canopy structure. In the grasses, 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 1975, for temperate grasses; and Gallagher 1979, for temperate cereals).

In sorghum, few quantitative data are available (Table 3) on the effects of temperature on leaf area development. Downes (1968) showed that the rate of leaf appearance (leaves/day) in sorghum increased from 13 to 23°C, and recent work (G.L. Wilson, unpublished) shows that the rate of leaf appearance, measured over a temperature range (day/night) of 20/15 to 35/30°C, increases with temperature. More recent work by Logan (1981) shows that the rate of leaf appearance in sorghum is closely related to thermal time after sowing. Leaf number in sorghum was increased when temperatures in GS1 were raised from 25/20 to 35/30°C (I. Baker, unpublished).

Leaf extension was shown by Johnson (1967) to closely parallel air temperature, and Figure 1 shows some recent data from ICRISAT on the effects of temperature on leaf extension. The continuous line represents the best fit of the data, and it can be seen that the rate of leaf extension starts to decline at temperatures above 34°C. The dotted line, fitted by eye, suggests that the base temperature (Tb) for leaf extension is around 15.5°C.

There is little information on the effects of temperature on leaf area development in sorghum and almost none on the effects of very high temperatures. Studies were initiated at ICRISAT in 1980 to examine the effects of temperature on leaf area development over a wide range of temperatures, with emphasis on the summer season where the effects of high temperature in the absence of water and nutrient stress were examined (Seetharama et al. 1982).

In summary, it is clear that leaf expansion in sorghum is very sensitive to temperature and that genetic variation in leaf growth rates in relation to temperature is large (Quinbv et al 1973: Wade et al. unpublished). Such information is already being used to form the basis of a sorghum growth model (Huda et al. these Proceedings), andTurner(1982)

Table 3. Summary of literature on the effects of temperature on leaf area development, stem growth, and tillering in *Sorghum bicolor.*

Temperature effect	Temperature range (°C)[1]	Reference
Leaf appearance rate increased	13 to 23	Downes (1968)
	20/15 to 35/30	Wilson (1981, unpublished)
		Logan (1981)
Leaf number increased	25/20 to 35/30	Baker (1981, unpublished)
Leaf number reduced	<13/8	Major et al. (1982)
Leaf extension rate reduced	< or >34	Wade et al. (1980, unpublished)
Leaf extension ceases	< 15 or >43	Wade et al. (1980, unpublished)
Leaf weight reduced	> 33/28	Downes (1972)
Leaf chlorosis	0	Slack et al. (1974)
Stem weight reduced	> 33/28	Downes (1972)
Plant height reduced	< 13/8	Major et al. (1982)
Tiller number reduced (100%)	>18	Downes (1968)
Tiller number increased	<13/8	Major et al. (1982)
(Strong interaction with high irradiance)		

[1] Temperatures separated by a slash indicate day /night temperatures.

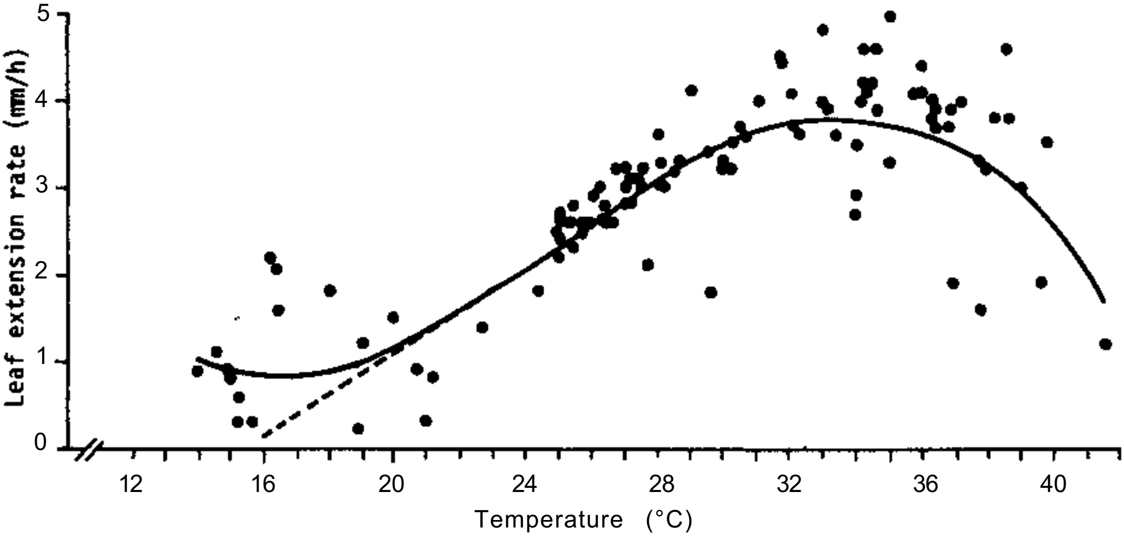

Figure 1. Relationship between leaf extension and temperature in sorghum cv CSH-8. (Source: Wade et al., unpublished.)

suggests that an understanding of the role of leaf expansion and leaf senescence in relation to water deficits and water use be given high priority in any crop-improvement program concerned with drought.

The effects of temperature on cell and leaf tissue survival are also of particular importance. Earlier work (Sullivan and Blum 1970; Sullivan 1972; 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 phenomenon known as "leaf firing" (Sullivan et al. 1977; Peacock 1979; Jordan and Monk 1980). Research in Botswana showed that leaf firing occurred in cv RS-610 at a leaf temperature of 43°C (Peacock 1979). 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.

The leaf disc method (which essentially estimates the electrolytic leakage from a leaf segment by measuring the electrical conductivity) has been extensively used to measure heat tolerance (Sullivan 1972). In two populations (M35-1 conversion hybrids and NP9-BR lines) Sullivan and Ross (1979) showed that heat tolerance was positively correlated with higher yields (Fig. 2). Selections from this NP9-BR population continue to do well under the very arid conditions in Arizona (INTSORMIL 1980).

At ICRISAT, germplasm and breeders' source materials have been screened for heat and desiccation tolerance (Peacock 1982). During the screening period air temperatures reached 43°C and leaf temperatures exceeded 55°C. Leaf desic-

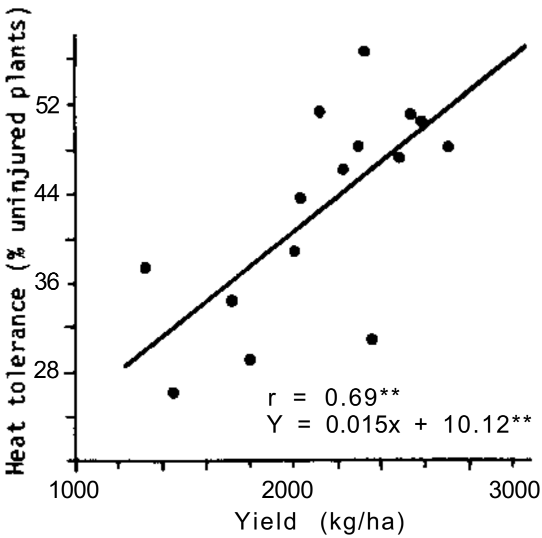

Figure 2. Relationship between heat tolerance and yield of 15 M-35-1 conversion hybrids, determined during a period of maximum stress in Nebraska, USA. (Source: Sullivan and Ross 1979.)

cation (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 and others partially fired, whilst some remained unaffected. Material was selected by visual scoring, and over 1000 lines could be evaluated per day. Similar results were obtained when the material was grown at Anantapur (India) and Gadambalia (Sudan) under naturally occurring drought during the normal growing season.

Experiments conducted at ICRISAT in 1981 (Hanks et al. 1976; ICRISAT 1981) and at Temple, Texas (Jordan and Sullivan 1982) provide further evidence that parental lines with high heat tolerance can be identified and that breeding for high-temperature 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. These workers 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, and 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 (Kaloyereas 1958, as modified by Murty and Majumder 1962) and (b) the measurement of increased chlorophyll fluorescence (Smillie 1979). 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 techniques to evaluate the inherent adaptability of sorghum lines to high 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 the visual score approach should be adopted in crop-improvement programs. It is possible that the simple approach used by Heyne and his colleagues in the 1930s will provide the basis for our heat- and drought-screening techniques for sorghum in the 1980s.

There is a dearth of information (Table 3) on the effects of low temperature on leaf area development, stem growth, and tillering in sorghum (Peacock 1982). A common symptom of chilling injury during early growth in sorghum 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. This is again an area that needs examining. Possible sites in countries of eastern Africa and Mexico could be identified for detailed studies in the 1980s. It is apparent that very little is known about sources of 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.

In outlining a breeding program for cold tolerance, Singh (1977) gave reasons for the failure of sorghum at low temperatures. These were listed by Peacock (1982) in a recent review, together with some promising screening techniques for chilling tolerance. In addition, inheritance studies (Paull et al. 1979) indicate that variation for chilling sensitivity within species is largely additive and under polygenic control. The transfer of genes for cold tolerance from wild species adapted to high altitudes in the tropics has been suggested with sorghum (Van Arkel 1977), and Guiragossian (1981) 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 high-temperature tolerance, should be given increasing support during the 1980s. We believe that success will depend not only on developing simple screening techniques for chilling tolerance, but also on locating suitable areas for field evaluation.

Root Growth and Nutrient Uptake

As reported earlier by Peacock (1982), there is apparently no information on the effects of temperature on root growth and nutrient uptake in sorghum. However, a recent thesis (Hem 1982) has examined the relationship between the rate of root elongation and soil temperature over a 12 to 30°C temperature range, both in pots and in the field. The relationship is very similar to the one previously shown between leaf extension and temperature (Fig. 1).

Panicle Initiation, Development, and Grain Filling

The initiation of the panicle meristem marks the end of GS1 and the onset of the reproductive phase. In sorghum this usually occurs between 30 and 40 days after emergence, but the timing, which may vary from 19 to 70 days (House 1981), is largely determined by temperature and temperature x photoperiod interactions (Caddell and Weibe! 1971; Downes 1972; Quinby et al. 1973). The interactions are complex, and how temperature affects the timing of panicle initiation (PI) is still unclear.

A recent study with ten sorghum maturity genotypes (Sorrells and Meyers 1982) showed that time to PI in two daylength-sensitive genotypes correlated positively with average minimum or average daily temperatures. (Average monthly temperatures ranged from 20 to 26°C: average monthly day/night differences ranged from 8 to 14°C.) However, for daylength-insensitive types, time to PI correlated best with differences in day/night temperatures; that is, larger day/night differences delayed PI. Other research has shown PI to be either hastened or delayed by increasing temperatures, depending on genotype (Table 4). Quinby (1974) stated that though it is apparent that temperature affects expression of maturity genes, the mechanisms are unclear, and hypothesized that it could be through temperature effects on plant hormones.

In brief then, temperature effects on plant growth prior to PI are various and complex, affecting photoperiodic responses and rate of development. While this must be important to later development of the plant, temperature effects on grain yield are not well quantified.

Grain yield is the product of grain number per unit land area and grain weight. Grain number per unit land area is the yield component most often and most strongly correlated with final grain yield. These correlations may be as high as 0.98 across locations (Heinrich 1981). Panicle development from PI to anthesis (GS2) is very important in determining final grain yield because the upper limit to grain number is set during this period. Temperature effects in GS2 are often manifested in terms of grain number per panicle (an important component of grains/unit land area) and are therefore strongly and directly related to final grain yield.

In general, higher temperatures tend to hasten anthesis (Doggett 1970; Ogunlela 1979; Heinrich

Table 4. Summary of temperature effects on panicle initiation (PI), development, and grain filling in *Sorghum bicolor.*

Growth stage	Temperature (°C)[1]	Reference
PI		
Floral initiation hastened	25/20 to 35/25	Baker (1981, unpublished)
Floral initiation delayed	> 32/28	Sorrells and Meyers (1982) Quinby (1974) Downes (1972)
GS2		
Floret abortion induced	33/28	Downes (1972)
	35/28	Baker (1981, unpublished)
	42/32	Pastemak and Wilson (1969)
Male sterility induced	13 night	Taylor (1973)
	10-12 night	Brooking (1976)
GS3		
Grain weight reduced (50%)	33/28	Chowdhury and Wardlaw (1978)
Grain weight reduced (43%)	35/30	Baker (1981)
Grain weight reduced	35/25	Tateno and Ojima (1978) Ogunlela(1974)
Length of GS3 reduced (18 days)	25/20 to 35/30	Baker (1981)
Length of GS3 reduced (≈20 days)	27/22 to 36/31	Chowdhury and Wardlaw (1978)

1. Temperatures separated by a slash indicate day/night temperatures.

1981). However, in one group of cultivars, Quinby (1974) noted that a decrease of about 3°C hastened bloom by as much as 10 days, had no effect, or delayed flowering by 8 days, depending on the genotype. So, although the reaction is genotype-specific, both sub- and super-optimal temperatures may hasten flowering and reduce the length of GS2. This is important, because a reduction in the length of GS2 caused by high temperatures has in some cases been associated with reduced yields in sorghum (Ogunlela 1979; Heinrich 1981). This reduced yield was associated with fewer grains per panicle. In a study with six genotypes in midwestern USA (Heinrich 1981), it was found that yield stability was more related to genotype x temperature than to genotype x moisture interactions, and that tolerance to high temperatures in GS2 was an important contributing factor to yield stability.

In addition to these general effects, high temperatures in GS2 may have negative effects on specific phases of panicle development, particularly in the latter part of GS2. Downes (1972) stated that temperatures above 33/28°C (day/night) (Table 4), caused floret abortion and that even moderately high temperatures at anthesis caused embryo abortion. Ogunlela (1979) found that floret differentiation was the stage of panicle development most susceptible to high-temperature stress. Night temperatures 5°C above ambient at this stage reduced seed number (30%) and grain yield (28%). Doggett (1970) also cites floral initiation as one of the most sensitive stages.

The mechanisms through which temperature affects panicle development are unclear. One hypothesis suggested by Downes (1972) is that high night temperatures limit yield because of competition for substrates by dark respiration. Without disagreeing with this, it has also been suggested (J.D. Eastin, personal communication) that above an optimum, higher temperatures increase vegetative growth relatively more than floral growth. (Leaf growth and stem elongation rates are maximized during GS2.) Vegetative growth may be a stronger sink, restricting floral development. Unpublished data (J.D. Eastin, personal communication) show that both day temperatures and night temperatures have important effects on panicle development and yield.

In brief, then, sub- or super-optimal temperatures may reduce the length of GS2 and super-optimal temperatures may reduce yields by decreasing seeds per panicle. High temperatures may have direct effects on specific phases of GS2, particularly floret differentiation. The specific mechanisms are unclear.

Sorghum genotypes show considerable diversity in reaction to temperature effects. Variation in temperature effects on days to flowering (Quinby 1974) has already been mentioned. The reduction in length of GS2 in response to higher temperatures (Heinrich 1981) varies with genotype, as does the yield reduction that occurs in conjunction with a shorter GS2 (Table 5). Because of this variation, the potential exists to improve sorghum tolerance to high temperature extremes that may occur in GS2. There is evidence to suggest that the length of GS2 and the period from anthesis to physiological maturity (GS3) may be influenced by maturity genes (Sorrells and Meyers 1982). If so, this fact might be used to manipulate sensitive growth periods to avoid times when temperature stress commonly occurs.

Screening genotypes specifically for tolerance to high temperatures during panicle development has not been done. However, maintaining daily records of temperature maxima and minima could be quite useful. Simple correlations between average daily or stress temperatures in GS2 and grain number could be calculated quite readily across locations and years during the final testing of genotypes. Selection of genotypes less sensitive to high temperatures in this growth stage might result in greater yield stability of released lines (Heinrich 1981).

There is apparently very little information on the effects of low temperature on panicle initiation and

Table 5. Correlations between temperature in GS2, length of GS2, and seed number in *Sorghum bicolor.*

Genotype	Average daily temperature in GS2 vs days in GS2	Days in GS2 vs seeds/m^2	Days in GS2 vs grain yield
1	-0.52*	NS	NS
2	-0.79**	NS	NS
3	NS	NS	NS
4	-0.79**	0.64**	0.62**
5	-0.69**	0.70**	0.59*
6	-0.53**	0.78**	0.74*

* and ** indicate significance at the 0.05 and 0.01 levels respectively. NS indicates nonsignificance. Correlations are across 14 environments (Heinrich 1981).

development (Peacock 1982) and most of this is on its effect on male sterility (Taylor 1973; Brooking 1976).

The maximum potential grain number is set by the end of GS2. Hence from this point onwards, final grain yield depends entirely on the grain weight achieved. Grain weight is a product of two factors: the rate of fill and the duration of the filling period. Both of these are markedly affected by temperature, although there is some disagreement as to which is more important.

In most studies of daily grain growth the growth curve is composed of a short period of logarithmic growth, followed by a linear phase during which the grains achieve 90 to 95% of their final dry weight. Near physiological maturity the rate again drops off.

In sorghum, Chowdhury and Wardlaw (1978) found that increasing temperatures increased the rate of grain fill but reduced the duration such that there was little change in grain size between 24/I9°C and 30/25°C (day/night). However, above 30/25°C, the rate of fill no longer increased, and the duration of filling was reduced such that at 33/28°C there was a 50% decrease in grain size. These results suggest that high temperatures reduce grain size through decreasing the duration of filling, when the decrease is not accompanied by a compensatory increase in rate of fill. Eastin et al. (1971) also found good evidence of the importance of length of fill to final grain size and yield.

At present little is known about the mechanisms through which temperature affects the rate or duration of grain growth. Duration, at least, does not appear to be related to flag-leaf photosynthesis in sorghum, as it sometimes is in other cereals (Chowdhury and Wardlaw 1978).

Heinrich (1981) concluded that sorghum genotypes may differ in both the rate and duration of grain filling and the way in which these are affected by stress. It was also found that sorghum genotypes with similar duration of GS3 may differ in the rate of fill and vice versa. It would seem possible, therefore, that the rate of grain fill could be improved without decreasing the duration of fill. It should also be possible to breed cultivars with a better capacity to fill grain under stress-level temperatures.

As with GS2, there is little information on effects of low temperatures in GS3. Peacock (1977), however, argued that the low yields of late-planted sorghum in Botswana were due to low night temperatures (4-12°C) occurring during GS3.

Specific screening for genotypes less sensitive to nonoptimal temperatures in GS3 is apparently not being carried out. In fact, more research is required to quantify the possible benefits from this type of screening before large-scale programs are initiated. Nonetheless, it is a promising area, and the variables involved are easy to measure, which would make screening large numbers of genotypes possible.

In summary, while temperature effects on panicle development and grain filling are generally subtle, they do often have important effects on final grain yield (temperature effects on panicle initiation, development, and grain filling are summarized in Table 4). The biochemical mechanisms remain unclear. Genetic variation in response to unfavorable temperatures does exist and could be exploited to improve cultivar resistance to temperature stress. Good quantification of temperature variation within environments would also aid in developing genotypes that could avoid temperature stress at critical stages.

Photosynthesis and Respiration

Total plant growth and grain yield (as related through harvest index) are essentially a direct product of net photosynthesis. Net photosynthesis represents gross photosynthesis minus the amount of fixed carbon lost through respiration. The portion lost through respiration may be as high as 25 to 50% (Wilson and Eastin 1982). Thus photosynthesis and respiration are an integral part of final yield.

Within the canopy, photosynthesis will depend on the amount of photosynthetically active radiation received by the plant parts involved, and the photosynthetic capacity of those surfaces. The latter is affected by genotype, age, acclimation, the persistence of unfavorable environmental conditions, water status, and also temperature (Wilson and Eastin 1982). A more detailed discussion, which puts the importance of photosynthesis and respiration of sorghum into perspective, is given by Wilson and Eastin (1982).

Photosynthesis. In C_4 species such as sorghum, high rates of photosynthesis only occur at high temperatures and light intensities. A range of temperature optima and upper limits for photosynthesis are given in Table 6. There is apparently a range of temperature optima across genotypes, and genotype differences do occur in the mainte-

Table 6. Summary of high and low temperature effects on photosynthesis in *Sorghum bicolor.*

Photosynthesis rate	Temperature (°C)	Reference
Maximum rate	35-42	Norcio(1976)
	30-36	Vong and Murata (1977)
Decline from maximum	> 33 (leaf temp)	Sumayao et al. (1977)
70% reduction	44	Chesnokov et al. (1974)
95% reduction	48	
100% reduction	45	Norcio(1976)
Rate reduced	<20	Pasternak and Wilson (1972)
	<10	McWilliam(1981)

nance of photosynthesis at high temperatures (43°C) (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 electroconductivity method (Sullivan 1972). However, in other crops selection for high photosynthetic rates per se has generally not been a productive approach to increasing yields. 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.

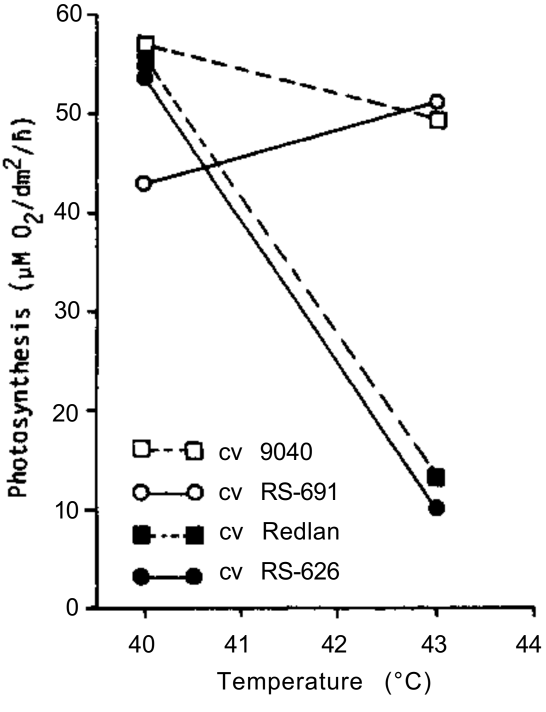

Figure 3. High-temperature effects on photosynthesis of four sorghum cultivars. (Source: Norcio 1976.)

The effects of low temperature on photosynthesis have been examined and are summarized in Table 6. 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 done on photosynthetic reactions to low temperatures (Taylor et al. 1974; Slack et al. 1974). Bagnall (1979) showed that the wild sorghum S. *leiocladum* had a higher photosynthetic rate over the range 3 to 20°C than S. *bicolor.*

Respiration. That respiration rates in sorghum (as in any crop) are influenced by temperature is well established (McCree 1974; Norcio 1976; Vong and Murata 1977; Eastin 1982). Wilson and Eastin (1982) 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 Mahalakshmi (1978) and Gerik (1979), the latter showing that whole-plant dark respiration varied from 4 to 10 mg CO_2/g/h at 30°C. More recent work by Eastin (1982) showed that respiration in sorghum at panicle initiation increased 15% for every 1 °C over the range from 12 to 27°C. Because of the close association between growth rate and respiration, McCree (1982) suggested that breeding strategies should be based on efficiency of conversion of photosynthate into plant biomass, rather than on photosynthesis or respiration rates per se. This seems a logical approach, and McCree has suggested a method. However, the effects of temperature on plant growth efficiency and the amount of variation in efficiency that exists are as yet unclear.

Conclusions

In summary, it is evident that temperature at all the critical stages of development has a major effect on the growth, development, and yield of sorghum. This is particularly so at the time of sowing, when both high and low temperatures drastically reduce germination. Temperature clearly has an important effect on leaf area development and both high and low temperatures cause serious leaf-tissue damage. Although the effects on panicle initiation and grain development are less obvious, temperature again plays an important role at these stages. It is also evident that there exist within the germplasm sources of resistance to temperature extremes that can be utilized to ensure better stability of yield.

To direct better the search for resistant material, it is vital that the agroclimatologists develop a clearer picture of the temperature conditions, particularly the timing and range of extremes of temperature, that occur throughout the sorghum-growing areas. Some excellent examples already exist (Rosenthal and Hammer 1979; Neild 1982), but we urge that this area be given further consideration during this symposium.

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Response of Sorghum and Pearl Millet to Drought Stress in Semi-Arid India

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Abstract

The wide range of environments in which sorghum and pearl millet are grown in semi-arid India can be grouped as variable, optimum (or near-optimum), and stored soil moisture types. Variations in specific plant responses such as phenology, leaf area development, root growth, and water-use efficiency under these three types of environments are discussed. Sorghum and millet are contrasted for their response to a variable moisture environment, and the response of sorghum grown under stored moisture during the postrainy season to terminal stress is described. Finally the role of timing, intensity, and duration of stress on grain yield is examined. Breeding and management strategies for obtaining consistently high grain yields should fully take into account specific plant responses to the basic environment to which research is directed.

Résumé

Réaction à un stress hydrique du sorgho et du mil cultivés dans les zones semi-arides de l'Inde : Les milieux de culture du sorgho et du mil dans les zones semi-arides de l'Inde ont été classés en trois types : variable, optimal (ou relativement optimal), en conditions d'humidité résiduelle. Les variations des réactions spécifiques des plantes, notamment la phénologie, le développement de la surface foliaire, la croissance des racines et l'efficacité de la consommation d'eau dans ces trois types de milieu sont décrites. Le sorgho et le mil se distinguent par leurs réactions spécifiques à un milieu hydrique variable. On décrit aussi la réaction d'un sorgho à un stress hydrique à la fin du cycle, lorsque ce sorgho est cultivé après les pluies avec la réserve hydrique. L'effet de la date, de l'intensité et de la durée du stress hydrique sur le rendement en grain est évalué. Les stratégies de sélection et de gestion visant à obtenir des rendements en grain toujours supérieurs devraient prendre en compte les réactions spécifiques des cultures au milieu sous étude.

The variation in the duration and amount of rainfall in India, caused by the southwest monsoon, creates a broad range of rainfall environments across the semi-arid tropical (SAT) regions of the country (Kanitkar et al. 1968). When combined with soils of varying depth, texture, and slope, the result is an even broader range of moisture environments for farming. Grain sorghum and pearl millet fit primarily into the drier parts of this range. As soil moisture is the major determinant of crop production, their adaptation to moisture deficit conditions is important. The erratic rainfall during the monsoon makes it difficult to predict the timing and intensity of drought stress during this season. During the postrainy season (*rabi*), sorghum is grown on Vertisols with stored soil moisture, in which case the

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increasing level of drought stress, especially after flowering, is fairly predictable. Other differences between these two seasons are described by Sivakumar et al. (these Proceedings).

To understand plant responses to drought, one should fully study the temporal and locational specificity that characterizes a particular drought condition. In this paper we will first examine the three most characteristic moisture environments of SAT India; second, describe various crop responses such as development, growth, and water use, and grain yield under different patterns of drought; finally, discuss the implications of these responses in solving the problems posed by different types of drought.

Moisture Environments of SAT India

The basic types of moisture environments can be classified as variable, optimum *or* near-optimum, and stored soil moisture conditions (Quizenberry 1982). In each of these environments both the seasonal pattern and the amount of evapotranspiration (ET) depend upon the rainfall distribution, the potential ET during the season, and the soil characteristics. We will illustrate the differences in these three environments by discussing rainfall probability estimates (Virmani et al. 1982) and soil moisture budgets.

Rainfall Probability Analysis

We have chosen three locations for discussion: Jodhpur in Rajasthan state, and Nanded and Ahmednagar in Maharashtra state. Jodhpur has a short rainy season (11 weeks) with a monsoon rainfall of approximately 300 mm. The probability of receiving less than 20 mm of rainfall per week during the season is 50 to 70% (Fig. 1). Soils are primarily sandy, with low water-holding capacity. Thus, Jodhpur is a variable soil moisture environment, where drought during the season is frequent and unpredictable. Pearl millet is the main crop grown in this zone, with very few or no purchased inputs.

Nanded in eastern Maharashtra is in an assured

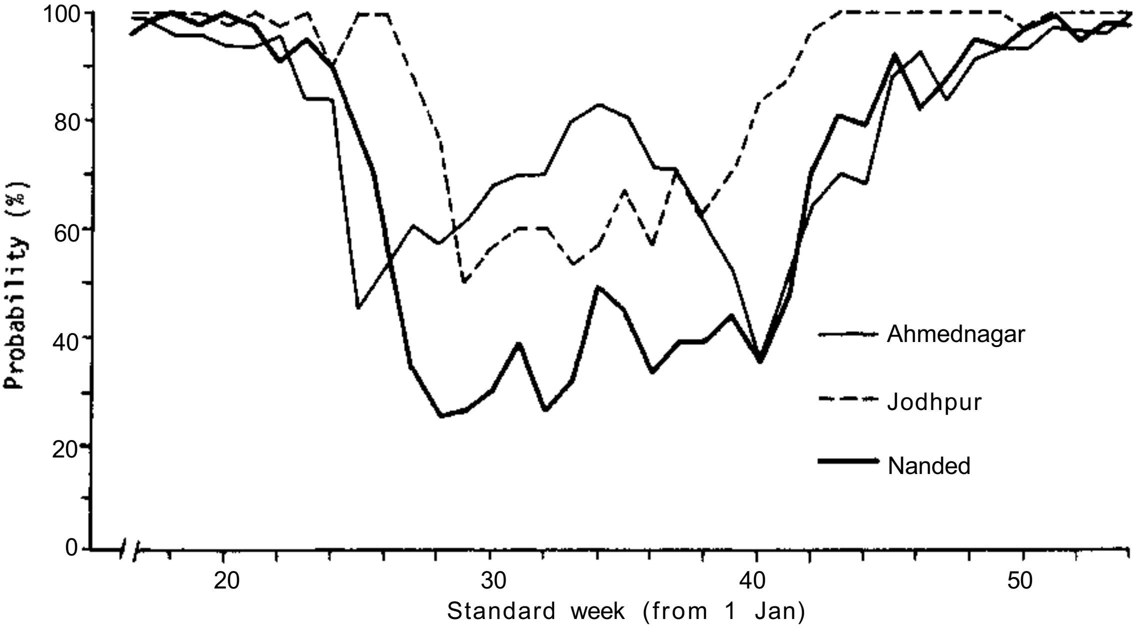

Figure 1. Probability of receiving <20 mm rainfall/week for three different moisture environments in India: Ahmednagar (19° 05'N, 74° 55'E), Jodhpur (26° 18'N, 73° 01'E), and Nanded (19° 08'N, 77° 20'E). The total rainfall, during the rainy season at these locations is 500, 300, and 810 mm, respectively; during the postrainy season, rainfall is less than 50 mm (adapted from Virmani et al. 1982).

rainfall zone with a longer rainy season (18 weeks) and a seasonal total of approximately 800 mm. The probability of receiving less than 20 mm of rainfall per week is much lower than that for Jodhpur (Fig. 1). Soils are deep Vertisols with high water-storage capacity; hence, sorghum is grown here in an optimum soil moisture environment. Towards the end of the season, rains are adequate to keep the profile sufficiently charged with water; hence an additional rabi crop can be grown on stored moisture.

Ahmednagar lies in the rain shadow of the Western Ghats mountain range, and, although the rainy season is of the same duration as in Nanded, the seasonal total is less than 500 mm. The probability of insufficient rainfall (<20 mm/week) during the rainy season is higher even than that at Jodhpur (Fig. 1). Both sorghum and millet are important in this district. Millet is grown on the shallow soils during the rainy season, and sorghum on the deep soils—similar to those at Nanded—with stored moisture during the postrainy season, following a rainy-season fallow or a short-duration pulse crop. The somewhat more reliable rains during the later part of the rainy season (Fig. 1) generally result in a fully charged soil profile at the beginning of the postrainy season and leave sufficient moisture for satisfactory crop establishment and growth, although drought may occur at the end of the season.

Soil Moisture Budgets

The partitioning of the seasonal total available moisture into its various end uses differs considerably in these three environments because of differences in rainfall, atmospheric demand, and soil characteristics. We have selected three sets of data on distribution and magnitude of various water-balance components—computed as described by Singh and Russell (1979) for three sorghum crops at Patancheru—to illustrate the differences between variable (Fig. 2a), optimum (2b), and stored soil moisture (2c) conditions.

Although there were small amounts of water available in the profiles at sowing in the medium-deep Alfisol (1977) and the deep Vertisol (1978), 80% or more of the total moisture available for the rainy-season crops came from rainfall received during the crop growth period. In the 1977 postrainy season, however, 72% of the seasonal moisture was stored in the soil at the time of sowing (Fig. 2).

Deep drainage (beyond the rooting zone) formed a significant portion (in both absolute and relative terms) of the water budget in both rainy seasons. In addition, during years of heavy storms, such as 1978, large amounts of water may be lost as surface runoff. Neither of these losses occurred during the postrainy season. Crop transpiration (T), in absolute terms was fairly similar in the three seasons (150, 200, and 130 mm for the rainy-season Alfisol and Vertisol and the postrainy-season crops, respectively). As a percentage of the total seasonal moisture, however, T varied from 19% to 66% over the three environments. Losses through soil evaporation (E) varied in direct proportion to the amount of seasonal rainfall received. Thus E during the postrainy season was minimum: only 15% of the total water budget and less than 25% of T (Fig. 2).

Finally, the moisture remaining in the profile at harvest varied from only 50 mm in the postrainy season (where the crop exhausts essentially all the available soil moisture in the root zone) to more than 200 mm in the high-rainfall Vertisol. In such Vertisols—in contrast to the Alfisol situation-extended and double-cropping possibilities are excellent.

Response of Sorghum and Millet to Drought

A precise study of plant responses during the rainy season is difficult, since the drought pattern varies widely across years. Hence, for the purpose of our study, we use the relatively rain-free summer (February-May) season to simulate various patterns of rainy-season stress. By withholding irrigations from the crop we are able to impose a stress of required intensity and duration at any time during its life cycle (Seetharama and Bidinger 1977). Due caution must be exercised, however, in extending these results to the rainy season; it has been necessary to confirm our results at specially selected, drought-prone sites during the normal rainy growing season. However, the response of sorghum grown during the postrainy season to terminal drought can be studied under natural conditions using a suitable irrigated control for comparison.

Crop Phenology

The effects of stress on the phenology of both sorghum and millet depend upon the severity of the

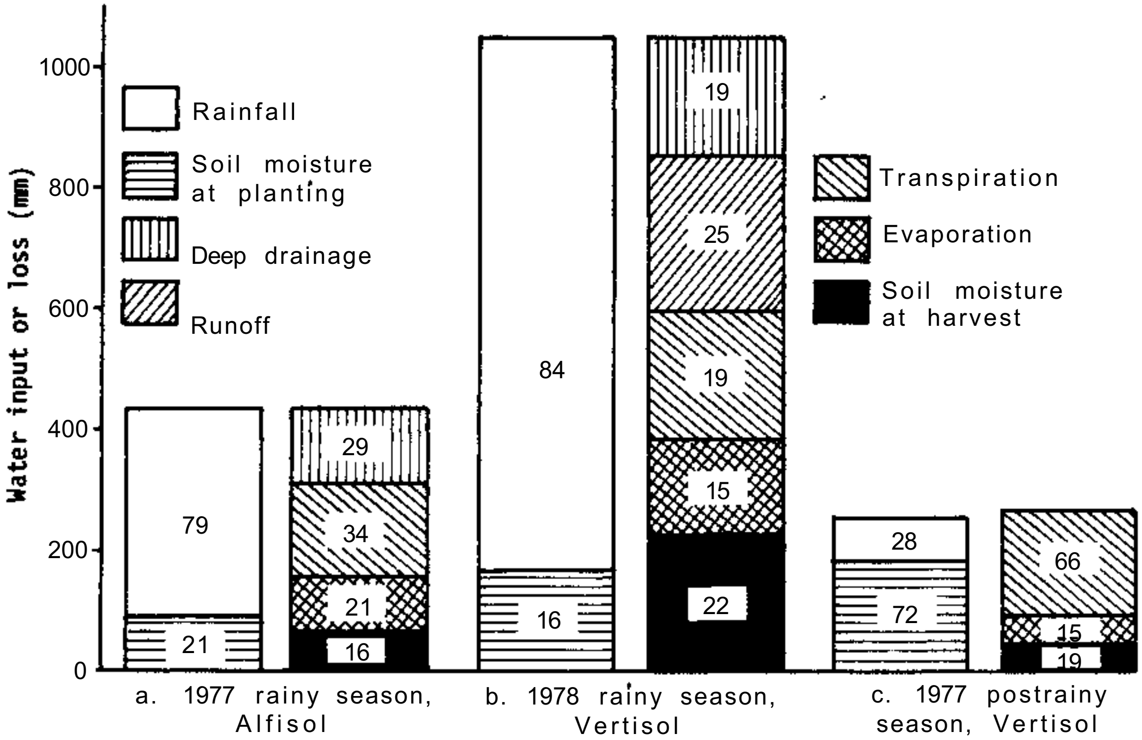

Figure 2. Seasonal water-balance components for Alfisols and Vertisols during the rainy and postrainy seasons at Patancheru, India. In each of the three sets (a-c), the left column represents the maximum quantity of water received during the season (stored moisture at planting + rainfall during the crop growth period); the right column, the various components of water loss through the system. The figures within each section of the column represent the quantity of water as percentage of the total input or loss from the system. Sorghum hybrids CSH-6 and CSH-8R were used during the rainy and postrainy seasons, respectively. Runoff was prevented during the 1977 rainy season by bunding. The maximum plant-available water-holding capacity of the Alfisol profile (127 cm deep) is 140 mm; that of the Vertisol (187 cm deep) is 240 mm.

stress itself (the degree and duration of plant water deficit) and on the stage of development of the crop at the time of stress. When the stress is not too severe, as often observed under near-optimum environments, the phonological responses are not apparent; effects are mainly on growth and yield. In the variable moisture environment, however, effects on phenology can be very evident, particularly when stress occurs before flowering. A comparison of the flowering patterns of two experimental hybrids of millet subjected to a period of severe stress between 20 and 45 days after sowing, illustrates this (Fig. 3). In the nonstressed conditions, mean flowering occurred at approximately 55 days for the earlier, high-tillering ICH-220 (Fig. 3c) and 60 days for the later, low-tillering ICH-162 (Fig. 3a), while the period of flowering was 20 to 30 days when both main shoot and tillers were considered. Under stress, the average flowering time was delayed by 10 to 15 days (occurring well after the termination of the stress), and the period of flowering was considerably extended. This was particularly obvious for ICH-220 (Fig. 3d), in which the tillers were delayed more than the main shoot.

Regular dissection of shoots during this experiment (Table 1) revealed that the delay in flowering in both main shoots and tillers in ICH-220 was due to a delay in development between floral initiation and flowering. In the late ICH-162, however, there was a delay in floral initiation in the tillers, as well as

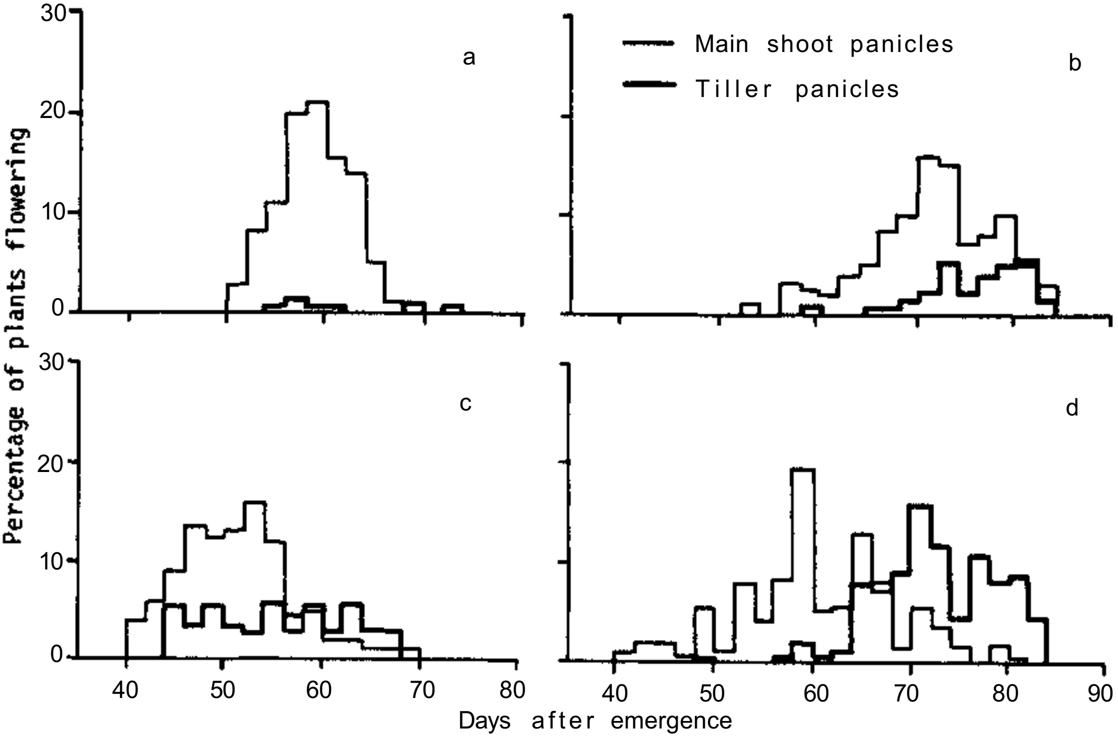

Figure 3. Frequency distributions of time of flowering of individual plants of pearl millet hybrids ICH-162 (a and b) and ICH-220 (c and d) in fully irrigated control (a and c) and stressed between 20 and 45 days after emergence—treatments (b and d).

Table 1. Days from emergence to panicle initiation (PI) and flowering (F) for main shoot and individual tillers in two pearl millet hybrids under control and drought-stress conditions. (Irrigations were withheld between 20 and 45 days from emergence in stressed plots; Patancheru, summer 1982).

	Main shoot		First tiller		Second tiller		Third tiller		Fourth tiller	
Water treatment	PI	F	PI	F	PI	F	PI	F	PI	F
Hybrid ICH-220										
Control	18	49	26	54	27	54	28	51	32	63
Stress	18	58	25	69	26	71	28	78	28	72
Hybrid ICH-162										
Control	25	58	36	58	38	NF	40	NF	41	NF
Stress	28	70	53	76	55	74	56	NF	57	NF

Source: V. Mahalakshmi and F.R. Bidinger, ICRISAT, unpublished data.

1. NF = Did not flower during the season.

a delay in subsequent development. Thus the responses are related to timing of the process affected: changes occurring before 30 to 35 days were not affected, whereas those occurring after this time were. Apparently the stress became severe enough at that point to affect panicle development.

The response of sorghum to a gradient of stress during the postrainy season was studied using a line source (Hanks et al. 1976) (Fig. 4). The mild

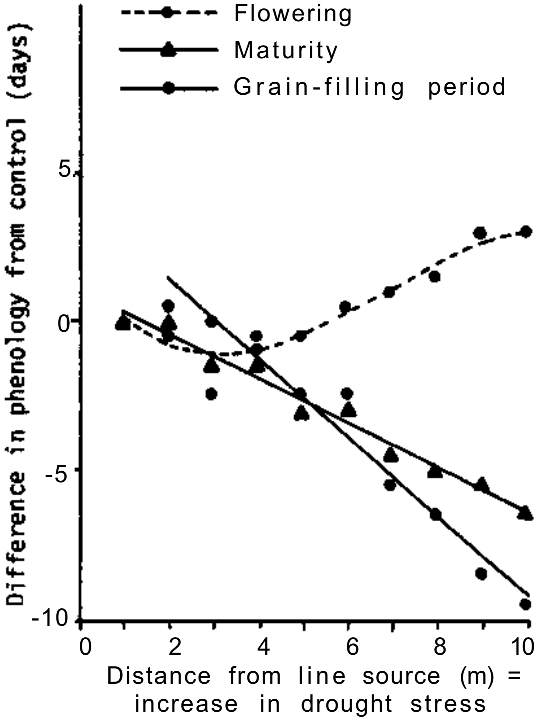

Figure 4. Effects of progressive drought stress on phenology of sorghum (cv CSH-8R). Data are from a line-source experiment; moisture gradient treatment started at 30 days from sowing and was repeated at 10-day intervals until maturity. In the plot nearest to the line source the water applied exceeded 80% of cumulative class A pan evaporation, values for the preceding 10-day period; flowering occurred at 73 days and maturity at 105 days. Regression equations: flowering $y = 75.30-1.63x + 0.20x^2 -0.006x^3$ (r=0.99*); maturity: $Y = 1.44-0.50x$ (r=*0.99***); grain-filling period; $Y = 4.83-0.89x$ (r=0.95***). 1980/81 postrainy season; ICRISAT, Patancheru, India.**

stress (very near to line source) during this cool season tended to accelerate flowering by a few clays (probably due to increase in the temperature of the meristem). Further along the gradient, however, flowering was progressively delayed as the stress intensity increased. In some instances of severe stress, this kind of delay could extend for almost the whole period of stress (Seetharama and Bidinger 1977). Physiological maturity is invariably hastened with increasing intensity of stress, thus curtailing the length of the grain-filling period (and also the grain yield).

Crop Growth under Variable Moisture Environments

The basic difference in growth habit between sorghum and millet is expected to influence the response of each to fluctuating soil moisture. We compared their growth responses under adequately irrigated and stressed conditions (irrigations withheld between 14 and 60 days after sowing) during summer (Fig. 5). Millet maintains its superiority both in leaf area and dry-matter increase, and in net assimilation rate (NAR) early in the season, even under drought (Fig. 5a). It also recovers faster than sorghum (compare the dry matter or NAR increase after release; Fig. 5a and 5c, respectively) by rapid regrowth of the tillers. However, sorghum still has higher dry matter at harvest because of its longer duration of growth, which is extended considerably more under stress than in millet (not shown in figure).

Leaf area of millet declines after the onset of stress; sorghum leaf development can remain "dormant" during the same period and resume later after the release of stress, even at the time when the leaf area in the regularly irrigated sorghum starts declining rapidly (Fig. 5b). Thus millet, with its shorter developmental phases, rapid regrowth, and greater plasticity conferred by asynchronous tillering (especially under stress), can make better use of short periods of water availability during short growing seasons in SAT India. The data in Table 2 illustrate the compensation for the reduction in grain yield of main shoot by increase in the yield of tillers (especially those developed after the release of stress; Table 1). In this experiment, the delay in tiller development has actually increased the grain yield significantly in the high-tillering hybrid ICH-220 ($P<0.05$), in which the contribution of tiller panicles to the total yield under stress exceeded that of main-shoot panicles. In the low-tillering ICH-162, the contribution of tillers increased threefold under stress. However, when there is an opportunity for an extended season facilitated by late, more assured rains, sorghum is more productive than millet, as it can withstand longer periods of drought during the earlier phases of development, and still recover to produce higher grain and fodder yields.

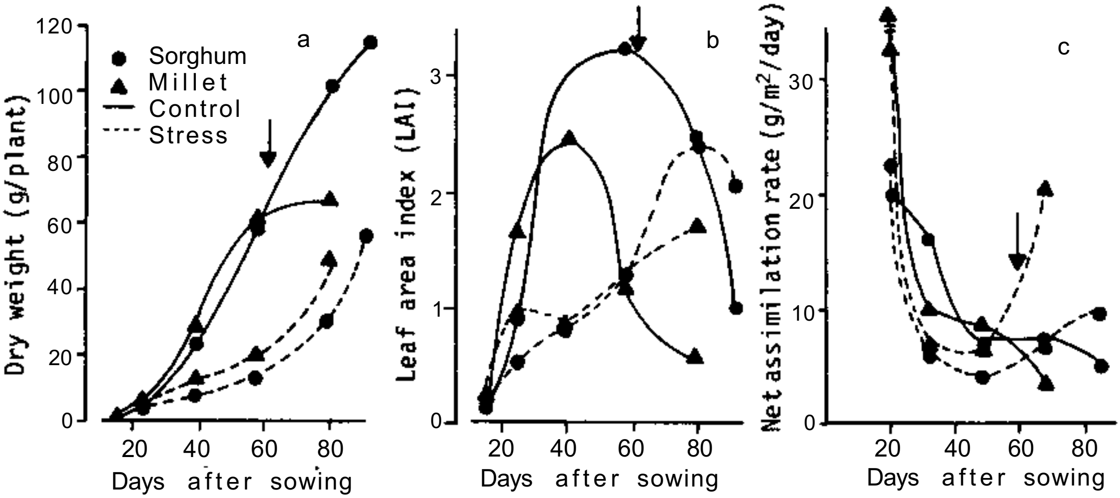

Figure 5. Dry-matter accumulation (a), leaf area changes (b), and net assimilation rate (c) of sorghum (CSH-6) and millet (ICH-425) under well-irrigated (control) and drought-stressed treatments during summer. Stress was initiated 14 days from sowing. Downward arrows indicate the time of release of stress by irrigation (1983 summer season; ICRISAT, Patancheru, India).

Table 2. Grain yield and percentage contribution of main shoot (panicle) and tillers to total grain yield in pearl millet hybrids under drought-stress conditions. (Irrigations were withheld between 20 and 45 days from emergence in stressed plots; Patancheru, summer 1982).

			Percentage contribution of			
	Total grain yield (t/ha)		Main shoot		Tillers	
Hybrid	Control	Stress[1]	Control	Stress	Control	Stress
ICH-220 (High-tillering)	2.6	3.0	68	44	32	56
ICH-162 (Low-tillering)	2.7	2.8	93	79	7	21

Source: V. Mahalakshmi and F.R. Bidmger, ICRISAT, unpublished data.

[1] Grain yields were not reduced by stress in either cultivar, as the growth duration was extended as shown in Table 1.

Sorghum Growth under Terminal Drought

The response of sorghum to stress—at the end of the season under receding soil moisture conditions on Vertisols during the postrainy season—was compared with that of an irrigated (unstressed control) crop (Fig. 6a). The relative transpiration rate (T/Eo; Fig. 6b) was about one-third of class A pan evaporation rate (Eo) at about 3 weeks after sowing. It reached the peak level of two-thirds of Eo at about 6 weeks, at which time the soil moisture also started declining rapidly. From then onwards the transpiration declined, unless the soil moisture was increased to high levels by irrigation. The seasonal transpirational water use was 160 mm for the dryland crop and 270 mm for the irrigated crop (which represented 95 and 90%, respectively, of the total water used in the season).

The dryland crop extracted a greater amount of the stored water from the profile (Fig. 6a) than the irrigated crop, since about one-third of its roots

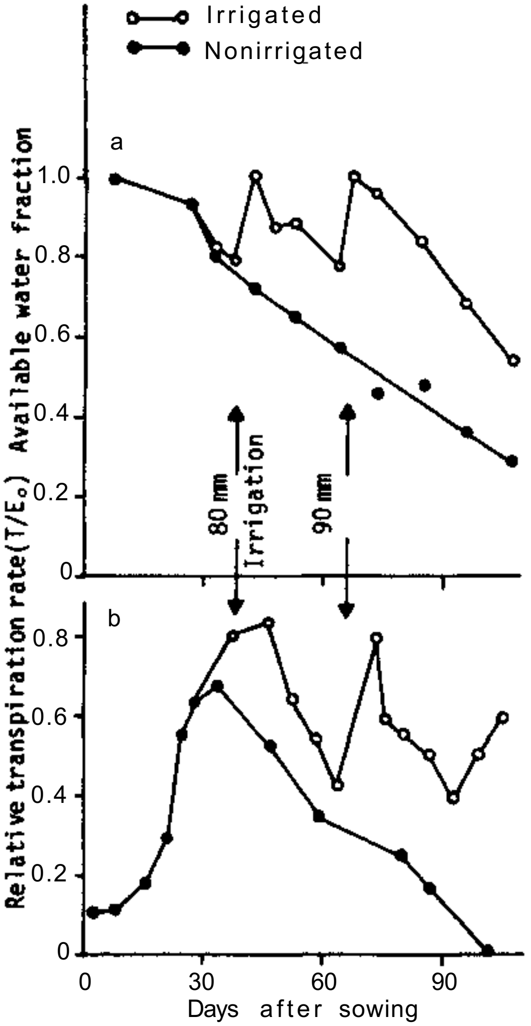

Figure 6. Seasonal changes in the (a) available water fraction in the 187 cm profile, and (b) transpiration/class A pan evaporation (T/Eo) ratios of sorghum under different moisture regimes on a Vertisol during the 1979/80 postrainy season at Patancheru. Transpiration was calculated by using the water-balance method of Singh and Russell (1979).

were in the soil layer 1 m below the surface (the irrigated crop had only one-sixth of its roots in this layer), although it had less dense roots in the profile as a whole at both stages of growth (Fig. 7). Thus "deep-roptedness" (Jordan and Monk 1980) is highly relevant under stored soil moisture conditions, especially in deep soils.

The dryland sorghum produced nearly the same grain yield as the irrigated crop because of greater use of stored moisture and better water-use efficiency (WUE, or ratio of yield : water use).

Water-Use Efficiency

Under comparable management conditions the water-use efficiency (WUE) of millet can reach the level of sorghum, but generally millet WUE is lower (Table 3) (See also Kanemasu et ai., these Proceedings). Both the grain yield and water use of millet are also lower than those of sorghum because of shorter crop duration. The WUE of sorghum grown on a deep Vertisol at Patancheru on stored moisture is higher than that of an irrigated crop (Table 4). Not only the genotype but also various management factors such as plant population, date of sowing, and application of fertilizers, mulches, and antitranspirants change WUE (see references in Tables 3 and 4).

Seasonal ET demands also influence WUE. For example, in both sorghum and millet the WUE is higher during the milder postrainy season than during summer. Under very severe drought conditions WUE can vary widely. We have plotted the WUE data of Lahiri (1980) and Mann and Lahiri (1979) against the reported seasonal rainfall for 4 years, two of which were very dry (Fig. 8). Under these conditions, WUE is clearly not a constant, and declines to very low values at rainfalls of less than 200 mm. No information was given on the seasonal distribution of rainfall in the papers cited above, but it is possible that evaporation was the major component of the ET if the rain in the dry years was received as very light showers. Thus ET under such conditions may not be a guide to potential production; the distribution of the rainfall may be the more critical factor, not only with respect to the time of the season at which the rain falls (as is commonly recognized) but also in the number and intensity of rainfall events, which may markedly affect the relative amounts of rainfall used for transpiration and other components of water balance.

Similarly the WUE of rabi sorghum was substantially higher at Patancheru on deep Vertisols than at Sholapur on shallower soils. While more than two-thirds of seasonal available water is used for transpiration at Patancheru (Fig. 2), only about one-third is used at Sholapur (Mane and Shingte 1982). At Patancheru WUE on Vertisols is lower than on Alfisols; under milder rabi conditions with reasonably assured moisture supply throughout the season,

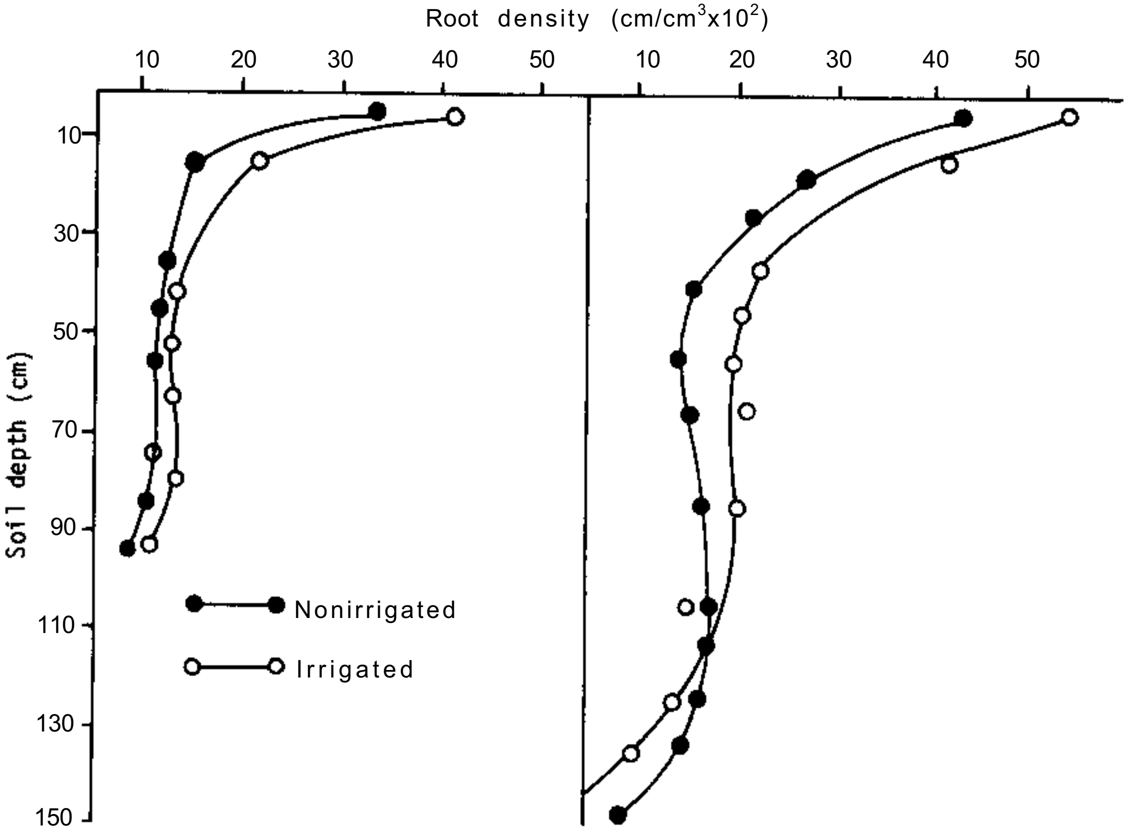

Figure 7. Effect of irrigation on root-density profiles of sorghum on a Vertisol at 57 (a) and 70 (b) days after sowing, 1979/80 postrainy season at Patancheru, India.

considerable yields and high WUE can be obtained with as little ET as 150 mm on the Alfisol (Table 4).

Effect of Stress on Grain Yields

Because periods of drought stress under variable environments, are unpredictable, generalizations on the effects of stress on grain yields are difficult. We have considered the effects during three basic stages of growth: seedling (between emergence and floral initiation), panicle development (between floral initiation, approximately 20 days after sowing, and flowering), and grain filling. The effect of stress on seed germination and crop establishment, especially in pearl millet grown in SAT India, is important, but the problem of seedling emergence will not be discussed here.

Stress during the seedling stage results primarily in poor crop establishment. Grain yields are reduced by such stress mainly through losses in plant stand. These losses may be general, or may occur in patches in the field; for example, in areas of shallow cr light-textured soils. Stress occurring after crop establishment (but still within the seedling phase) generally has very little effect on grain yields either in millet (Lahiri and Kharbanda 1965; Lahiri and Kumar 1966) or in sorghum (Scientific Liaison Office 1974; Shipley and Regier 1970). This is particularly true for millet, where the nonsynchronous tillering habit provides plasticity in development during early stages (Rao et al. 1977).

Midseason stress has more severe effects on grain yield, and both the timing and the severity of such stresses are important. The effect of the time of termination of a period of midseason stress of 15 to 20 days duration on millet is illustrated in Figure 9. If the stress is terminated at or before flowering (of main shoot), the reductions in yield are small

Table 3. Seasonal evapotranspiration, biomass and grain yields, and water-use efficiency of pearl millet in semi-arid India.

Year/location	Seasonal evapotranspiration (m)	Biomass (t/ha)	Grain yield (t/ha)	Water-use eficiency (t/ha per m)		Soil type and treatment	Reference number
				Biomass	grain		
Rainy Season							
1968 Jodhpur	0.14 [a]	1.17	0.02	8.4	0.2	Sandy loam: 20kg N/ha	1
1969 Jodhpur	0.07 [a]	0.07	0.00	1.0	0.0	Sandy loam: 20kg N/ha	1
1970 Jodhpur	0.15 [a]	5.56	1.85	37.1	12.3	Sandy loam: 20kg N/ha	1
1971 Jodhpur	0.18 [a]	3.17	0.96	17.6	5.3	Sandy loam: 20kg N/ha	2
1974-77 Jodhpur	0.25		1.27		5.1	Sandy loam: mean of 60 and 120 kg N/ha	2
1977 Jodhpur	0.29	5.09 [a]	1.74	17.6	6.0	Sandy loam: control crop	3
1973 Bawal	0.29	8.54	2.30	29.5	7.9	Sandy loam: control crop	4
1976 New Delhi	0.23	8.75		38.0		Sandy loam: mean of 4 cvs	5
1978 Patancheru	0.30	8.09	2.23	27.0	7.4	Medium-deep Alfisol	6
Mean	0.21	5.06	1.30	22.0	5.5		
Range	0.07-0.30	07-8.75	0.0-2.30	1.0-38.0	0.0-12.3		
Postrainy Season							
1977 Patancheru	0.16	5.99	1.86	37.4	11.6	Medium-deep Alfisol 60 mm rain + 3irrigations	7
1977 Patancheru	0.10	3.13	1.10	31.3	11.0	As above except irrigations5	7
Mean	0.13	4.56	1.48	34.4	11.3		
Summer Season							
1969-75 Rajendranagar	0.31 -0.42		2.14-3.53		6.9-8.4	Loamy sand: irrigated crop	8
Mean	0.37		2.84		7.7		

a. Calculated from data presented.

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(< 20%), because this is a less sensitive stage of development, and tillers formed during the period of stress then complete development following the end of the stress. However, if the stress extends to the post-flowering period, yield reduction is more severe, as the opportunity to recover is gradually lost (Lahiri and Kumar 1966).

The effects of variation in severity of a midseason stress on millet is shown in Figure 9b (data from line-source experiment). Small deficits during this period have little effect on yield, and even severe deficits (essentially no irrigation at all during the period) do not reduce yields more than 30%, again because of the recovery ability of the crop once the stress period is terminated. Stress during the grain-filling period, however, has far more drastic effects. Timing of such a stress is particularly important (Fig. 9a), yield being reduced as much as 70% if the stress period begins at or just before flowering. Similarly, the yield reduction due to varying levels of stress is linearly proportional to the severity of the stress during grain filling (Fig. 9b).

In rabi sorghum grown with stored moisture on Vertisols the degree of terminal stress would depend upon the amount of soil moisture available at flowering. About 17 kg of extra grain is harvested per hectare, for every additional 1 mm of water available during grain filling (Fig. 10).

Plant Responses to Drought: Research Imperatives

Two points applicable to all stress situations are:

Table 4. Seasonal evapotranspiration, biomass and grain yields, and water-use efficiency of sorghum in semi-arid India.

Year/location	Seasonal evapotrans-piration (m)	Biomass (t/ha)	Grain yield (t/ha)	Water-use eficiency (t/ha per m)		Soil type and treatment	Reference number
				Biomass	grain		
Rainy Season							
1970 New Delhi	0.34		5.07		14.9	Sandy loam: cv Swarna	1
1977 New Delhi	0.32		4.38		13.7	Sandy loam: CSH-5 control crop	2
1978 New Delhi	0.30		3.32		11.1	Sandy loam: CSH-5 control crop	2
1978 Patancheru	0.43	9.83	4.47	22.9	10.4	Medium-deep Vertisol	3
1977 Patancheru	0.24	14.50	3.70	60.4	15.4	Deep Alfisol	4
1978 Patancheru	0.44	25.00	5.50	56.8	12.5	Vertisol, hydraulic lysimeter data	5
Mean	0.35	16.44	4.41	46.7	13.0		
Range	0.24-0.44	9.83-25.0	3.32-5.50	22.9-60.4	10.4-15.4		
Postrainy Season							
1970 Sholapur	0.14		0.69		4.9	90 cm black soil no rain during season, cold stress	6
1971 Sholapur	0.18		1.75		9.7	Rains during season 50 kg N/ha	6
1970 Sholapur	0.12	2.33	0.28	19.4	2.3	Medium-deep black soil control treatment	7
1973 Sholapur	0.19	6.61	1.21	34.8	6.4	Medium-deep black soil control	7
1971 Sholapur	0.25	2.85[a]	0.69[a]	11.4	2.8	Medium-deep black soil control	7
1969-75 Rajendranagar	0.23		3.77		16.4	Sandy loam: irrigated	8
1977 Patancheru	0.21	5.10	2.43	24.3	11.6	Vertisol: stored moisture	9
1978 Patancheru	0.22	11.00	2.74	50.0	12.5	Vertisol: stored moisture	10
1977 Patancheru	0.32	9.30	5.99	29.1	18.7	Vertisol: irrigated	9
1978 Patancheru	0.41	14.50	3.13	35.4	7.6	Vertisol: irrigated	10
1978 Patancheru	0.25	11.66	5.43	46.6	21.7	Deep Alfisol: 6 irrigations	11
1978 Patancheru	0.15	7.09	2.71	47.3	18.1	Deep Alfisol: 4 irrigations	11
1978 Patancheru	0.48	22.50	8.55	46.9	17.8	Medium-deep Alfisols hydraulic lysimeter data: irrigated	5
1979 Patancheru	0.50	19.95	7.58	39.9	15.2	Medium-deep Alfisols hydraulic lysimeter data: irrigated	5
Mean	0.26	10.26	3.36	35.0	11.8		
Range	0.12-0.50	2.33-22.5	0.28-8.55	11.4-50.0	2.3-21.7		
Summer Season							
1969-75 Rajendranagar	0.34-0.50		2.76-4.53		8.10-9.10	Sandy loam: irrigated	8
Mean	0.42		3.65		8.6		

a. Calculated from data presented.

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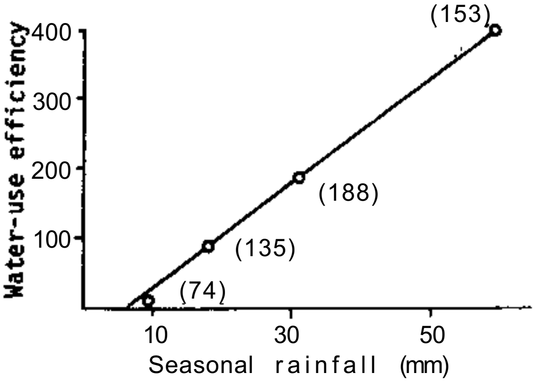

Figure 8. Calculated water-use efficiency (WUE; kg above-ground dry-matter at harvest/10 mm evapotranspiration *per* ha) in relation to total seasonal rainfall in pearl millet. Data are average of four to five cultivars per year, 1961-71. Figures in parentheses are the average reported seasonal water-use figures (in mm) for all genotypes for each year (adapted from Lahiri 1980).

(1) the duration of the variety must be matched to the expected period of available moisture and (2) the crop demand for water must be matched to the expected rate of soil water supply by adjusting plant population, fertility, or time of sowing. In peninsular India, replacing the traditional long-duration local cultivars of sorghum maturing after the cessation of rains with the early-maturing, high-yielding ones has been quite successful (Rao 1982), both in escaping possible terminal drought, and in allowing for flexibility in the time of sowing. Adjustment of farm practices to varying crop water demand is widely practiced by farmers in both sorghum- and millet-growing areas of India. Considerable research has also been done on management practices (Singh et al. 1980), although often the relationship of management and water availability or demand is not clearly spelled out.

Despite these generalities, the problems posed by drought are different in each of the three environments described earlier; consequently, varietal requirements and management practices for adaptation to these situations are also different. In an optimal environment, where high yields are possible with adequate management, the primary varietal requirement is high yield potential, to take full advantage of good moisture conditions (Quizenberry 1982). Smaller yield reductions under mild stress are strongly related to yield potential (Seetharama et al. 1982). Although the occasional short periods of drought at critical growth stages can reduce yield considerably, crop and soil man-

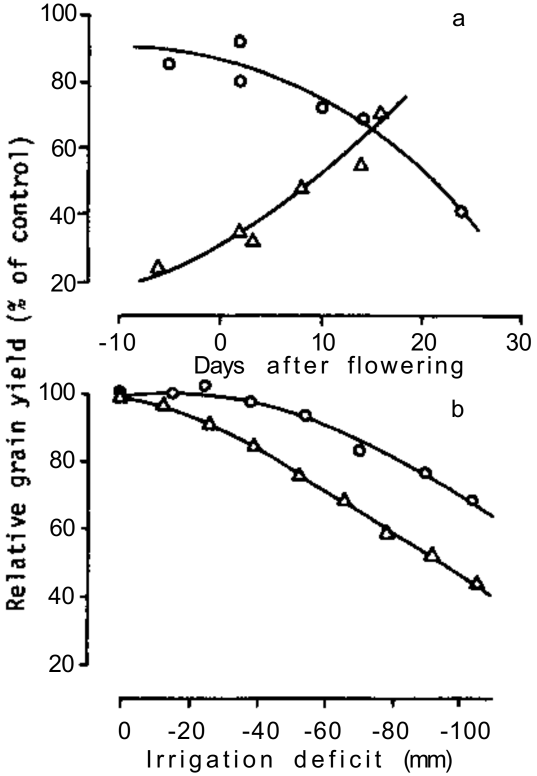

Figure 9a. Relationships between relative grain yield and the timing of stress (relative to time of flowering) in pearl millet. o: effect of time of termination of stress in relation to flowering, for a midseason stress of 15 to 30 days duration;Δ: effect of time of initiation, of terminal (end-of-season) stress in relation to time of flowering. (Data are averages of eight cultivars; 1978 and 1979 summer season experiments; F.R. Bidinger and G. Alagarswamy, ICRISAT, India, unpublished data.)

Figure 9b. Relative grain yield as a function of severity of stress (= irrigation deficit during stress period, in mm of water); o : for a 30-day midseason stress; rewatered at flowering;Δ: for a terminal stress begun at flowering. (Data are averages of 16 cultivars from the 1980 summer season; (V. Mahalakshmi and F.R. Bidinger, ICRISAT, India, unpublished data.)

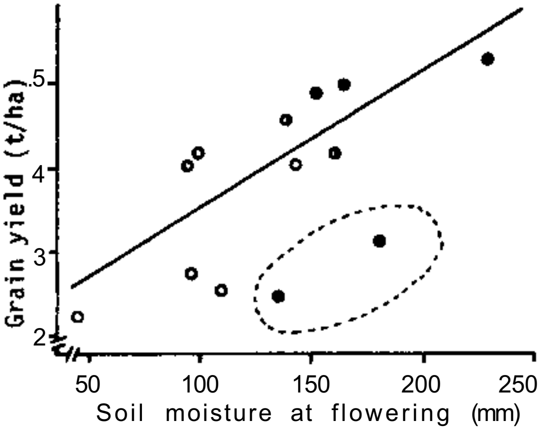

Figure 10. Relationships between total soil moisture at flowering during postrainy season in the upper 157 cm profile of a Vertisol and sorghum (cv CSH-8R) grain yield. o: nonirrigated; o, •: one and two supplementary irrigations before flowering, respectively. The two data points shown in the broken circle represent years in which response to irrigation was poor, due either to severe stalk rot or to very low nitrogen content in the profile; both are left out from the regression. Y = 1737-17x (kg/ga; r=0.81; data from Vertisol watersheds at Patancheru collected during the 1977-1982 postrainy seasons).**

agement techniques may be the best means of balancing yield and risk of drought in this environment.

In the variable moisture environment, drought can limit plant growth at any time during the season. Under such conditions crops must be able to take full advantage of periods of available moisture, to withstand periods of stress, and to resume growth rapidly when moisture is again available (Quizenberry 1982; Seetharama et al. 1983). Many of the developmental and growth characteristics and the higher heat resistance of millet (Sullivan et al. 1977) clearly provide adaptation to a variable moisture environment (Bidinger et al. 1982). Land and water management practices—especially to reduce runoff, and increase the moisture storage in the soil—are important. Intercropping sorghum and millets with a wide range of pulses (Singh et al. 1980) is a common practice in SAT India, which reduces the risk of crop failure in the system as a whole.

In the stored moisture environment the terminal stress is much more predictable; both breeding and cultural means can be effectively used to increase the amount of water available during grain filling by reducing the proportion of water used before flowering (Passioura 1976). Specific plant characteristics in the sorghum crop, such as deep roots, osmotic adjustment, and translocation of stem reserves to the grain (unpublished data; Sardar Singh et al., ICRISAT, India) improve performance under receding moisture conditions. Breeding strategy for sorghum for this season should be different from that for the rainy season (Seetharama et al. 1978).

Conclusions

Given the wide variability in drought stress due to variation in rainfall, soil water storage, and evaporative demand, plant responses to drought vary enormously. There is an urgent need to (1) classify the variation in crop environments in agronomically relevant terms and (2) quantify the usefulness of specific mechanisms of adaption to drought that are of practical value in each type of moisture environment. Finally, research and operational plans should be responsive to the needs of different moisture environments, as the relative importance of yield stability, risk minimization, and potential production will vary greatly among them.

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Water Use and Water-use Efficiency of Pearl Millet and Sorghum

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Abstract

Pearl millet and sorghum are major food crops in semi-arid regions of the world. About 95% of the world's millet is grown in Africa and south Asia. These areas typically have short rainy seasons, high temperatures, high potential evapotranspiration rates, and soils with low water-holding capacity. Therefore, water use and water-use efficiency (yield: water use) are important to the management and production of these crops.

Because millet and sorghum are grown in the droughty areas of the world, they are adaptive to both variable and low rainfall amounts; however, the specific mechanisms of their drought resistance are not known. There is evidence that they possess developmental and morphological traits that permit them to yield in a stressful climate. Water stress during the vegetative periods is less harmful than during the grain-filling period. Some genotypes will delay development when exposed to severe stress during late vegetative growth and resume it when soil water is again available. It has been reported that the plant organs most affected by water stress are those that are growing most rapidly at that time. One observes that the yield components will frequently compensate for one another.

In this review we summarize some of the recent studies in water use and water-use efficiency (WUE) of pearl millet and sorghum. In general, the WUE is greater for sorghum than for millet. There is an indication that the WUE of millet may increase slightly with water stress. A linear relationship was found between canopy-air temperature and vapor pressure deficit for millet and sorghum.

Résumé

Consommation d'eau et efficacité de la consommation d'eau chez le mil et le sorgho · Le sorgho et le petit mil sont des cultures vivrières importantes dans les régions semi-arides. Environ 95% du mil est cultivé en Afrique et dans le sud de l'Asie. Ces régions sont caractérisées par une courte saison des pluies, de hautes températures, des taux élevés d'évapotranspiration potentielle et des sols ayant une faible capacité de rétention de l'eau. C'est pourquoi la consommation d'eau et son efficacité (rendement : consommation d'eau) sont des éléments importants dans la gestion et la production de ces cultures.

Le mil et le sorgho sont cultivés dans les régions exposées à la sécheresse, ils s'adaptent donc à des précipitations variables et faibles. Cependant, les mécanismes particuliers de leur résistance à la sécheresse ne sont pas connus. Ils possèdent certaines caractéristiques morphologiques et de développement leur permettant de produire même sous un climat peu propice. Le manque d'eau au cours de la période végétative est moins préjudiciable que pendant le remplissage des grains. Chez certains génotypes le développement est interrompu quand la plante est exposée à un stress vers la fin de la croissance végétative et

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il n'est repris que lorsque le sol est à nouveau humide. Les organes de la plante qui sont en pleine croissance à l'époque du stress sont les plus touchés par le manque d'eau. Par ailleurs, les composantes du rendement se compensent souvent mutuellement.

Certaines études récentes sur la consommation d'eau chez le petit mil et le sorgho et son efficacité sont récapitulées. En général, cette efficacité est plus grande chez le sorgho que le mil; chez ce dernier elle peut augmenter légèrement avec le manque d'eau. On a constaté l'existence d'une relation linéaire entre la température de l'air au niveau du couvert végétal et le déficit de tension de vapeur d'eau pour le mil et le sorgho.

Transpiration plays a necessary role in plant growth and development. The same stomata that exchange CO2 for photosynthesis permit the diffusion of water vapor into the atmosphere. The transpiration stream cools the plant and transports nutrients from the soil-water reservoir to the plant organs. Transpiration is closely correlated with photosynthesis. Tanner and Sinclair (1982) suggest that the ratio of photosynthesis to transpiration is relatively invariant and coin the term, "transpirational efficiency." This would indicate that (a) in order to promote growth, transpiration needs to be increased; (b) improvements in yield have been obtained by management and increases in harvest index (ratio of grain to total dry matter); and (c) improved water management should reduce evaporation.

From a practical standpoint it is difficult to separate transpiration from evaporation. One technique is to model the component losses of evapotranspiration (Kanemasu et al. 1976). In most field studies, evapotranspiration and deep drainage or upward flow are estimated from a water balance where rainfall/irrigation, runoff, and soil moisture are measured. Usually, the residual terms in the water balance (evapotranspiration and drainage) are given as crop water use. Obviously, there can be substantial errors in the measurement of runoff and irrigation amounts. Soil-moisture measurements should be taken to a depth well below the root zone to minimize the error in measuring drainage below the root zone. These potential problems should be kept in mind when comparing studies of water use. It will be the objective of this paper to summarize some of the water use and water-use efficiency (yield: water use) data for pearl millet and sorghum.

Water Use and Water-use Efficiency

Seasonal water use by a crop will depend on the green leaf area index (LAI) and leaf area duration of the plants. Near-maximum water use usually occurs at LAI of about 2.5 to 3.0. In arid regions without irrigation, the crop may never attain LAI values this high; however, under favorable water conditions, the LAI will often exceed 3.0. The late-maturing genotypes usually have more leaves and their seasonal water use is higher because of a longer active growing period. Other factors, such as plant density, row spacing, genotype, and irrigation also strongly influence transpiration and evaporation amounts. The atmosphere imposes a transpirational demand on plants. The major sources of energy for both transpiration and evaporation are solar radiation and the heat from the air. Because transpiration includes both physical and physiological factors, the water relations of the plant affect the transfer of water vapor from the leaves. In particular, the stomatal resistance and leaf temperature are affected.

Tables 1 and 2 show data from several studies on water use, yield, and water-use efficiency (WUE) in pearl millet and sorghum. The list is not meant to be exhaustive but represents typical values for semi-arid and arid areas. The average water use for sorghum was about 10% greater than for pearl millet; however, the water-use efficiency for sorghum grain production was more than twice that of millet, and that for total dry-matter production, about 40% higher than for pearl millet. The major difference in WUE between the crops can be attributed to the numerator—yield. The WUE of sorghum is greater than that of most agronomic crops.

Irrigation Studies

Most irrigation studies indicate that increased irrigation provides increased WUE. An exception is the study in the Negev Desert of Israel, where the highest irrigation did not have the highest WUE (Table 2). We would expect that higher applications of water would not permit the yield to keep pace with increased water use, because of waterlogging

Table 1. Grain yield, total yield, water use, and water-use efficiency (WUE)[1] of pearl millet as observed in seven studies.

Irrigation treatment	Grain yield (t/ha)	Total yield (t/ha)	Water use (m)	Grain WUE (t/ha per m)	Total WUE (t/ha per m)	Reference
Irrigated at						
all stages	2.5	10.0	0.38	6.6	26.1	Singh (1981)
flowering	1.9	0.7	0.35	5.5	24.7	
grain filling	1.9	9.4	0.36	5.3	26.4	
Irrigated	3.3	22.3	0.58	5.7	38.4	
Rainfed	1.6	12.7	0.34	4.8	28.0	
Rainfed	2.2		0.56	3.9		Hattendorf (1982)
Rainfed	4.6	17.8	0.60	7.7	29.5	Chaudhuri and Kanemasu (unpublished)
Rainfed	12		0.48	2.5		Oswal and Dakshinamurti (1975)
Rainfed	1.7	12.2	0.26[2]	6.8	47.7	Singh et al. (1978)
Irrigated[3]	1.8	16.0	0.60	3.1	26.9	Dancette (1978)
Nonirrigated[3]	0.6	11.4	0.40	1.6	28.6	
Irrigated[4]	2.8	9.0	0.42	6.8	21.7	
Nonirrigated[4]	2.9	8.8	0.40	7.2	22.1	
Irrigated[5]	2.2	1.6	0.32	6.7	25.3	
Nonirrigated[5]	2.3	1.5	0.32	7.1	24.9	
Rainfed	3.8	22.5	0.33	11.6	68.2	Kassam and Kowal (1975)
Mean	2.3	10.3	0.42	5.8	31.7	

1 WUE - water-use efficiency, or ratio of yield : water use; 2. Soil moisture to 90-cm depth; 3. 120-day maturity millet; 4. 90-day maturity; 5. 75-day maturity.

Table 2. Water use, grain yield, and water-use efficiency (WUE)[1] of sorghum as observed in six studies.

Irrigation treatment	Grain yield (t/ha)	Water use (m)	Grain WUE (t/ha per m)	Total WUE (t/ha per m)	Reference
35 cm	8.7	0.51	16.8	45.7	Chaudhuri and Kanemasu (1982)
30-35 cm	8.7	0.51	17.1	46.6	
25-29 cm	7.7	0.49	15.6	41.7	
20-24 cm	7.2	0.47	15.2	39.7	
Rainfed	6.1	0.42	14.4	36.3	
Rainfed	7.4	0.41	18.0	43.0	Owonubi and Kanemasu (1982)
Rainfed	7.8	0.35	22.0	68.0	
8 irrigations	7.2	0.72	10.1		Bielorai et al. (1964)
4 irrigations	5.8	0.52	11.2		
3 irrigations	3.1	0.44	7.2		
2 irrigations	2.3	0.38	6.0		
1 irrigation	0.4	0.21	1.7		
Rainfed	7.4	0.52	14.2		Hattendorf (1982)
Rainfed	7.7	0.58	13.3	32.0	Chaudhuri and Kanemasu (unpublished)
Irrigated at 50% availability	4.0	0.42	9.5		Reddy et al. (1975)
Mean	6.1	0.46	12.8	44.1	

1. WUE = Water-use efficiency, or ratio of yield : water use.

and leaching of nutrients. One reason to overirrigate would be to permit leaching of salts out of the rhizosphere. Possible objectives of irrigation include maximization of economic return, maximization of yield, or maximization of water-use efficiency. In many subsistence-type operations, yield is the most important, while other operations would maximize profit.

In a study by Dancette (1978), there is an indication that in the short- to medium-duration millets (Table 1), WUE increases with less water use. This increase in efficiency under less favorable conditions and less water use is of considerable interest in areas of marginal water supplies. If the water-use values were very high under irrigation, then these findings would be comparable to those of Bielorai et al. (1964) (Table 2). Singh's (1981) data, obtained in very hot and dry summer, also indicate little difference in WUE of total dry matter between irrigated and rainfed millet (Table 1). On the contrary, sorghum grown at this same site in the same year (Chaudhuri and Kanemasu 1982) shows substantial difference in WUE of total dry matter between a well-watered (>35 cm) and a rainfed crop.

Developmental Stages

In determinate crops, the components of grain yield are formed at specific stages of development. The vegetative stage (GS1) is indicated as the time between emergence and floral initiation. Maiti and Bidinger (1981) provide a detailed discussion on the growth stages of millet. They report a duration of GS1 of about 25 days for their cultivars in India, during which time seminal and adventitious roots are developed and all leaves are initiated. Tiller buds are formed and some are emerged. Floral initiation is observed by the elongation of the apical dome. The yield component of potential head number is determined at this time. The next stage is the panicle development phase (GS2) of about 21 days (Maiti and Bidinger 1981). During GS2, the development of spikelets, florets, and flowers is completed; therefore, the potential number of kernels on the main stem and early tillers is determined. The third major growth phase is the grain-filling phase (GS3), which is approximately the same duration as GS2. This phase is marked by the filling of kernels and the final stages of development of the late tillers. Physiological maturity is observed by the dark layer of tissue in the hilar region of the grain, and the kernels attain maximum dry weight.

The duration of the developmental stages is dependent upon the temperature, daylength, biological and environmental stresses, and genotype. Comprehensive models for predicting developmental stages of millet and sorghum are not available. This indicates a need for basic research on the phenological response of these crops to temperature and photoperiod.

In assessing sensitive stages of development for purposes of irrigation scheduling, it appears that the boot through bloom stages (GS2) are the most sensitive for sorghum (Lewis et al. 1974); however, Stone et al. (1978) reported that their irrigation study did not indicate any particular sensitive stage (Table 3). We would anticipate that stress at this stage would adversely affect grain number; however, component compensation may improve grain weight (Blum 1973). In most irrigation studies, it is difficult to assess sensitivity of a particular stage because of the seasonal variability of rainfall. If one could conduct a study in which there were no precipitation events and only irrigation as a source of soil water, the chance of assessing sensitivity would be better. Such a study is further complicated by the compensation of yield components and by environmental and genetic interactions. There are very few comparable studies on pearl millet (Singh 1981); however, we would anticipate results similar to those obtained with sorghum.

Comparisons between Pearl Millet and Sorghum

Shown in Table 4 are yield, yield components, xylem water potential (ψ xylem), and stomatal resistance of pearl millet and sorghum. These values represent the average of four genotypes of each species and four replications. Xylem water potential and stomatal resistance were measured at midday on several upper exposed leaves throughout the growing season (1981, Manhattan, Kansas, USA). Due to abnormal amounts of rainfall, the crops were not exposed to water stress. The grain yield of sorghum was about 40% greater than that of millet, but the total dry-matter production for sorghum was only about 5% greater than for millet. Consequently, the harvest index (ratio of grain: total dry matter) for sorghum (0.41) was substantially higher than for millet (0.27) under optimal condi-

Table 3. Grain yield, water use, and water-use efficiency (WUE)[1] of grain sorghum.

Irrigation treatment	Grain yield (t/ha)	Water use (m)	Grain WUE (t/ha per m)	Reference
Well-watered (control)	7.4	0.48	15.6	Howell and Hiler (1975)
Stressed at				
vegetative to boot	5.9	0.38	15.7	
boot to bloom	4.5	0.39	11.4	
milk to soft dough	5.9	0.40	14.7	
Well-watered (control)	7.0	0.50	14.1	
Stressed at				
reproduction	6.6	0.48	13.7	Stewart et al. (1975)
grain filling	7.1	0.50	14.3	
Irrigated at				
vegetative stage	4.4	0.46	9.8	Musick and Dusek (1971)
heading	5.9	0.46	13.0	
milk	6.0	0.47	12.7	
boot	7.2[2] (6.0)[3]	0.47[2] (0.43)[3]	14.7[2](13.7)[3]	Stone et al. (1978)
half bloom	7.5 (5.6)	0.48 (0.41)	15.7(13.5)	
soft dough	7.1 (6.0)	0.48 (0.40)	14.8(15.0)	

1. WUE = ratio of yield : water use; 2. Manhattan, Kans, USA; 3. Tribune, Kans, USA.

Table 4. Average grain yield, total dry matter, yield components, xylem water potential, and stomatal resistance of four sorghum and four millet genotypes grown at Manhattan, Kansas, USA, 1981.

Parameters	Sorghum	Millet	Difference
Grain yield (t/ha)	7.5	4.6	2.9**
Total dry matter (t/ha)	18.3	17.3	1.0**
Head weight (g)	40.37	17.68	22.69**
Head number (no./m^2)	10.46	27.15	16.69**
Seed weight (mg/100 kernels)	30.80	10.39	20.41**
ψ xylem water potential (kPa)	-.9	1.8	0.1*
Stomatal resistance (sec/m)	0.79	1.41	0.62**
Canopy temperature (°C)	28.9	27.8	1.1*

* Significant at 0.10; ** at 0.05 levels.

tions. This would suggest that significant gains in grain yield and water-use efficiency can be expected in pearl millet.

Major differences were observed in the yield components. Seed weight and head weight of pearl millet were less than of sorghum, but the number of heads was more in millet. Usually the late tillers show a decrease in harvest index. Therefore, perhaps improved millet grain yields can be obtained by decreasing head number (reducing later tillers) and increasing head and kernel weights. Blum (1973) suggests that drought-resistant sorghum genotypes are characterized by reduced tillering and stability in tiller number under various environmental conditions, small grains, and large number of grains per head.

The xylem water potential and stomatal resistance of sorghum were lower than of pearl millet (Table 4). (Xylem potential and stomatal resistance were taken with a pressure chamber and a steady-state porometer, respectively.) The lower stomatal resistance would indicate higher transpiration and photosynthetic rates for sorghum than millet, which is consistent with yield data. Canopy temperature measurements with an infrared thermometer indicate a warmer sorghum canopy than a millet canopy. These results would appear to be inconsistent, since a warmer canopy would indicate a lower transpiration rate. However, a possible explanation is that the infrared thermometer looked deep into the canopy and sampled structures that were different from those sampled by the porometer (upper exposed leaves). Idso et al. (1981) found a linear

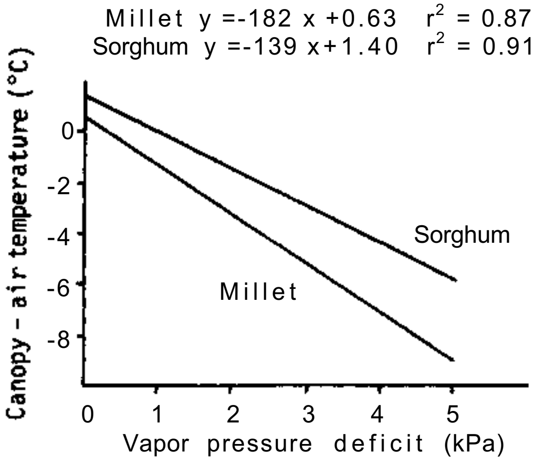

Figure 1. Regression lines of canopy-air temperature versus vapor pressure deficit of well-watered sorghum and pearl millet.

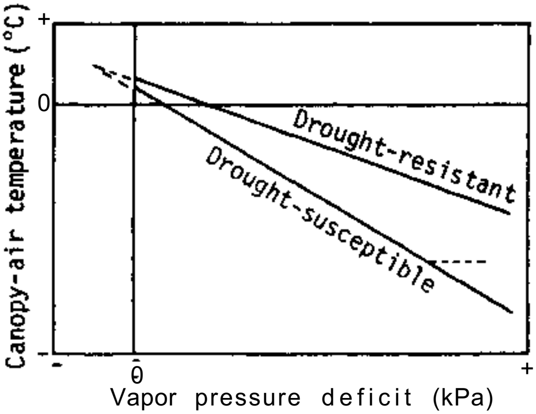

Figure 2. Hypothesized regression lines of canopy-air temperature (T_f-T_a) versus vapor pressure deficit of well-watered plants, for possible use in screening of drought-resistant genotypes.

relationship between canopy-air temperature (T_f-T_a) and vapor pressure deficit (VPD) of plant canopies that were well watered and exposed to sunny conditions. Figure 1 shows those relationships for sorghum and millet. Data were taken over several days to obtain a range in vapor pressure deficits. Again these data indicate a higher canopy temperature for sorghum than millet for any given VPD. We may hypothesize that genotypes with warmer canopy temperatures under well-watered conditions indicate lower transpiration rates (conserve water) and represent a drought-resistance trait (Fig. 2). Canopy temperatures could be used to screen for drought resistance in a breeding program, since an infrared thermometer could be used to screen hundreds of genotypes rapidly.

Reference has been made (Hsiao et al. 1976; Stout and Simpson 1978) to the ability of plants to adjust osmotically under water-stress conditions as a drought-resistance mechanism. This osmotic adjustment permits the plant to have a lower water potential for stomatal closure and cell elongation. Osmotic adjustment has been reported in sorghum (Jones and Turner 1978; Acevedo et al. 1979) and in pearl millet (Henson et al. 1982). Henson et al. (1982) conclude that the osmotic adjustment in sorghum is greater than that in pearl millet. Cell-wall elasticity is another mechanism for maintenance of turgor; however, Henson et al. (1982) found little change in elasticity in pearl millet, while Jones and Turner (1978) observed a twofold change in sorghum.

Summary

The water-use efficiency (WUE) of sorghum is greater than that of pearl millet both for grain and for total dry matter (c.f. also Seetharama et al., these Proceedings). The crop water use for sorghum is slightly greater than for pearl millet. The primary reason for the greater WUE in sorghum is in the grain yield, in which there is about a twofold difference.

While the growth period from boot to bloom would appear to be somewhat sensitive, it is not overwhelmingly so. There have been many more water-stress studies on sorghum than on pearl millet. Direct comparisons between sorghum and pearl millet are lacking. It appears that the osmotic adjustment and changes in cell-wall elasticity are greater for sorghum than pearl millet under water-stress conditions. Under favorable conditions, the stomatal resistance is lower in sorghum than in millet. Apparent canopy temperatures measured with an infrared thermometer indicate a warmer canopy in sorghum than in millet. We hypothesize that under well-watered conditions a warmer canopy would suggest a water-conserving trait, and perhaps this technique could be applied to the screening of genotypes.

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Developing Practical Agroclimatic Models for Sorghum and Millet

George H. Hargreaves*

Abstract

Crop yield or production depends upon several factors. These include temperature, potential evapotranspiration, availability of water, fertility available to the plant, etc.

For a particular crop and variety there exists a temperature range for satisfactory growth and a narrower range of optimum temperatures. The differences between maximum and minimum temperatures is also of importance and should be reported and used in agroclimatic models.

Although there is considerable difference in drought tolerance of plants, crop yields, on the average, are reduced approximately in proportion to reductions in crop water use below the maximum possible use. The ratio of actual yield to potential yield is proportional to actual crop evapotranspiration divided by potential maximum crop evapotranspiration.

Methods are given for estimating potential evapotranspiration; for calculating rainfall dependability, soil water-holding capacity, available soil water, some missing data, the optimum level for nitrogen fertilization, rainfall depth duration, amounts, or intensities; and for developing some simple economic models.

Although climatic data are not usually as adequate as desirable, the principal limitation on the use of agroclimatic models for increasing crop production is the number of trained professionals and technicians familiar with the potential uses of agroclimatic models.

Résumé

***Mise au point de modèles agroclimatiques pratiques pour le sorgho et le mil :** Le rendement ou la production des cultures dépendent dc plusieurs facteurs dont la température, l'évapotranspiration potentielle, la disponibilité d'eau et les éléments fertilisants.*

L'étendue des températures assurant une croissance efficace varie d'une espèce et d'une variété à l'autre; l'étendue de températures optimales est plus restreinte. Compte tenu de l'importance de la différence entre les températures maxima et minima, elle devrait être intégrée dans les modèles agroclimatiques.

La tolérance à la sécheresse varie chez les plantes; cependant le rendement baisse en général en proportion avec la réduction de l'utilisation d'eau par les plantes en-dessous de l'utilisation maximum. Le rapport entre le rendement réel et le rendement potentiel est en proportion avec l'évapotranspiration réelle de la culture divisée par son évapotranspiration potentielle.

Les méthodes d'évaluation de l'évapotranspiration potentielle sont données, ainsi que des méthodes pour évaluer la fiabilité des pluies, la capacité de rétention d'eau, la

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disponibilité en eau, certaines données manquantes, le niveau optimal de l'apport d'azote, la hauteur et la durée des pluies ou leur intensité; ainsi que les méthodes d'élaboration de modèles économiques simples.

Plutôt que l'insuffisance des données climatiques, la contrainte principale à l'utilisation des modèles agroclimatiques est le manque d'experts compétents et de techniciens pouvant exploiter le potentiel des modèles agroclimatiques.

As world population increases, greater emphasis will be required on food-grain production in the semi-arid tropics. Under improved management there is a large potential for increasing production under rainfed agricultural conditions.

Some basic relationships between climate, management, and crop yield appear to have rather universal application. It is therefore not necessary that experimental research be carried out in each area. Technology is often transferable to areas of similar conditions.

Procedures have been developed for zonation of soil and climatic conditions. Careful attention to sound methodology provides a basis for planning, research, demonstration, and development. Usefulness of methods and of agroclimatic models is decreased when the procedures become too complex or require data that are not readily available. Emphasis is therefore assigned to simplicity and ease of application without sacrificing reliability of estimates beyond acceptable limits.

Temperature and Production

For a particular crop and variety there exists a lower lethal temperature, a range of optimum temperatures, and an upper lethal temperature. Crop response to temperature depends upon leaf temperature, which may be higher or lower than air temperature, depending upon the soil matric potential or the moisture available to the crop.

Crop selection for a given climate must consider mean daily temperature and also the daily range between maximum and minimum temperatures. Adaptation to temperature conditions for sorghum and millet has been roughly defined but requires more specific evaluation, including varietal variations. Net photosynthesis depends both upon radiation amounts and temperatures, as well as upon other factors such as fertility of the soil, water availability, and plant spacing.

Yield Response to Water

One of the simpler models, the Stewart Model, is given by Doorenbos et al. (1979) in the form:

$$\left(1 - \frac{Y_a}{Y_m}\right) = ky \left(1 - \frac{ET_a}{ET_m}\right) \qquad (1)$$

in which Y_a is actual yield, Y_m is maximum or potential yield, ky is a yield response factor, ET_a is actual crop evapotranspiration, and ET_m is maximum or potential evapotranspiration.

Estimating ET_m

Potential evapotranspiration, PET, or reference crop evapotranspiration, ETo, can be estimated using various equations. Three methods are presented by Doorenbos et al. (1979). A simple and probably more reliable and consistent method developed by Hargreaves (Hargreaves and Samani 1982), can be written:

$$PET = 0.0075 \times RS \times T°F \qquad (2)$$

in which PET and RS are in the same units of equivalent water evaporation and T°F is mean temperature in degrees Fahrenheit. RS is solar radiation at the earth's surface; RS in mm is obtained by dividing global radiation in calories per cm^2 by 58.5 (the constant corresponding to the latent heat of evaporation for an average temperature of 20°C).

If radiation is not measured or reported, RS can be calculated from mean percentage of possible sunshine, S (measured sunshine hours times 100 divided by the theoretical number of possible sunshine hours for the time period selected) or from the temperature difference, TD (the mean maximum minus the mean minimum temperature). The equations can be written:

$$RS = KS \times RA \times S^{1/2} \qquad (3)$$

$$RS = KT \times RA \times TD^{1/2} \qquad (4)$$

in which KS and KT are calibration coefficients and RA is extraterrestrial radiation in mm. KS is usually in the range of 0.070 to 0.075 and KT for °C is generally between 0.16 and 0.17, except for locations near the foot of mountains or near the ocean. Some local calibration of these constants is recommended whenever radiation measurements have been made in areas of similar climatic conditions.

ET_m or maximum crop evapotranspiration is estimated by multiplying PET times crop coefficients KC given by Doorenbos et al. (1979). The equation can be written:

$$ET_m = PET \times KC \tag{5}$$

Values of ET_m and Ym can be estimated for the crop-growing season using the coefficients, yields, and procedures given by Doorenbos et al. (1979).

Dependable Precipitation (PD)

Mean precipitation is sometimes said to be meaningless. Monthly averages are biased by unusual events. An average monthly value of 175 mm may be obtained from a long series of years containing a number of records of zero monthly rainfall. The mean of values ranging from 7 to 700 mm tells little about dependability. A given probability or several probability levels more clearly describe the dependability of rainfall. Numerous studies by Utah State University, ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), CIAT (Centro Internacional de Agricultura Tropica), and by others have been made using the 75% probability of occurrence (that amount equaled or exceeded three-fourths of the time, based upon a mathematical probability distribution).

If computer facilities are available, the incomplete Gamma distribution is preferred. For manual computation the ranking probability can be used. For long records the 75% probability is usually very similar for both of these methods.

Moisture Availability Index (MAI)

The moisture availability index, MAI, is defined as the 75% rainfall probability amount, PD, divided by the potential evapotranspiration, PET; that is:

$$MAI = PD/PET \tag{6}$$

Where values of MAI, PD, and PET have been calculated, some useful relationships can usually be developed. Low MAI values of less than 0.33 indicate that rainfall is deficient for most crops; high values indicate a need for natural or artificial drainage.

For those months having MAI values of 0.33 or above, a regression analysis can be made for estimating PD from mean monthly rainfall, PM. The equation is in the form:

$$PD = a + b \times PM \tag{7}$$

Frequently the coefficient of determination, R^2, for an entire country or geographic area will exceed 90%. A regression analysis for India, with 109 degrees of freedom, (DOF), produced the equation:

$$PD = -19 + 0.71 \times PM \tag{8}$$

with R^2 = 98 for precipitation in mm.

Results of regression analyses using data from *World Water for Agriculture* (Hargreaves 1977) are given in Table 1.

I have previously suggested that a climate be considered tropical when all months have mean

Table 1. Coefficients a and b in equation (7) for various countries.

Country	Coefficient a	Coefficient b	R^2	SD (mm)	DOF
Bangladesh	-31	0.76	94	25	30
Brazil	-31	0.86	93	23	63
Chad	-20	0.83	92	17	31
Taiwan	-10	0.58	90	25	32
Congo Republic	-7	0.76	63	26	50
Dahomey	-40	0.93	92	14	25
Dominican Republic	-2	0.55	80	17	13
Ghana	-5	0.70	79	21	18
India	-19	0.71	98	47	109
Ivory Coast	-10	0.67	93	26	18
Mali	-18	0.83	96	14	35
Mauritius	-9	0.65	82	22	32
Niger	-10	0.77	95	10	8
Nigeria	-35	0.91	96	12	29
Philippines	-19	0.68	90	27	83
Senegal	-30	0.85	98	14	14
Sierra Leone	-6	0.79	96	36	15
Sri Lanka	-33	0.73	92	20	19
Sudan	-25	0.88	94	8	28
Tanzania	-20	0.78	95	11	10
Thailand	-25	0.78	85	20	27
Togo	-25	0.83	93	11	26
Uganda	-22	0.84	97	10	14
Upper Volta	-15	0.83	99	8	7
Zambia	-38	0.90	91	17	17

temperatures above 17°C, and subtropical when 10 to 12 months have mean temperatures above 10°C. In several studies the term "semi-arid" has been used to indicate areas having 3 or 4 months with MAI of 0.34 or above.

Cochrane and Jones (1981) have defined the tropical wet season as those months with MAI of 0.33 or above. Total wet-season potential evapotranspiration, TWSPE, was used as an index of energy availability during the period for which water could support growth and production.

A very good correlation was found between TWSPE and the type of native vegetation found on the well-drained tropical soils in South America. The native vegetation is determined principally by TWSPE and, over the range of conditions evaluated, was not influenced very much by the length of the wet season. This indicates that crop selection should also be based upon potential evapotranspiration and water availability for meeting evaporative demands.

Current definitions of the semi-arid tropics are inadequate. The use of a mean annual temperature of 18°C and above and a specified number of months within which mean rainfall exceeds potential evapotranspiration are not adequate criteria. The definition of the semi-arid tropics should include potential evapotranspiration and some form of rainfall probability distribution analysis.

Estimating Temperature

By using equations 2 and 4, values of PET can be estimated from temperature. For locations where temperature data are not available, values for each month for mean maximum and mean' minimum temperature can be estimated from those at nearby locations and the temperature change for the month and latitude for differences in elevation. The average temperature reduction for increase in elevation is frequently in the range of 0.55 to 0.60°C per 100 m.

Optimum Nitrogen Fertilizer (N)

For several crops the optimum level of nitrogen fertilizer, N, required in kg/ha is given by an equation that can be written:

$$N = KN \times ET_a \qquad (9)$$

in which ETa is total growing season crop evapotranspiration. ET_a may be limited by low values of ET_m or by limitations of water availability or both. Values of the constant KN vary from about 0.32 for corn to 0.10 for cotton. KN values should be determined for sorghum and millet by use of data from research and demonstration. By plotting variations in ETa on the X axis and variations in N on the Y axis, isoquants of yields can be graphed and a best-fit line drawn through the origin and the locations where the isoquants have approximately the maximum change in direction. The equation of this line gives a value for KN.

Values of MAI were used in Central America to estimate ETa for corn production. Application of the corresponding amounts of N nearly doubled yields on areas of the more fertile soils with near-optimum rainfall amounts and distributions.

Rainfall Depth Duration Amounts

Rainfall intensities that exceed soil infiltration rates produce runoff, and a portion of the precipitation is unavailable to meet crop water requirements. Depth duration amounts, D, can be estimated from an annual series or partial series of extreme events of daily rainfall or from monthly probabilities. The basic equation developed by Hargreaves (1981) can be written:

$$D = K \times T^{1/6} \times t^{1/4} \qquad (10)$$

in which K is a station or location constant, T is return period in years from 5 to 100, and t is time of concentration in hours from 1 to 96.

If P10.24 represents 10-year return period 24-hour rainfall, PMX is 30-year maximum monthly rainfall, and P05 is the 5% monthly probability value of precipitation occurrence or exceedance, then some useful equations are:

$$P10{,}24 = 22 + 0.30\ PMX \qquad (11)$$

$$P10{,}24 = 30 + 0.30\ P05 \qquad (12)$$

The equations are for rainfall in mm.

Ten-year return period precipitation for 1 hour can be estimated from the value of P10,24 by dividing by 2.21, or the fourth root of 24. Twenty-four-hour rainfall probabilities were found by Hershfield (1961) to average 1.13 times daily values; ratios of short-duration rainfall to 1 -hour duration amounts are approximately as follows:

Duration	5 min	15 min	30 min	1 h
Ratio	0.20	0.57	0.84	1.00

Field Capacity of a Soil (FC)

The field capacity, FC, of a soil is frequently taken as the soil water content at a matric potential of about -0.33 bars (atmospheres). If the percentages of sand (Sa), silt (Si), clay (Cl), and organic matter (OM) are known, and BD is the bulk density or dry-weight density of the soil, then the-0.33 bar value or FC can be estimated from an equation by Gupta and Larson (1979) that can be written:

$$FC = 0.0031\ Sa + 0.0059\ Si + 0.0080\ Cl + 0.0022\ 0M - 0.143\ BD \qquad (13)$$

Percentage of carbon is converted to OM by multiplying by 1.7.

Permanent Wilting Point (PWP)

The permanent wilting point, PWP, is usually estimated from the water content retained by the soil at -15.0 bars. The equation from Gupta and Larson (1979) can be written:

$$PWP = 0.00006\ Sa + 0.0011\ Si + 0.0058\ Cl + 0.0022\ 0M + 0.0267\ BD \qquad (14)$$

Available Soil Water (ASW)

The available soil water when the soil is at the field capacity is given by the equation:

$$ASW = FC - PWP \qquad (15)$$

Usually the allowable percentage extraction, P, of the ASW does not exceed 60% if good growth is to be maintained.

Doorenbos et al. (1979) give values of KC and ky for sorghum of 0.75 and 0.90 for the full crop-growing season. The coefficients or factors are not given for millet but should be estimated at somewhat lower values.

Short-Period Rainfall

A monthly moisture availability index is a useful criterion for many purposes but may fail to be adequate in several circumstances. If available soil water, ASW, is at a low value, a weekly or 10-day index may be desirable. This is the case for a large area of Oxisols in Brazil. In El Salvador, monthly MAI may be about optimum in April; however, the first 15 days may be quite dry, and the last half of the month receive twice as much rain as needed.

Sarker et al. (1982) present various weekly probabilities both graphically and in tabular form; these allow for decisions as to the level of risk that may be taken (see also Sarker, these Proceedings).

An Economic Model

Any one of several factors may limit production to a low level. If levels of water availability and energy for evapotranspiration are not too limiting, then nitrogen may determine the upper limit on yield. If this is the case, then a graph showing nitrogen, N, in kg/ha on the X axis and increase in yield in kg of grain sorghum or millet per kg of N added on the Y axis is useful. The value of 1 kg of grain produced can then be compared with the cost of 1 kg of N. Safe economic levels for fertilization can be assumed when the value of resulting production equals two to three times the cost of the additional N required to achieve that production.

Summary and Conclusions

Within a range of favorable conditions yield or production of grain sorghum or millet may be directly proportional to any one of three factors, providing all other conditions are not seriously limiting. These three cardinal factors are energy, water, and fertility. Models for evaluating the effect of and interactions of these factors are presented.

Procedures are given for estimating the dependability of rainfall amounts and available soil water storage capacity. An economic model is suggested relating yield to nitrogen application.

The agroclimatic models presented are simple, useful, and require a minimum of data. The principal limitation on benefits from agroclimatic models is not climatic data scarcity but a shortage of trained professionals and technicians familiar with the potential uses of agroclimatic models.

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Session 3

Agroclimatological Studies in Sorghum- and Millet-growing Regions

Adaptation des mils et sorghos a la photoperiode, au parasitisme et a la capacite hydrique du sol

P. Franquin*

Résumé

Adaptation des mils et sorghos à la photopériode, au parasitisme et à la capacité hydrique du sol : La productivité d'une culture de mil ou de sorgho résulte, parmi d'autres, d'une combinaison de trois facteurs indépendants : réaction photopériodique, sensibilité au parasitisme, capacité hydrique du sol. La date de plantation et la réaction photopériodique commandent la durée et la position dans le temps des phases de développement des cultivars (phases végétative, florale, fructifère), par rapport aux disponibilités hydriques et à l'occurence du parasitisme, celles-ci étant déterminées par la répartition des pluies et par la capacité en eau du sol. La démonstration repose sur deux outils : un modèle probabiliste de la période climatique de végetation et un modèle d'évaluation, en termes de rendement relatif R/100, du calage des cultivars.

Introduction

Il n'y a pas de relation apparente entre ces trois conditions de l'environnement que sont la duree du jour (photoperiode), la capacite du sol pour l'eau et le parasitisme. Or, pour une grande part, la productivite d'un mil ou d'un sorgho resulte de l'interference de ces trois conditions, ainsi qu'il peut etre montre au moyen de deux modeles :

- un modele frequentiel de la periode climatique de vegetation. Ce modeie geometrique, qui integre ensemble des caracteristiques physiques de l'atmosphere et du sol, rend compte en termes probabilistes des durees et positions dans le temps de cette periode de vegetation. Le principe de ce systeme a ete presente ici-meme a l'ICRISAT en 1978, a l'occasion d'une conference (International Workshop on the Agroclimatological Research Needs of the Semi-Arid Tropics);
- un modeie devaluation des effets, sur la productivite, du "calage" des cycles des cultivars par rapport aux caracteristiques statistiques de duree et de position de la periode, etablies au moyen du modeie precedent.

Ce dernier modele est fonde sur la supposition que la production de matiere seche (M.S.) est une fonction de l'integrale des valeurs instantees de l'evapotranspiration relative ETR/ETP (Franquin 1980):

$$\text{Rendement (M.S.)} = f\left(\int_{t_1}^{t_2} \frac{ETR}{ETP}\, dt\right) \tag{1}$$

Pour l'ensemble du cycle de vegetation d'un cultivar et pour des intervalles de temps d'un jour, le rendement en matiere seche peut alors etre formule comme suit:

$$R(M.S.) = \bar{m} d \frac{E\bar{T}R}{E\bar{T}P} \tag{2}$$

Cette formulation differe de celle de de Wit [$Y = m(T/E_o)$, 1958], qui neanmoins la confirme, en ce que ETR et ETP se substituent respectivement a la transpiration T et a l'evaporation-bac E_o; en ce que aussi le parametre "temps", c'est-a-dire la duree d, en jours, du cycle de vegetation, est explicite; m est alors, pour ETR = ETP, le taux journalier moyen de M.S., taux qui depend de la

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photosynthese (en rapport avec le rayonnement et la temperature) et de la fertilite du sol.

Le produit rnd represente done, pour une annee particuliere, le rendement R_o qui eut ete obtenu cette annee-la pour ETR = ETP. D'ou :

$$R/\bar{m}d = R/R_o = \frac{E\bar{T}R}{E\bar{T}P} \qquad (3)$$

Si on admet que $\bar{m}$ ne varie pas sensiblement d'une annee a l'autre en regions tropicales (sol et densite de plantation identiques; saturation de la photosynthese par la lumiere et la temperature), le rendement R_o varie chaque annee avec d. En effet, la duree de cycle d'un cultivar photoperiodique, par exemple, varie avec la date de plantation, c'est-a-dire avec la photoperiode. Soit d_o la duree de cycle optimale pour le rendement: le rendement potentiel interannuel est md_o. Soit 100 ce rendement potentiel: alors la duree relative variable du cycle est $\delta = d/d_o$, avec $0 \leq \delta \leq 1$. D'ou:

$$R/100 = \delta \frac{E\bar{T}R}{E\bar{T}P} \qquad (4)$$

On admettra ici que le rendement R est lineairement proportionnel a δ, duree relative du cycle de vegetation, du moins en premiere approximation.

Mais toutes les phases de developpement d'une plante ne varient pas en duree de la meme facon, certaines meme pouvant rester constantes. Soit, par exemple, trois phases. A condition de ponderer, relativement aux exigences en eau, chacune des phases par un exposant k_1 on ecrira :

$$R/100 = \delta_1\left(\frac{E\bar{T}R}{E\bar{T}P}\right)_1^{k_1} \cdot \delta_2\left(\frac{ETR}{E\bar{T}P}\right)_2^{k_2} \cdot \delta_3\left(\frac{E\bar{T}R}{E\bar{T}P}\right)_3^{k_3} \qquad (5)$$

ou, plus generalement:

$$R/100 = \prod_{i=1}^{p} \delta_1 \left(\frac{E\bar{T}R}{E\bar{T}P}\right)_1^{k_1} \qquad (6)$$

Les coefficients k_i notent, eu egard au facteur eau, l'importance relative de chacune des phases dans le determinisme du rendement (Jensen 1968).

Si donc on admet qu'en regions tropicales m reste interannuellement a peu pres constant, cette formulation est generalisable a toute plante, qu'elle soit ou non photoperiodique, que les δ_i varient ou non avec la photoperiode et/ou la temperature. Dans le cas d'un cultivar non-photoperiodique en conditions de temperature optimales pour la duree, les δ_i sont egaux a 1. D'ou, pour un developpement en trois phases:

$$R/100 = \left(\frac{E\bar{T}R}{E\bar{T}P}\right)_1^{k_1} \cdot \left(\frac{E\bar{T}R}{E\bar{T}P}\right)_2^{k_2} \cdot \left(\frac{E\bar{T}R}{E\bar{T}P}\right)_3^{k_3} \qquad (7)$$

On retrouve ici la formulation de Jensen (1968), qui s'applique de meme au cas d'un cultivar photoperiodique que l'on planterait chaque annee a date fixe, considerant que les δ_1 sont egaux a 1.

Chez les mils et sorghos, on considerera trois phases de developpement:

- une phase "vegetative", de la germination a l'initiation florale, de duree relative δ_1;
- une phase "florale", de initiation florale a la nouaison (fruit setting), de duree relative δ_2;
- une phase "fructifere", de la nouaison a la maturation (grain filling), de duree relative δ_3.

Si le cultivar est strictement photoperiodique (absolu) et en admettant que les temperatures varient peu interannuellement, les durees relatives δ_2 et δ_3 peuvent etre egalees a 1 (les phases 2 et 3 sont a peu pres fixes dans le temps). Seule varie, avec la date de plantation, la duree relative δ_1 de la phase vegetative. Si, par ailleurs, on considere non pas le rendement en matiere seche, mais le rendement en grain, ETM (evapotranspiration maximale) se substituant a ETP, on aura:

$$R/100 = \delta_1\left(\frac{E\bar{T}R}{E\bar{T}M}\right)_1^{k_1} \cdot \left(\frac{E\bar{T}R}{E\bar{T}M}\right)_2^{k_2} \cdot \left(\frac{E\bar{T}R}{E\bar{T}M}\right)_3^{k_3} \qquad (8)$$

La duree optimale de la phase vegetative peut etre tiree d'une experience sur le terrain ou determinee par la premiere date possible de plantation ou obtenue par un ensemble de relations donnees en Annexe (voir a la fin).

On considerera, dans la suite, d'abord les cultivars absolument photoperiodiques, puis, ensemble, les cultivars non-photoperidiques et ceux qui sont relativement photoperiodiques.

Cultivars absolument photoperiodiques

A condition de semer ces mils ou sorghos dans un certain intervalle de temps (qui peut aller jusqu'a 2 mois), les phases florale et fructifere restent approximativement stables en duree et fixes dans le temps. Seule varie, avec la date de plantation, la durée d_1 de la phase végétative, cette durée étant un facteur très important de la productivité.

Curtis (1968) a montré que les populations de sorgho photopériodiques traditionnellement cultivées au Nigeria "épient" généralement vers la fin des grosses pluies. Cette observation peut être précisée si l'on trace, pour une station, la courbe mensuelle moyenne des pluies et qu'on l'intersecte par les courbes moyennes de ETP et ETP/2 (Fig. 1). Numérotant de 1 à 4 les intersections, on constate que les populations en question épient aux environs proches de l'intersection 3, et donc "fleurissent" entre les intersections 3 et 4.

Or cette situation se retrouve en Haute-Volta pour les mils photopériodiques. Des échantillons de mils, prélevés dans des villages de Haute-Volta, ont été collectés en 1976 par Clément, Perret et al. Ces échantillons ont été semés le 1 juillet à l'ICRISAT à Kamboinsé, stations proche de Ouagadougou. Puis les dates de floraison femelle ont été relevées. La Figure 1 rapporte aux événements 3 et 4 les dates de floraison des échantillons prélevés près de Ouahigouya (13°55) dans le Nord, Ouagadougou (12°21) dans le Centre, Bobo-Dioulasso (11°10) dans le Sud. On constate que les dates de floraison femelle à Kamboinsé se situent très généralement dans l'intervalle entre les intersections 3 et 4, si du moins on ajoute plus ou moins 5 jours selon que la station est plus au nord ou au sud de Kamboinsé.

Par ailleurs, Cochemé et Franquin (1967), Franquin (1969) a montré que le rendement d'un mil photopériodique (Sanio) de Bambey (Sénégal) était maximal dans les années où la date d'épiaison, à peu près fixe (le 20/09), se trouvait proche de l'intersection 3. L'écart entre la date variable de cette intersection et la date du 20/09 explique à lui seul 55% de la variance du rendement.

Cochemé et Franquin (1967), Franquin (1969), Curtis (1968), Kassam (1974), et Wien et Summerfield (1980) qui rapportent les mêmes observations pour des niébés photopériodiques, donnent l'explication suivante de l'effet sur le rendement de la date de floraison par rapport à la fin des pluies : si la date de floraison est trop précoce, le grain est endommagé par des maladies et parasites; si, par contre, la floraison est trop tardive, échappant par là aux effets de l'impact direct des pluies sur l'épi, le remplissage des grains et la maturation sont incomplètes en raison de l'insuffisance d'eau dans le sol pour assurer la fructification.

Les variétés photopériodiques locales sont partout mieux adaptées à ces exigences contraires que les variétés d'origine plus méridionale ou plus septentrionale. L'adaptation répond à la nécessité, pour la culture du mil ou du sorgho, d'échapper d'une part à l'impact direct des pluies sur la plante et d'autre part à l'insuffisance d'eau dans le sol. Cette adaptation, qui constitue un compromis entre deux risques opposés, résulte d'une sélection ancestrale en rapport avec la réaction photopériodique et la température, qui ne changent guère interannuellement au plan local. Il convient donc de "caler", dans toute situation géographique, des cultivars dont la date de floraison est compatible avec la susceptibilité aux parasites et avec la capacité hydrique du sol.

Calage de cultivars absolument photopériodiques

La floraison d'un cultivar photopériodique absolu se réalisant à date à peu près fixe (si le semis n'est pas trop tardif), la durée du cycle de végétation varie avec la date de plantation.

En fait, seule varie la durée d_1 de la phase végétative, les durées d_2 et d_3 des phases florale et fructifère restant constantes et à peu près fixes dans le temps. Toutes autres choses égales, la productivité de la culture est fonction de cette durée d_1 de la phase végétative et sa productivité "relative" (R/100), de la durée relative δ_1 de cette phase.

En rapport avec la formulation (8), le calage du cycle d'un tel cultivar (absolument photopériodique) de mil ou sorgho, se présente comme dans l'exemple ci-après :

– La durée de la phase "florale" est constante ($d_2 = 50$ jours) et fixe dans le temps, de la 2ème décade d'août à la 3ème de septembre, l'épiaison s'étant déterminée dans la 2ème décade de septembre (cas réel à Ouagadougou).

– La durée de la phase "fructifère", qui suit la phase florale, est constante ($d_3 = 30$ jours) et fixe, s'étendant sur la totalité d'octobre.

– La durée d_1 de la phase "végétative", qui précède la phase florale, est variable avec la date de semis. Cette date de semis est simulée au départ de chacun des 50 bilans hydriques annuels, eux-mêmes simulés selon un pas de temps de 10 jours (voir exemple Fig. 2). La

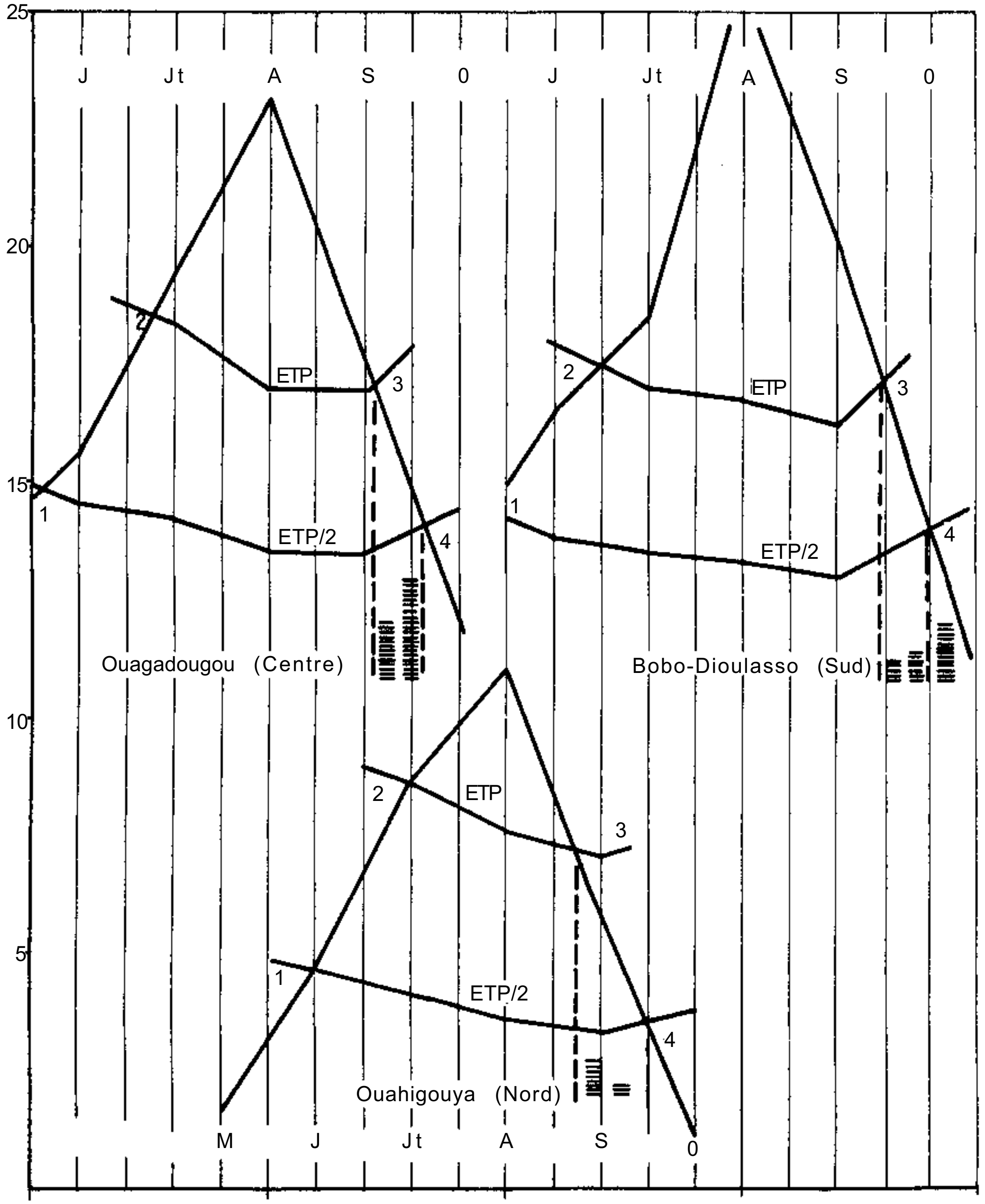

Figure 1. Frequences, a la station de Kamboinse (proche de Ouagadougou), des dates de floraison femelle d'echantillons de mils collectes dans des villages voisins de Ouahigouya (Nord), Ouagadougou (Centre), Bobo-Dioulasso (Sud). Les instants de floraison tombent entre les Intersections 3 et 4 des courbes pluviometriques mensuelles moyennes et des courbes de ETP et ETP/2. A Bobo-Dioulasso, les mils devraient fleurir un peu plus tot qua Kamboinse; a Ouahigouya, un peu plus tard.

	Périodes		P	HD	HR	ETP	K	ETM	ETR	RS	RDR	RDRC	D(RS)	ETM-ETR/ETM	ETR/ETP	ETM-ETR	RU
1	Janvier	1ère	0.0	0.0	0.0	54.0	0.50	27.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	27.0	0.0
2	Janvier	2ème	0.0	0.0	0.0	56.0	0.50	28.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	28.0	0.0
3	Janvier	3ème	0.0	0.0	0.0	56.1	0.50	28.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	28.0	0.0
4	Février	1ère	0.0	0.0	0.0	62.0	0.50	31.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	31.0	0.0
5	Février	2ème	0.5	0.5	1.00	63.0	0.50	31.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	31.5	0.5
6	Février	3ème	0.0	0.5	1.00	57.6	0.50	28.8	0.0	0.5	0.0	0.0	0.0	1.00	0.0	28.8	0.5
7	Mars	1ère	0.0	0.5	1.00	67.0	0.50	33.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	33.5	0.5
8	Mars	2ème	0.0	0.5	1.00	69.0	0.50	34.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	34.5	0.5
9	Mars	3ème	0.0	0.5	1.00	71.5	0.50	35.7	0.0	0.5	0.0	0.0	0.0	1.00	0.0	35.7	0.5
10	Avril	1ère	0.0	0.5	1.00	71.0	0.50	35.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	35.5	0.5
11	Avril	2ème	0.4	0.9	1.00	71.0	0.50	35.5	0.0	0.9	0.0	0.0	0.0	1.00	0.0	35.5	0.9
12	Avril	3ème	5.0	5.9	1.00	71.0	0.50	35.5	5.9	0.0	0.0	0.0	5.9	0.83	0.08	29.6	5.9
13	Mai	1ère	20.8	20.8	1.00	70.0	0.50	35.0	20.8	0.0	0.0	0.0	20.8	0.41	0.30	14.2	20.8
14	Mai	2ème	44.0	44.0	1.00	69.0	0.50	34.5	34.5	9.5	0.0	0.0	34.5	0.0	0.50	0.0	44.0
15	Mai	3ème	47.8	50.0	1.00	72.6	0.50	36.3	36.3	13.7	7.3	7.3	36.3	0.0	0.50	0.0	50.0
16	Juin	1ère	25.7	39.4	0.79	64.0	0.55	35.2	35.2	4.2	0.0	7.3	45.0	0.0	0.55	0.0	50.0
17	Juin	2ème	69.9	50.0	1.00	60.0	0.65	39.0	39.0	11.0	23.8	31.1	39.0	0.0	0.65	0.0	50.0
18	Juin	3ème	24.0	35.0	0.70	58.0	0.80	46.4	35.0	0.0	0.0	31.1	50.0	0.25	0.60	11.4	50.0
19	Juillet	1ère	38.5	38.5	0.77	56.0	1.00	56.0	38.5	0.0	0.0	31.1	50.0	0.31	0.69	17.5	50.0
20	Juillet	2ème	50.6	50.0	1.00	55.0	1.10	60.5	50.0	0.0	0.6	31.7	50.0	0.17	0.91	10.5	50.0
21	Juillet	3ème	23.1	23.1	0.46	56.1	1.10	61.7	23.1	0.0	0.0	31.7	50.0	0.63	0.41	38.6	50.0
22	Août	1ère	158.0	50.0	1.00	47.0	1.10	51.7	50.0	0.0	108.0	139.7	50.0	0.03	1.06	1.7	50.0
23	Août	2ème	176.1	50.0	1.00	45.0	1.10	49.5	49.5	0.5	126.1	265.8	49.5	0.0	1.10	0.0	50.0
24	Août	3ème	88.9	50.0	1.00	49.5	1.10	54.4	50.0	0.0	39.4	305.2	50.0	0.08	1.01	4.4	50.0
25	Septembre	1ère	36.9	36.9	0.74	46.0	1.10	50.6	36.9	0.0	0.0	305.2	50.0	0.27	0.80	13.7	50.0
26	Septembre	2ème	30.4	30.4	0.61	48.0	1.10	52.8	30.4	0.0	0.0	305.2	50.0	0.42	0.63	22.4	50.0
27	Septembre	3ème	20.8	20.8	0.42	50.0	1.10	55.0	20.8	0.0	0.0	305.2	50.0	0.62	0.42	34.2	50.0
28	Octobre	1ère	10.3	10.3	0.21	56.0	0.90	50.4	10.3	0.0	0.0	305.2	50.0	0.80	0.18	40.1	50.0
29	Octobre	2ème	0.0	0.0	0.0	59.0	0.70	41.3	0.0	0.0	0.0	305.2	50.0	1.00	0.0	41.3	50.0
30	Octobre	3ème	2.2	2.2	0.04	60.5	0.50	30.2	2.2	0.0	0.0	305.2	50.0	0.93	0.04	28.0	50.0
31	Novembre	1ère	0.0	0.0	0.0	56.0	0.50	28.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	28.0	50.0
32	Novembre	2ème	0.0	0.0	0.0	57.0	0.50	28.5	0.0	0.0	0.0	305.2	50.0	1.00	0.0	28.5	50.0
33	Novembre	3ème	0.0	0.0	0.0	54.0	0.50	27.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	27.0	50.0
34	Décembre	1ère	0.0	0.0	0.0	52.0	0.50	26.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	26.0	50.0
35	Décembre	2ème	0.0	0.0	0.0	52.0	0.50	26.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	26.0	50.0
35	Décembre	3eme	0.0	0.0	0.0	55.0	0.50	27.5	0.0	0.0	0.0	305.2	50.0	1.00	0.0	27.5	50.0
	Totaux		873.6			2116.9		1388.2	568.4							819.8	
	Moyennes													0.66	0.29		

Figure 2. Exemple de simulation du bilan hydrique décadaire pour un cultivar photopériodique de mil ou de sorgho qui fleurit à date à peu près fixe. La durée de la phase végétative (ici 90 jours) varie avec la date de semis; les phases florale (50 jours) et fructifère (30 jours) restent à peu près stables en durée et en position. Cette simulation permet d'évaluer les indices ETR/ETP et ETR/ETM.

decade de semis est ici, par convention, ia premiere decade pour laquetle la pluie P est egale ou superieure a ETP/2 (35 mm en moyenne a Ouagadougou). Dans ces conditions, la periode de semis s'etend sur 2 mois, de la lere decade de mai (M1) a la lere decade de juillet (Jt1). De M1 a la 2eme decade d'aoGt, la phase vegetative est de 10 decades: c'est la duree "optimale" d_o a laquelle se rapportent les durees d_1 variables. Ainsi, quand le semis tombe en Jt1, la phase vegetative recouvre 4 decades, d'ou : $\delta_1 = 0.4$; la decade moyenne de semis etant la lere de juin (J1), d_1 est alors egale a 7 decades, d'ou : $\delta_1 = 0.7$; etc.

Les bilans hydriques ont ete calcules respectivement selon des RU de 50, 100 et 150 mm.

Dans le cas extreme ou le semis tombe en M1, les coefficients culturaux K appliques au bilan hydrique de la culture constituent la suite ci-apres, les parentheses delimitant les phases:

(0.50-0.50-0.55-0.65-0.80-1.00-1.10-1.10-1.10-1.10) (1.10-1.10-1.10-1.10-1.10) (0.90-0.70-0.50).

Dans l'autre cas extreme ou le semis tombe en Jt1, la suite des K est ainsi:

(0.50-0.50-0.55-0.65) (0.80-1.00-1.10-1.10-1.10) (0.90-0.70-0.50).

La Figure 2 presente un bilan annuel etabli sur ces principes, avec RU de 50 mm, pour ia station de Ouagadougou tout proche de celle de Kamboinse.

Enfin, a defaut de rendements de mil ou sorgho qui permettraient d'estimer les coefficients k_1, k_2, k_3 de ta formule (8), on adopte ici ceux qui ont ete obtenus pour un sorgho irrigue par Jensen et Sletten (1965): 0.5-1.5-0.5.

L'operation consiste maintenant, pour chacun des 50 bilans annuels etablis respectivement sur la base des trois RU (50, 100 et 150 mm). a evaluer l'expression :

$$R/100 = \delta_1 \left(\frac{E\bar{T}R}{E\bar{T}M}\right)_1^{0.5} \cdot \left(\frac{E\bar{T}R}{E\bar{T}M}\right)_2^{1.5} \cdot \left(\frac{E\bar{T}R}{E\bar{T}M}\right)_3^{0.5} \quad (9)$$

La Figure 3 presente, pour chacune des trois RU, les valeurs moyennes - sur 50 annees - de chacun des trois termes multiplicatifs de ('expression (9) et les valeurs moyennes de R/100.

On comparera aussi les distributions de frequences de RU/100 etablies pour chacune des trois RU (Tab. 1).

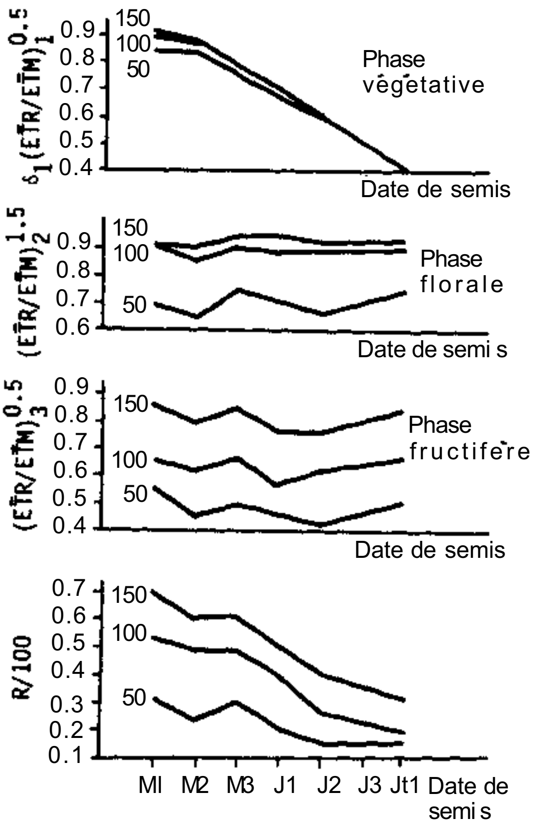

Figure 3. Variations, selon la RU (50, 100, 150 mm) et selon la date de semis (M1: lere decade de mai, etc.), des termes relatifs du rendement propres aux phases vegetative, florale et fructifere. Les variations du rendement retatif (R/100) resultant de la combinaison des variations de ces trois termes. δ_1 varie avec la date de semis, de 0.4 (Jt1) a 1.0 (M1). Le rendement diminue avec la date de semis, c'est-a-dire avec δ_1; par ailleurs, le rendement augmente avec la RU (50, 100, 150 mm) au niveau des phases florale et fructifdre.

Enfin, on peut visualiser, en les positionnant en frequence dans le temps, les deficits hydriques des phase florale et fructifere (Fig. 4). Ces deficits sont concretises par les surfaces hachurees delimitees:

- a gauche, par les courbes continues resultant de l'application aux bilans hydriques du principe de "periode frequentielle de vegetation", principe evoque dans l'introduction. Les courbes du bas de la figure, qui se rapportent a la phase florale,

Tableau 1. Distributions de frequences de RU/100 pour trots valeurs de RU

R/100	RU: 50 mm	RU: 100 mm	RU: 150 mm
0.01-0.10	IIIIIIIII	II	
0.11-0.20	IIIIIIIIIIIIII	IIIIII	IIII
0.21-0.30	IIIIIIIIIIIIII	IIIIIIII	IIIII
0.31-0.40	IIIIII	IIIIIII	IIIIIIIIII
0.41-0.50	IIIII	IIIIIIIIIIIII	IIIIIIIIIII
0.51-0.60	II	IIIIII	IIIIIIIIIIII
0.61-0.70		IIII	IIII
0.71-0.80		IIII	IIII
Moy.	0.23	0.40	0.45

donnent les probabilites observees de depassement de 0.90 ETR/ETP; les courbes du haut, qui se rapportent a la phase fructifere, aonnent les probabilites observees de depassement de 0.50 ETR/ETP; ces niveaux de ETR/ETP sont fixes quelque peu arbitrairement comme representant des seuils inferieurs necessaires pour l'obtention d'un rendement convenable; tous autres seuils peuvent etre preferes et trouves dans les bilans hydriques.

- a droite, par les courbes tiretees correspondent a la probabilite 1.00 de depassement des seuils 0.90 et 0.50 a la date finale de realisation des phases florale et fructifere.

Conclusion

Il est aise de comprendre que, pour un cultivar d'epiaison plus tardive, echappant a l'impact des pluies sur l'epi, les deficits hydriques des phases florale et fructifere seraient encore plus importants; neanmoins, les risques decroissent a mesure qu'augmente la capacite hydrique du sol.

Une autre alternative, au contraire, est de rechercher un cultivar d'epiaison plus precoce, mais de bonne tolerance au parasitisme, afin d'exploiter des sols de capacite hydrique faible.

On peut encore faire d'autres remarques:

Pour le cultivar en question, dont l'epiaison se determine dans la 2eme decade de septembre, le taux d'augmentation de R/100 (voir les distributions de frequence) est beaucoup plus fort de 50 a 100 mm que de 100 a 150 mm. Les Figures 3 et 4 montrent que, dans ce dernier cas, l'amelioration porte presque uniquement sur la phase fructifere.

. Les disponibilites hydriques durant la phase vegetative paraissent toujours convenables quelle que soit la date simulee du semis (premiere decade totalisant une lame de pluie depassant ETP/2, soit 35 mm en moyenne a Ouagadougou). Cela est vrai quelle que soit la RU (Fig. 3). Si, dans la realite, il n'en allait pas ainsi, c'est qu'il y aurait des pertes d'eau par ruissellement, pertes qu'il conviendrait de limiter. Il est vraisemblable neanmoins qu'un bilan hydrique calcule selon un pas de temps de 5 jours mettrait en evidence des deficits en eau que masque le pas de 10 jours. Enfin, des pluies excedentaires durant cette phase vegetative peuvent exercer un effet depriment sur le rendement.

. Les rendements seraient d'autant plus eleves que les semis sont plus precoces (Fig. 3), en raison de l'augmentation de duree de la phase vegetative. Mais ils n'augmenteraient plus, du fait des aleas pluvior retriques, anterieurement a la decade M1, M1 definissant la duree optimale d_o = 10 decades de la phase vegetative du cultivar en question.

Cultivars non-photoperiodiques et relativement photoperiodiques

Exprimee en "somme de degres-jour", la duree de cycle des cultivars strictement non-photoperiodiques se montre constante. Evaluee en "nombre de jours", la duree reste constante quand la temperature (nocturne) varie peu ellememe, comme c'est le cas durant la saison des pluies.

La duree de cycle de ces cultivars non-photoperiodiques est tres courte (80/70 jours et moins). Pour cette raison, ils ne possedent pas le potentiel de productive des cultivars photoperiodiques dont la phase vegetative est extensible. Aussi rencontre-t-on des mils non-photoperiodiques, en Haute-Volta, surtout dans le nord ou la periode de vegetation des cultures est tres courte; mais aussi dans le sud, dans la region de Leo par exemple, ou leur interet est de constituer des cultures dites "de soudure".

Un autre interet des cultivars non-photoperiodiques est leur souplesse d'emploi puisqu'ils ne fleurissent pas a date fixe, au contraire des cultivars absolument photoperiodiques. Ce caractere permet de caler leurs phases de floraison et- de fructification en conditions hydriques optimales; ou de les semer en tout

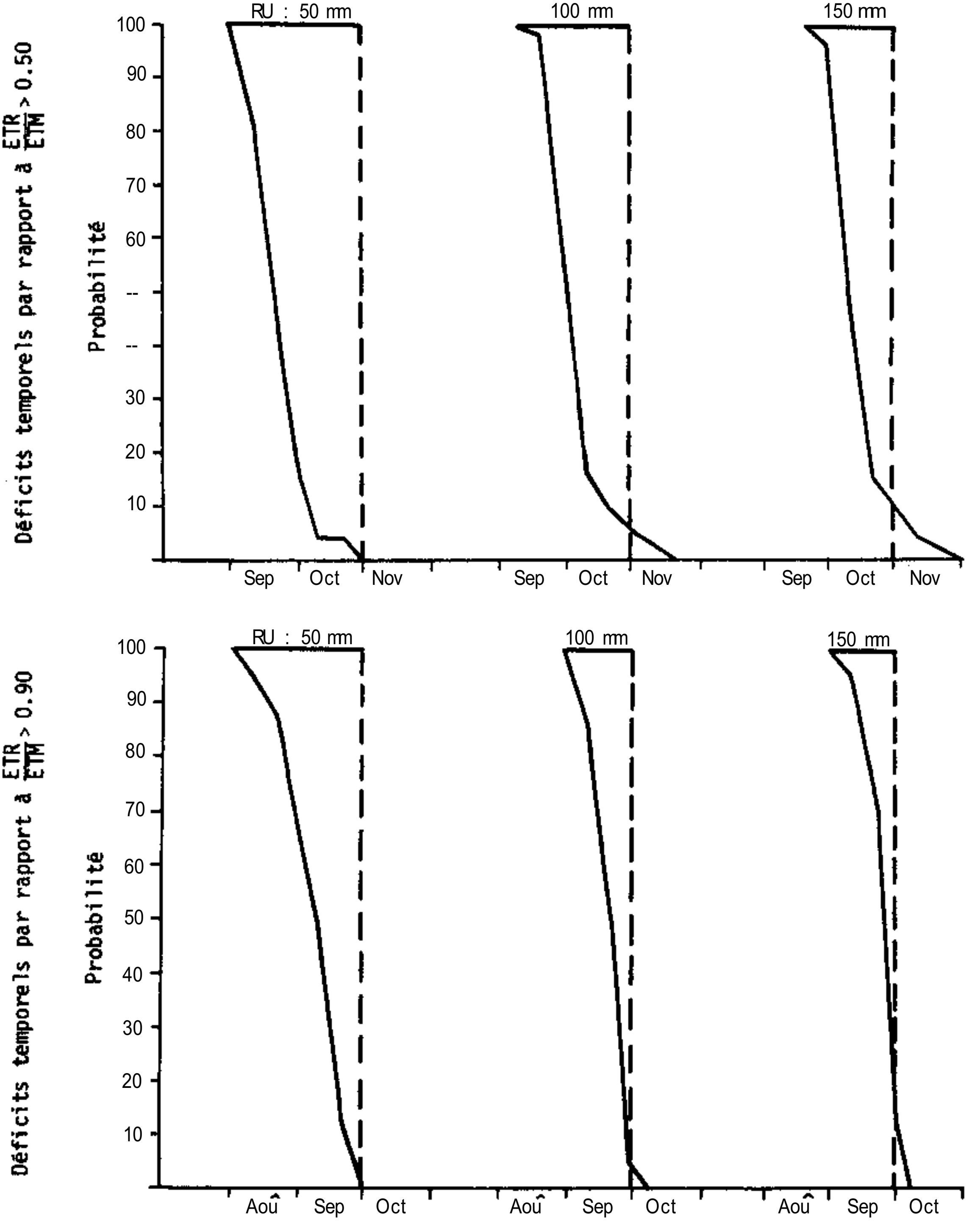

Figure 4. Representation en frequence et dans le temps, selon la RU (50, 100,150 mm), des deficits en eau :en bas, concemant la phase florale, deficit par rapport au critere ETR/ETM > 0.90; en haut, concernant la phase fructifere, deficit par rapport au critere ETR/ETM $\overline{>}$ 0.50. La duree du deficit s'exprime en termes de probabilite, qui dlmlnue avec la RU.

début de saison afin d'assurer la soudure. Il conviendrait de pouvoir allonger leur cycle, jusqu'à 100 jours par exemple, afin d'améliorer leur potentiel de productivité.

A cet égard, on peut encore s'adresser aux cultivars "relativement" photopériodiques (non absolus), dont les cycles sont de durée d'autant plus longue qu'ils sont semés plus tôt (quoique non pas trop tôt) et dont la floraison et la fructification ne sont fixes que pour une date de semis fixe, comme c'est le cas pour les non-photopériodiques. Ils se comportent donc comme ces derniers lorsque la date de semis varie peu.

Calage des cultivars non-photopériodiques ou relativement photopériodiques.

Le calage des phases florale et fructifère est grandement facilité si l'on dispose d'un modèle de la "période climatique fréquentielle de végétation". De tels modèles ont été établis pour Ouagadougou à partir d'une simulation de bilans hydriques (Fig. 2) calculés sur la base de RU de 50 mm (Fig. 5) et 100 mm (Fig. 6). Le contour extérieur du modèle caractérise la sous-période dite "semi-humide" définie par les probabilités que ETR/ETP soit égal ou supérieur à 0.50; le contour intérieur caractérise la sous-période dite "humide" définie par les probabilités que ETR/ETP soit égal ou supérieur à 0.90.

Supposons un cultivar non-photopériodique de 100 jours dans les conditions de température de Ouagadougou; ou un cultivar relativement photopériodique dont le cycle serait de 100 jours s'il était semé aux mêmes dates que l'est le précédent. Le cycle et les coefficients culturaux se présentent comme suit :

(0.50–0.55–0.60) (0.80–1.00–1.10–
1.10) (0.90–0.70–0.50)

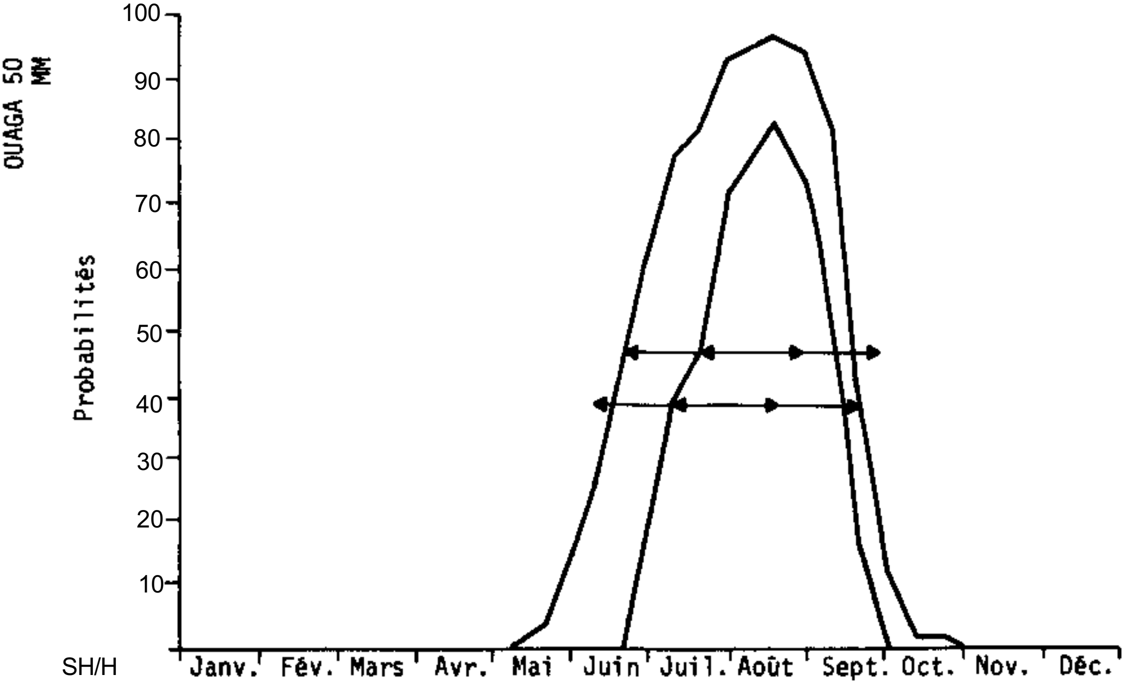

Figure 5. Calage, dans le cadre des sous-périodes fréquentielles "humide" (contour interne) et "semi-humide" (contour externe) des phases "florale" et "fructifère" d'un mil ou sorgho de 100 jours à Ouagadougou. La sous-période humide est délimitée par les probabilités que ETR/ETM soit supérieur à 0.90; la sous-période semi-humide, par les probabilités que ETR/ETM soit supérieur à 0.50. La RU est de 50 mm : l'intervalle de temps convenable pour le semis n'est que de 20 jours (J2+J3) et les probabilités de calage des phases florale et fructifère ne dépassent pas 0.38 et 0.42 respectivement.

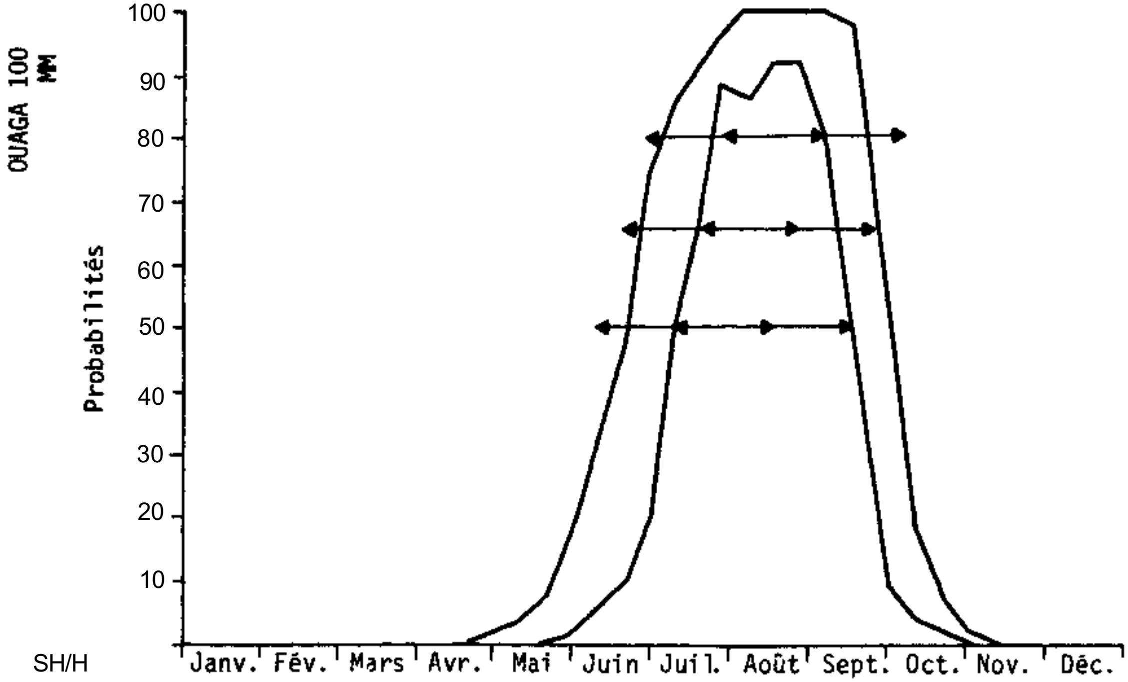

Figure 6. Idem que pour la Figure 5. Mais la RU est de 100 mm : l'intervalle de temps pour le semis est de 30 jours (J2+J3+Jt1) et les probabilités de calage des phases florale et fructifère sont respectivement de 0.70 et 0.98.

La phase florale de 40 jour est la plus critique pour le rendement à l'égard des disponibilités en eau. Il convient donc de la caler à la meilleure probabilité dans le cadre de la sous-période "humide" (contour intérieur, Fig. 5). Cette meilleure probabilité est : 0.70 (le 01/08) × 0.54 (le 10/09) = 0.38.

Ce calage apparemment optimal de la phase florale exigerait de semer dans la lère décade de juillet (Jt1). Mais il n'est pas concevable de semer chaque année dans une même décade. Il est indispensable de se donner un intervalle moins étroit de 20 à 30 jours. Si alors on déplace vers l'arrière (Fig. 5) la phase florale de une, deux ou trois décades – ce qui correspond à des semis effectués dans les décades J3, J2, J1 – les probabilités de calage de la phase florale sont respectivement 0.34, 0.31, 0.12, cette dernière étant trop faible : ainsi l'intervalle de temps pour semer serait celui des trois décades : J2+J3/Jt1. Il est remarquable, au plan phytosanitaire, qu'un tel calage fait coïncider la phase florale avec le maximum des pluies, d'où la nécessité de disposer de cultivars tolérants à l'égard du parasitisme.

Mais il importe d'examiner encore les conditions de calage de la phase fructifère de 30 jours par rapport aux probabilités liées à la sous-période "semi-humide" (branche droite du contour extérieur, Fig. 5). Au semis Jt1 correspond une probabilité très faible (le 10/10), pour la phase fructifère, d'être réussie au mieux; au semis J3, une probabilité de 0.12 (le 30/09); au semis J2, une probabilité de 0.42 (le 20/09). L'intervalle convenable de semis est finalement réduit à deux décades : J2+J3.

Cet intervalle est impératif si l'on s'efforce d'obtenir le rendement le moins variable et le meilleur en moyenne. Supposons en effet que l'on opère une simulation de semis identique à celle qui a été pratiquée concernant le cultivar absolument photopériodique. Au moyen de la formule

$$R/100 \; (E\bar{T}R/E\bar{T}M)_1^{0.5} \cdot (E\bar{T}R/E\bar{T}P)_2^{1.5} \cdot (E\bar{T}R/E\bar{T}P)_3^{0.5} \qquad (10)$$

appliquée aux bilans hydriques simulés, on peut comparer les distributions de fréquences de R/100 :

– d'une part, pour des semis effectués dans la décade J2;

– d'autre part, de façon dispersée, dans les décades M1 à Jt1.

Ces distributions sont montrées dans le Tableau 2.

Tableau 2. Distributions de frequences de R/100 pour des semis effectues dans differentes decades

R/100	Semis disperse	Semis decade J2
0.21-0.30	II	
0.31-0.40	III	
0.41-0.50	IIII	
0.51-0.60	IIIII	
0.61-0.70	IIIIIIIIIII	IIIIII
0.71-0.80	IIIIIII	III
0.81-0.90	IIIIIIIIIII	IIIIIIIIIIIIIIIIIIIII
0.91-1.00	IIIIIII	IIIIIIIIIIIIIIIIIIII

Supposons encore que les mêmes cultivars soient cultivés sur un sol de capacité hydrique égale non plus à 50 mm mais à 100 mm. Il suffit de se reporter à la Figure 6 pour constater que l'intervalle de temps convenable pour le semis passe de 20 à 30 jours (J2+J3+Jt1) et que les probabilités de calage des phases florale et fructifère augmentent beaucoup.

Conclusion

Un cultivar non-photopériodique ou relativement photopériodique présente une souplesse de calage meilleure que pour un cultivar absolument photopériodique, surtout s'il est cultivé sur un sol de capacité hydrique convenable. Il devra nécessairement présenter une bonne résistance au parasitisme en raison de la position variable dans le temps des phases florale et fructifère par rapport au maximum des pluies.

Remerciements

Mes plus vifs remerciements vont à MM. Clément, Perret et al. qui ont rempli la mission de collecte des échantillons de mils en Haute-Volta; ainsi qu'à l'ICRISAT dans ce pays pour les observations de floraison de ces échantillons.

Annexe

Durée de la phase végétative et nombre de noeuds foliaires

– Chez une plante strictement non-photopériodique, la durée d de la phase végétative ne dépend (à saturation de lumière) que de la température, selon la relation :

$$d(\bar{T}_i - T_o) \simeq \Sigma(T_i - T_o) = K \qquad (A1)$$

où T_i est la température moyenne (de la nuit, chez une plante d'espèce nyctipériodique) du jour i, T_o une température de base; K est une constante variétale.

– Chez une plante strictement photopériodique, la durée d dépend à la fois de la photopériode et de la température, selon la relation :

$$d(\bar{T}_i - T_o) \simeq \Sigma(T_i - T_o) = k_o + \frac{\pi m}{2a} \left[1 + \mathrm{tg}^2\left(\frac{\pi}{2} \frac{N_o/H_o}{\bar{N}_i/\bar{H}_i}\right)\right] \qquad (A2)$$

Ce résultat, pour une plante nyctipériodique comme l'est un mil ou un sorgho, est établi à partir des principes suivants : la plante est le siège d'un "rythme circadien" qui comporte deux périodes en 24^h, l'une de sensibilité "lumineuse" de durée H_o, l'autre de sensibilité "obscure" de durée N_o (avec $H_o + N_o = 24$). L'oscillation du système endogène N_o/H_o constitue la "base" à laquelle sont comparées, au moyen du phytochrome, les oscillations exogènes N_i/H_i des durées réelles de la nuit et du jour. Cette pulsation "forcée" N_i/H_i (à l'égard de la pulsation "propre" N_o/H_o) est pour la plante une information qui peut être effectivement introduite dans l'équation différentielle d'un oscillateur harmonique forcé, amorti par frottement de l'alternance nuit/jour :

$$u'' + \mathrm{cotg}^2\left(\frac{\pi}{2} \frac{N_o/H_o}{N_i/H_i}\right) u' + \left(\frac{\pi}{N_o/H_o}\right)^2 u = a(T_i - T_o) \frac{1}{N_i/H_i} \sin\left(\frac{\pi}{N_i/H_i} h\right) \qquad (A3)$$

L'intégration, par rapport à h (h = t/(24−t), 0≤t≤24), de l'excitation thermique liée à

$a(T_i - T_o)$ – excitation dont un seuil minimum m est requis pour l'induction de la floraison – conduit à la relation (2), où a et m sont des paramètres.

Le nombre n de noeuds ou d'entrenoeuds foliaires de la tige, à l'initiation de la floraison, dépend de la photopériode et de la température selon les relations :

$$n = n_o + \alpha m \mathrm{tg}^2\left(\frac{\pi}{2} \frac{N_o/H_o}{\bar{N}_i/\bar{H}_i}\right) \qquad (A4)$$

$$n = n_o + \alpha \frac{2a}{\pi} \sin^2\left(\frac{\pi}{2} \frac{N_o/H_o}{\bar{N}_i/\bar{H}_i}\right) \Sigma\, (T_i - T_o) \qquad (A5)$$

k_o et n_o sont respectivement la somme de température et le nombre de noeuds correspondant à la phase "juvénile"; $\pi m/2a$ peut se ramener à un seul paramètre k; on montre que : $k_o + k = K$, k étant la somme de températures séparant 2 noeuds.

L'expérience vérifie bien ces relations, pour un sorgho par exemple, si on en juge par les ajustements statistiques des relations (2) et (4) (Fig. 7).

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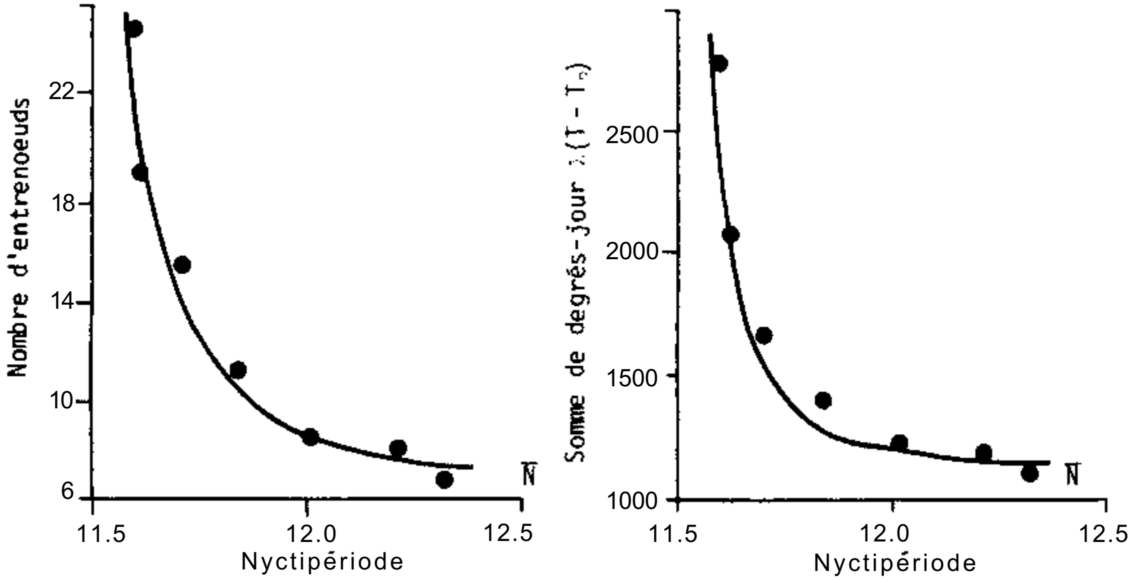

Figure 7. Données relatives à un sorgho cultivé au Tchad en conditions naturelles. A droite, ajustement de la relations (2) de l'Annexe à la somme de degrés-jour $\Sigma(T_i - T_o)$, en fonction de la nyctipériode moyenne $\bar{N}_i$; à gauche, ajustement de la relation (4) au nombre de noeuds de la tige, en fonction de la nyctipériode moyenne $\bar{N}_i$.

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Sorghum and Millet Adaptation to Photoperiod, Pest Incidence, and Soil Moisture-Retention Capacity

P. Franquin*

Abstract

Three independent factors—photoperiodic response, pest resistance, and soil moisture-retention capacity—frequently combine to determine sorghum and millet yields. The duration and time of occurrence of the different development phases (vegetative, flowering, and fruiting) of a cultivar depend on the planting date and photoperiodic response, in relation to available water and pest incidence. These last two factors are in turn determined by rainfall distribution and the water-holding capacity of a soil. This is demonstrated through a probabilistic model of the climatic period corresponding to the growing period and a model for evaluating the fitting of cultivar cycles based on relative yield, Y/100.

Introduction

There is no apparent relationship between daylength (photoperiod), water-holding capacity, and parasitism but in reality, sorghum and millet yields are determined to a large extent by the combined effect of these factors. This can be illustrated with the help of two models:

- The frequency model of the climatic growing period is a geometrical model that combines the physical characteristics of the soil and atmosphere, and describes this growing period in probabilistic terms of its duration and time of occurrence. The principle of this model was presented at ICRISAT in 1978 at the International Workshop on the Agroclimatological Needs of the Semi-Arid Tropics.
- A model for evaluating the effect on yield of the fitting of cultivar cycles to the statistical characteristics—duration and time of occurrence—of the growing period as established by the frequency model.

The second model is based on the hypothesis that dry-matter (DM) production is a function of the sum of instantaneous values of relative evapotranspiration; i.e. the ratio of actual evapotranspiration to potential evapotranspiration (AET/PET) (Franquin 1980 a):

$$\text{Yield (DM)} = f\left(\int_{t_1}^{t_2} \frac{AET}{PET}\, dt\right) \qquad (1)$$

Dry-matter yield for the entire growing period of a cultivar and for 1-day intervals can be formulated as:

$$\text{Yield (DM)} = \bar{m}d\, \frac{A\bar{E}T}{P\bar{E}T} \qquad (2)$$

This differs slightly from de Wit's (1958) formula, $Y = m(T/Eo)$, yet at the same time confirms it, since AET and PET are substituted by transpiration T and pan evaporation Eo, respectively; the time factor or the duration d (in number of days) of the growing period is explained; m is then for AET = PET, the daily average DM rate that is determined by photo-

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*ORSTOM, Bondy, France.

Note: This is an edited translation of the original French paper immediately preceding.

International Crops Research Institute for the Semi-Arid Tropics. 1984. Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics: Proceedings of the International Symposium, 15-20 Nov 1982, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

synthesis (in relation to radiation and temperature) and soil fertility.

The product $\bar{m}d$ therefore represents, for a particular year, the yield Yo for the year when AET = PET. Hence

$$Y/\bar{m}d = Y/Y_o = \frac{A\bar{E}T}{P\bar{E}T} \tag{3}$$

Given that there is little variation in m from one year to another in the tropics (identical soil and plant density, and photosynthetic saturation due to light and temperature), the yield Yo varies each year with d. In fact, the duration of a photosensitive cultivar, for instance, varies according to the planting date and hence the photoperiod. If do is the optimum duration for yield; the potential interannual yield is md_o. If this potential yield is 100, the variable relative duration is $\delta = d/do$ with $0 \leqslant \delta \leqslant 1$. Thus:

$$Y/100 = \delta \cdot \frac{A\bar{E}T}{P\bar{E}T} \tag{4}$$

It is supposed that there is a linear relation between yield Y and δ, the relative growing period, at least in the first approach.

But the duration of the different development phases of a plant do not vary in the same way; some may even remain constant. For example, in the case of three phases, when each phase is weighted by an exponent ki according to the water requirements, the following equation is obtained:

$$Y/100 = \delta_1 \left(\frac{A\bar{E}T}{P\bar{E}T}\right)_1^{k_1} \cdot \delta_3 \left(\frac{AET}{P\bar{E}T}\right)_2^{k_2} \cdot \delta_3 \left(\frac{A\bar{E}T}{P\bar{E}T}\right)_3^{k_3} \tag{5}$$

or, more generally:

$$Y/100 = \prod_{i=1}^{P} \delta_i \left(\frac{A\bar{E}T}{P\bar{E}T}\right)_i^{k_i} \tag{6}$$

The ki coefficients show, in relation to the water factor, the relative importance of each phase in determining yield (Jensen 1968). If $\bar{m}$ is supposed to remain almost constant in the tropics, this formula can be applied to any photosensitive or photoinsensitive cultivar, whether or not δ_i varies with photoperiod and/or temperature. For a photoinsensitive cultivar under optimum temperature conditions throughout the growing period, δ values are equal to 1. Hence, for a three-phase development:

$$Y/100 = \left(\frac{A\bar{E}T}{P\bar{E}T}\right)_1^{k_1} \cdot \left(\frac{A\bar{E}T}{P\bar{E}T}\right)_2^{k_2} \cdot \left(\frac{A\bar{E}T}{P\bar{E}T}\right)_3^{k_3} \tag{7}$$

This is Jensen's formula (1968), which is also applicable to a photosensitive cultivar that is sown every year on a fixed date, with δ_i equal to 1.

Three major development phases have been considered for sorghum and millet crops:

- The vegetative phase—from germination to floral initiation, of relative duration δ_1;
- The flowering phase—from floral initiation to fruit setting, of relative duration δ_2;
- The fruiting phase—from fruit setting to grain filling, of relative duration δ_3.

If the cultivar is completely photosensitive and there is little interannual fluctuation in temperature, the relative durations δ_2 and δ_3 may be equal to 1 (the time of occurrence of the second and third phases is almost fixed). The relative duration *6* of the vegetative phase alone varies according to the planting date. If grain yield and not dry-matter production is considered and MET (maximum evapotranspiration) replaces PET, the following equation is obtained:

$$Y/100 = \delta_1 \left(\frac{A\bar{E}T}{M\bar{E}T}\right)_1^{k_1} \cdot \left(\frac{A\bar{E}T}{M\bar{E}T}\right)_2^{k_2} \cdot \left(\frac{A\bar{E}T}{M\bar{E}T}\right)_3^{k_3} \tag{8}$$

The optimum length of the vegetative phase can be deduced through field experiments or determined by the first possible planting date or inferred from the equations in Annexure 1.

In this paper, the completely photosensitive cultivars are discussed first, followed by photoinsensitive and relatively photosensitive cultivars.

Completely Photosensitive Cultivars

The duration and time of occurrence of the flowering and fruiting phases remain quite stable, provided that these sorghums and millets are sown within a certain time interval (up to 2 months). The duration d_1 of the vegetative phase alone varies according to the planting date. This duration (d_1) plays an important role in determining crop productivity.

Curtis (1968) has shown that the photosensitive sorghum varieties that are traditionally grown in Nigeria generally head towards the end of the heavy rains. This can be seen more clearly from the monthly average rainfall curve for a station that is intersected by the mean PET and PET/2 curves (Fig. 1). When the points of intersection of these curves are numbered from 1 to 4, it can be seen that these varieties head near intersection 3 and therefore flower between intersections 3 and 4.

The same phenomenon was observed for photosensitive millet samples collected from villages in Upper Volta by Clement et al. in 1976. These samples were sown on 1 July at ICRISAT Center, Kamboinse, near Ouagadougou, and the female flowering dates were recorded. Figure 1 shows that the flowering dates of the samples collected near Ouahigouya (13°55'N) in the north, at Ougadougou (12° 21') in the center, and at Bobo-Dioulasso (11 ° 10') in the south, fall between intersections 3 and 4. At Kamboinse, the female flowering dates generally occur between intersections 3 and 4, with a margin of 5 days more or less, depending on whether the station is further north or south of Kamboinse.

Yield of a photosensitive millet variety (Sanio) from Bambey, Senegal, was highest in those years when the heading date (20 Sept) was almost fixed and near intersection 3 (Cocheme and Franquin 1967; Franquin 1969). The deviation of the variable date of this intersection and the date 20 September accounts for 55% of the variance in yield.

Cocheme and Franquin (1967), Franquin (1969), Curtis (1968), Kassam (1974), and Wien and Summerfield (1980), who reported the same kind of observations for photosensitive cowpeas, give the following explanation of the effect of the flowering date on yield in relation to the end of the rains. If the flowering date is very early, the grain is damaged by pests and diseases; with delayed flowering, the crop escapes the direct impact of the rains on the earhead, but grain filling and physiological maturity are incomplete due to lack of water for fruiting.

The local photosensitive varieties generally meet these contradictory requirements better than the more northern or southern varieties. Through natural selection, these sorghum and millet varieties have grown to adapt themselves to two extremes of the local environment—the direct impact of rain on the plant and inadequate water in the soil. This adaptation is related to their response to photoperiod and temperature, two factors that hardly change over the years at a local level. For any location, those cultivars should be grown whose flowering dates are compatible with water availability and pest incidence.

Fitting of Completely Photosensitive Cultivars

A completely photosensitive cultivar usually flowers on a fixed date (except for a very late planting), but the duration of the vegetative cycle (d) varies with the planting date. In fact, only the duration (d_1) of the vegetative phase fluctuates, while the flowering and fruiting phases (d_2 and d_3) remain practically constant in duration and time of occurrence. All other things being equal, crop production depends on duration d_1 of the vegetative phase and "relative" productivity (Y/100) on the relative duration δ_1 of this phase.

Based on equation 8, the position in time of such a completely photosensitive sorghum or millet cultivar is adjusted as in the following example:

- The duration of the flowering phase is constant ($d_2 = 50$ days) and fixed in time, from the second 10-day period in August to the third 10-day period in September; heading occurs in the second 10-day period of September (actual case at Ouagadougou).
- The duration of the fruiting phase, which follows the flowering phase, is constant ($d_3 = 30$ days) and fixed in time, and continues through October.
- The duration d_1 of the vegetative phase, which precedes the flowering phase, varies according to the planting date. This planting date is simulated at the beginning of each of the 50 annual water balances which are in turn simulated for 10-day intervals (Fig. 2). The 10-day period for planting is the first 10-day period when rainfall is usually equal to or higher than PET/2 (average 35 mm at Ougadougou). Under these conditions, the planting period extends over 2 months—from the first 10-day period of May (M1) to the first 10-day period of July (Jy1). The vegetative phase covers ten 10-day periods, from M1 to the second 10-day period of August; this is the optimum duration, do. The durations d_1 are related to this optimum duration, do = 10. Therefore, when the crop is sown in Jy1 the vegetative phase covers four 10-day periods; hence $\delta_1 = 0.4$; if the 10-day period for planting is the first one in June (J1), d_1 is then equal to seven 10-day periods, hence $\delta_1 = 0.7$; and so on.

The water balances were calculated on the basis

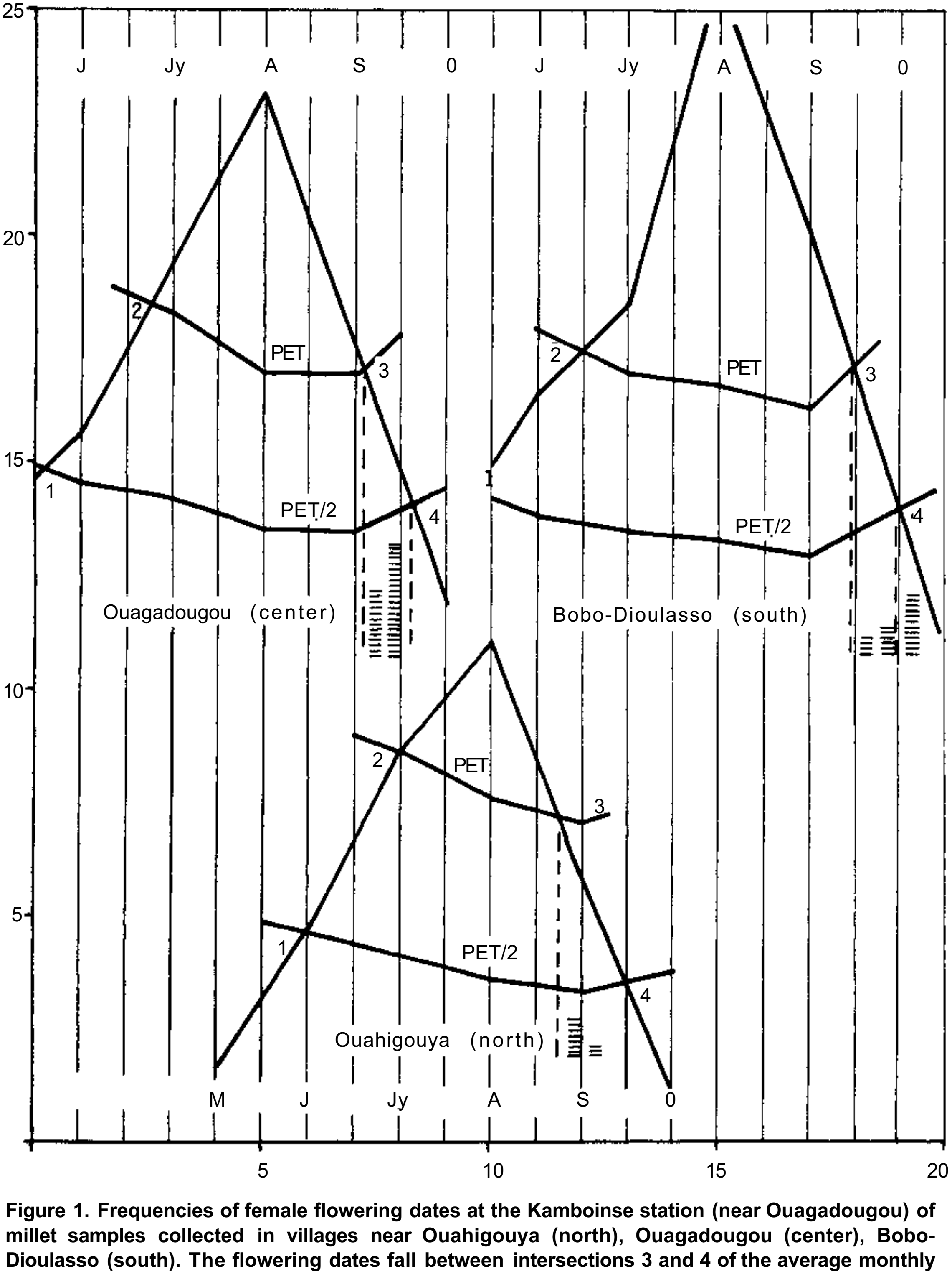

Figure 1. Frequencies of female flowering dates at the Kamboinse station (near Ouagadougou) of millet samples collected in villages near Ouahigouya (north), Ouagadougou (center), Bobo-Dioulasso (south). The flowering dates fall between intersections 3 and 4 of the average monthly rainfall curves and PET and PET/2 curves. At Bobo-Dioulasso, millets flower earlier than at Kamboinse and at Ouahigouya, a little later.

	Period		P	MD	MR	PET	K	MET	AET	RS	RDR	RDRC	D(RS)	MET-AET/ MET	AET/PET	MET-AET	AWC
1	January	1st	0.0	0.0	0.0	54.0	0.50	27.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	27.0	0.0
2	January	2nd	0.0	0.0	0.0	56.0	0.50	28.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	28.0	0.0
3	January	3rd	0.0	0.0	0.0	56.1	0.50	28.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	28.0	0.0
4	February	1st	0.0	0.0	0.0	62.0	0.50	31.0	0.0	0.0	0.0	0.0	0.0	1.00	0.0	31.0	0.0
5	February	2nd	0.5	0.5	1.00	63.0	0.50	31.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	31.5	0.5
6	February	3rd	0.0	0.5	1.00	57.6	0.50	28.8	0.0	0.5	0.0	0.0	0.0	1.00	0.0	28.8	0.5
7	March	1st	0.0	0.5	1.00	67.0	0.50	33.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	33.5	0.5
8	March	2nd	0.0	0.5	1.00	69.0	0.50	34.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	34.5	0.5
9	March	3rd	0.0	0.5	1.00	71.5	0.50	35.7	0.0	0.5	0.0	0.0	0.0	1.00	0.0	35.7	0.5
10	April	1st	0.0	0.5	1.00	71.0	0.50	35.5	0.0	0.5	0.0	0.0	0.0	1.00	0.0	35.5	0.5
11	April	2nd	0.4	0.9	1.00	71.0	0.50	35.5	0.0	0.9	0.0	0.0	0.0	1.00	0.0	35.5	0.9
12	April	3rd	5.0	5.9	1.00	71.0	0.50	35.5	5.9	0.0	0.0	0.0	5.9	0.83	0.08	29.6	5.9
13	May	1st	20.8	20.8	1.00	70.0	0.50	35.0	20.8	0.0	0.0	0.0	20.8	0.41	0.30	14.2	20.8
14	May	2nd	44.0	44.0	1.00	69.0	0.50	34.5	34.5	9.5	0.0	0.0	34.5	0.0	0.50	0.0	44.0
15	May	3rd	47.8	50.0	1.00	72.6	0.50	36.3	36.3	13.7	7.3	7.3	36.3	0.0	0.50	0.0	50.0
16	June	1st	25.7	39.4	0.79	64.0	0.55	35.2	35.2	4.2	0.0	7.3	45.8	0.0	0.55	0.0	50.0
17	June	2nd	69.9	50.0	1.00	60.0	0.65	39.0	39.0	11.0	23.8	31.1	39.0	0.0	0.65	0.0	50.0
18	June	3rd	24.0	35.0	0.70	58.0	0.80	46.4	35.0	0.0	0.0	31.1	50.0	0.25	0.60	11.4	50.0
19	July	1st	38.5	38.5	0.77	56.0	1.00	56.0	38.5	0.0	0.0	31.1	50.0	0.31	0.69	17.5	50.0
20	July	2nd	50.6	50.0	1.00	55.0	1.10	60.5	50.0	0.0	0.6	31.7	50.0	0.17	0.91	10.5	50.0
21	July	3rd	23.1	23.1	0.46	56.1	1.10	61.7	23.1	0.0	0.0	31.7	50.0	0.63	0.41	38.6	50.0
22	August	1st	158.0	50.0	1.00	47.0	1.10	51.7	50.0	0.0	108.0	139.7	50.0	0.03	1.06	1.7	50.0
23	August	2nd	176.1	50.0	1.00	45.0	1.10	49.5	49.5	0.5	261.1	265.8	49.5	0.0	1.10	0.0	50.0
24	August	3rd	88.9	50.0	1.00	49.5	1.10	54.4	50.0	0.0	39.4	305.2	50.0	0.08	1.01	4.4	50.0
25	September	1st	36.9	36.9	0.74	46.0	1.10	50.6	36.9	0.0	0.0	305.2	50.0	0.27	0.80	13.7	50.0
26	September	2nd	30.4	30.4	0.61	48.0	1.10	52.8	30.4	0.0	0.0	305.2	50.0	0.42	0.63	22.4	50.0
27	September	3rd	20.8	20.8	0.42	50.0	1.10	55.0	20.8	0.0	0.0	305.2	50.0	0.62	0.42	34.2	50.0
28	October	1st	10.3	10.3	0.21	56.0	0.90	50.4	10.3	0.0	0.0	305.2	50.0	0.80	0.18	40.1	50.0
29	October	2nd	0.0	0.0	0.0	59.0	0.70	41.3	0.0	0.0	0.0	305.2	50.0	1.00	0.0	41.3	50.0
30	October	3rd	2.2	2.2	0.04	60.5	0.50	30.2	2.2	0.0	0.0	305.2	50.0	0.93	0.04	28.0	50.0
31	November	1st	0.0	0.0	0.0	56.0	0.50	28.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	28.0	50.0
32	November	2nd	0.0	0.0	0.0	57.0	0.50	28.5	0.0	0.0	0.0	305.2	50.0	1.00	0.0	28.5	50.0
33	November	3rd	0.0	0.0	0.0	54.0	0.50	27.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	27.0	50.0
34	December	1st	0.0	0.0	0.0	52.0	0.50	26.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	26.0	50.0
35	December	2nd	0.0	0.0	0.0	52.0	0.50	26.0	0.0	0.0	0.0	305.2	50.0	1.00	0.0	26.0	50.0
36	December	3rs	0.0	0.0	0.0	55.0	0.50	27.5	0.0	0.0	0.0	305.2	50.0	1.00	0.0	27.5	50.0
	Total		873.6			2116.9		1388.2	568.4							819.8	
	Average													0.66	0.29		

Figure 2. Example of a simulation of a 10-day water balance for a photosensitive sorghum or millet cultivar with almost fixed flowering date. The duration of the vegetative phase (in this case 90 days) varies with the sowing date; the duration and occurrence of the flowering (50 days) and fruiting (30 days) phases remain almost constant. The AET/PETand AET/MET values can be estimated from this simulation'

of available water capacity (AWC) of 50,100, and 150 mm.

In the extreme case of a crop sown in M1, the sequence of the crop coefficient K related to the water balance is as follows; the brackets serve to mark off the phases:

(0.50-0.50-0.55-0.65-0.80-1.00-1.10
-1.10-1.10-1.10)
(1.10-1.10-1.10-1.10-1.10) (0.90-0.70-0.50)

In the other extreme case of a crop sown in Jy1, the sequence of K is as follows:

(0.50-0.50-0.55-0.65)
(0.80-1.00-1.10-1.10-1.10) (0.90-0.70-0.50).

Figure 2 shows an annual water balance established on these principles, with an AWC of 50 mm for the Ouagadougou station near Kamboinse.

As millet or sorghum yields were not available, the coefficients obtained in an experiment conducted under irrigation by Jensen and Sletten (1965) are used here to calculate the k_1, k_2, and k_3 coefficients of equation 8, which are 0.5, 1.5, and 0.5, respectively. The next step is to calculate, for each of the 50 annual water balances based on three AWC values (50, 100, and 150 mm), the expression:

$$Y/100 = \delta_1 \left(\frac{\bar{AET}}{\bar{MET}}\right)_1^{0.5} \cdot \left(\frac{\bar{AET}}{\bar{MET}}\right)_2^{1.5} \cdot \left(\frac{\bar{AET}}{\bar{MET}}\right)_3^{0.5} \qquad (9)$$

The mean values, calculated over 50 years, of each of the three multiplicative terms of equation 9 and the mean values of Y/100 for each of the three AWC values are given in Figure 3. The frequency distributions of AWC/100 for each of the three AWC values are compared in Table 1.

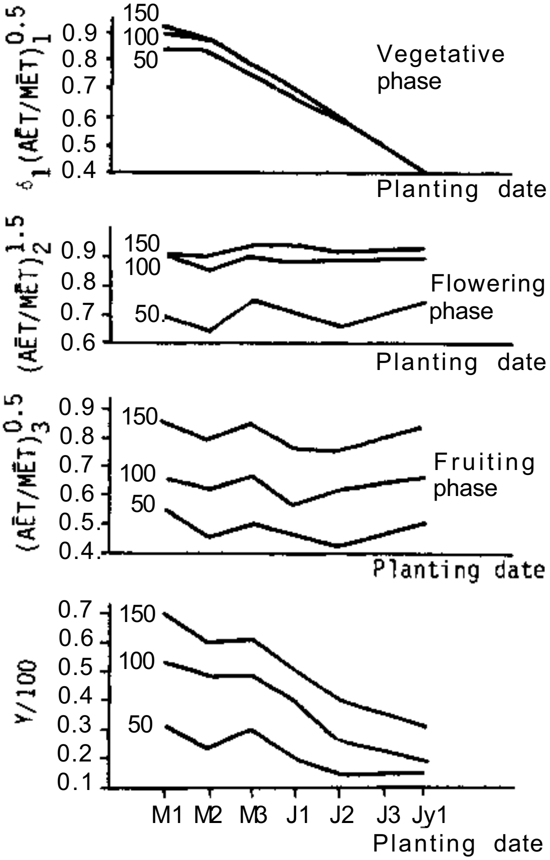

Figure 3. Variations in relative terms of yield corresponding to the vegetative, flowering, and fruiting phases according to AWC values (50, 100, 150 mm) and the sowing date. The combined variations in these terms bring about variations in relative yield (Y/100). δ_1 varies with the sowing date, from 0.4 (Jy1) to 1.0 (M1). Yield decreases with the sowing date (i.e. with δ 1) and increases with AWC (50,100,150 mm) for the flowering and fruiting phases.

Table 1. Frequency distributions of AWC/100 for three values of AWC.

Y/100	AWC: 50 mm	AWC: 100 mm	AWC: 150 mm
0.01-0.10	IIIIIIIII	II	
0.11-0.20	IIIIIIIIIIIIII	IIIIII	IIII
0.21-0.30	IIIIIIIIIIIIII	IIIIIIII	IIIII
0.31-0.40	IIIIII	IIIIIII	IIIIIIIIII
0.41-0.50	IIIII	IIIIIIIIIIIII	IIIIIIIIIII
0.51 -0.60	II	IIIIII	IIIIIIIIIIII
0.61-070		IIII	IIII
0.71-0.80		IIII	IIII
Mean	0.23	0.40	0.45

In Figure 4, the water deficits during the flowering and fruiting phases are seen through a frequency representation in time. These deficits, represented by the dotted areas in the figure, are bounded:

1. On the left, by continuous curves, obtained by applying the principle of the frequency period of vegetation (see Introduction) to the water balances. The curves at the bottom of the figure, related to the flowering phase, show the

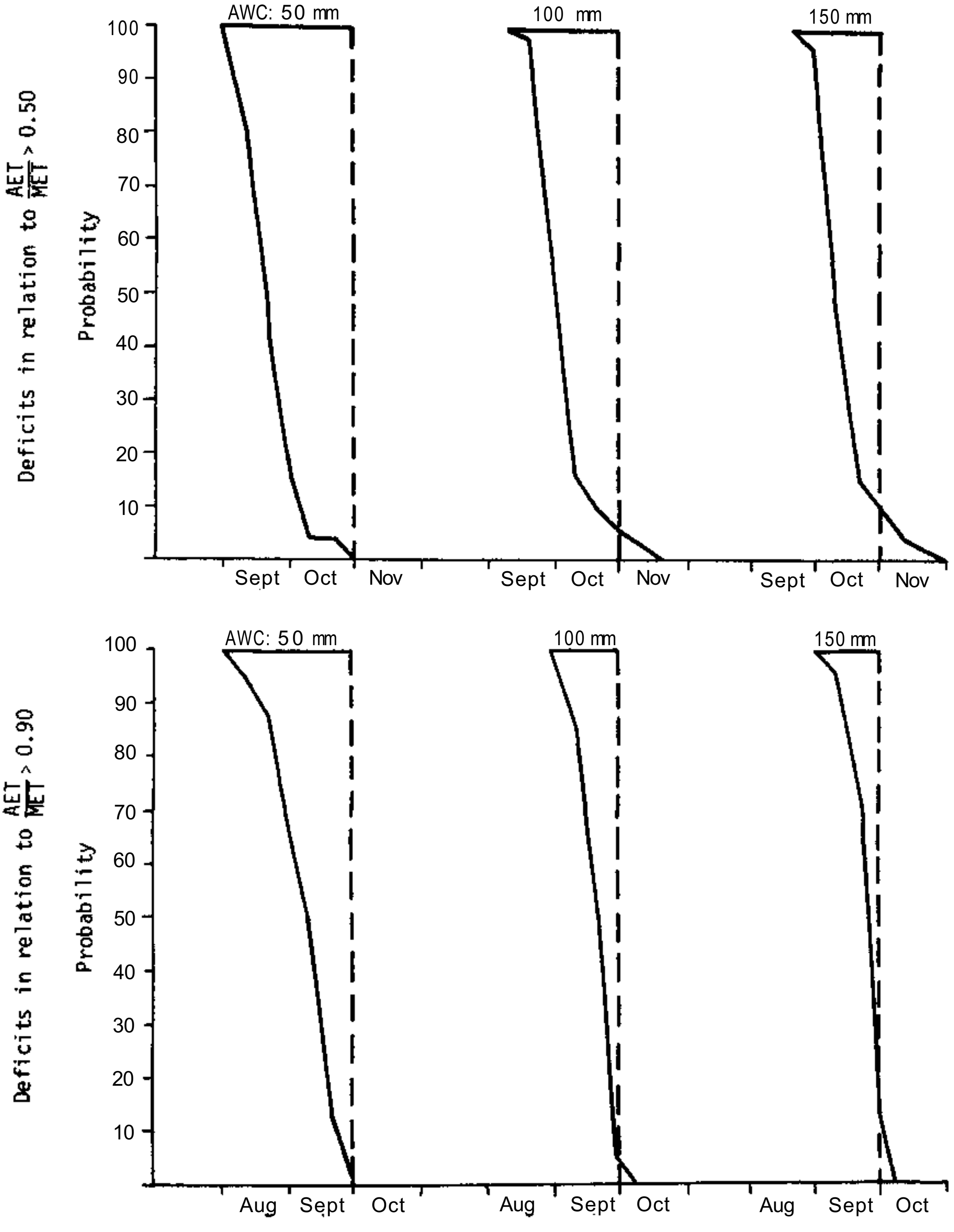

Figure 4. Representation in frequency and in time of water deficits according to AWC values of 50, 100, 150 mm: above, deficit in relation to AET/MET > 0.50 in the fruiting phase; below, deficit in relation to AET/MET > 0.90 in the flowering phase. The duration of the deficit is expressed in terms of probability, which decreases with the AWC.

observed probabilities of exceeding 0.90 AET/PET; the curves at the top related to the fruiting phase show the observed probabilities of exceeding 0.50 AET/PET; these AET/PET levels have been somewhat arbitrarily fixed to represent the minimum value required for adequate yields. However, it is possible to choose any other threshold values in the water balances.

2. On the right, by broken curves, corresponding to the 1.00 probability of exceeding the 0.90 and 0.50 threshold values on the last date of the flowering and fruiting phases.

Conclusion

It is quite clear that for a late-heading cultivar that avoids the impact of rainfall on the earhead, the water deficit during the flowering and fruiting phases would be much higher. However, this risk is reduced as the water-holding capacity of the soil increases.

Another alternative is to identify an early-heading cultivar with pest resistance for soils with a low water-holding capacity.

Remarks

The rate of increase of Y/100 (see the frequency distribution) is higher for 50 to 100 mm than for 100 to 150 mm for a cultivar that heads during the second 10-day period in September.

The water available during the vegetative phase always appears to be adequate, irrespective of AWC (Fig. 3) and the simulated planting date (first 10-day period with total rainfall exceeding PET/2 or an average of 35 mm at Ouagadougou). If this does not occur in reality, it is because water is lost through runoff and should be checked. A water balance calculated on the basis of 5-day intervals would probably reveal water deficits more frequently than one calculated on the basis of 10-day intervals. Excess rain during the vegetative phase may depress yields.

An early planting increases yields (Fig. 3), as it extends the duration of the vegetative phase. However, due to the low rainfall, there is no further increase if the crop is sown before the 10-day period M1, which marks the limit of the optimum duration d_o (ten 10-day periods for the vegetative phase).

Photoinsensitive and Relatively Photosensitive Cultivars

Expressed in terms of the "sum of degree-days," the duration of the completely photoinsensitive cultivars appears to be constant. Evaluated in terms of the "number of days," the duration remains constant if there is little variation in the night temperature, as during the rainy season.

As photoinsensitive cultivars are of short duration (70-80 days or even less), they do not have the same yield potential as the photosensitive cultivars whose vegetative phase can be extended. Photoinsensitive millets are found in northern Upper Volta where the growing season is very short, but they are also grown in the south in the region of Leo, for example, where they are used as a stop-gap crop.

Photoinsensitive cultivars are flexible, since their flowering date is not fixed, unlike completely photosensitive cultivars. This makes it easier to synchronize their flowering and fruiting phases with optimum moisture availability. They can also be sown at the beginning of the rainy season as a stop-gap crop. Their duration should be extended to 100 days, for example, to increase their yield potential.

The relatively (not completely) photosensitive cultivars are also useful, since their duration increases as the crop is sown earlier (but not too early). Like photoinsensitive cultivars, they have fixed flowering and fruiting dates only if their planting date remains fixed. When there is little variation in the planting date, the relatively photosensitive cultivars behave like the photoinsensitive cultivars.

Fitting of Photoinsensitive or Relatively Photosensitive Cultivars

The fitting of the flowering and fruiting phases is facilitated by using a model of the "frequency climatic period of vegetation." Such models were constructed for Ougadougou by simulating water balances (Fig. 2) based on an AWC of 50 (Fig. 5) and 100 mm (Fig. 6). The outer line represents the "semi-humid" subperiod determined by the probability that AET/PET is equal to or higher than 0.50. The inner line defines the "humid" subperiod determined by the probability that AET/PET is equal to or higher than 0.90.

If a photoinsensitive cultivar of 100 days, under

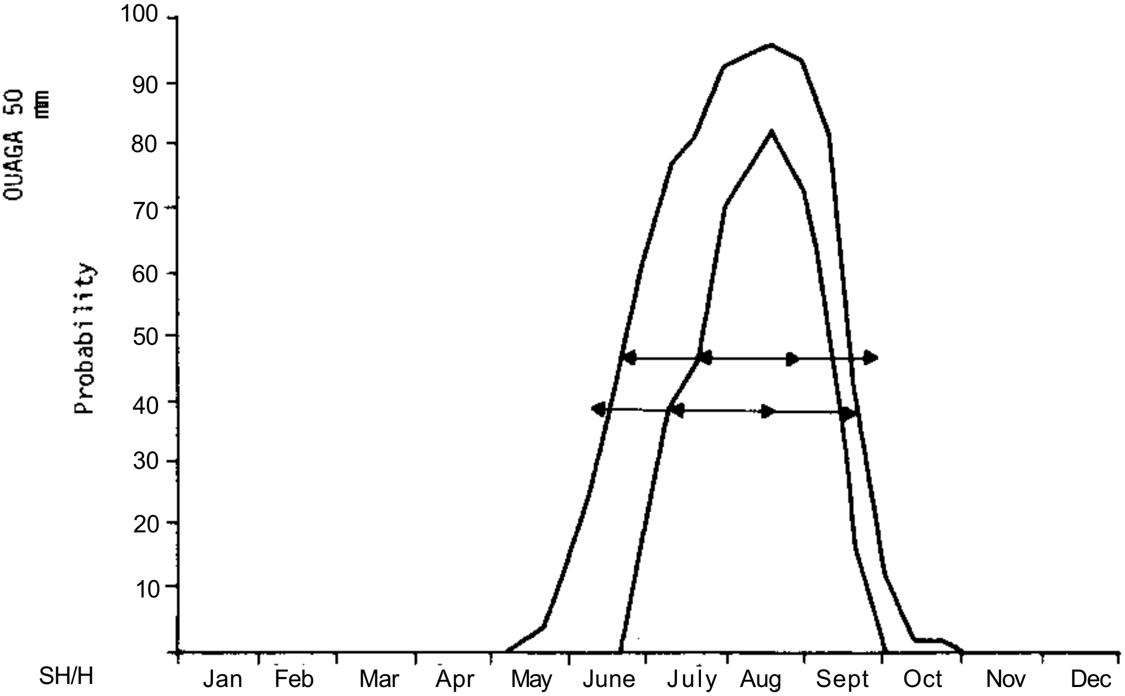

Figure 5. Fitting the flowering and fruiting phases of a 100-day sorghum or millet variety within the frequency "humid" (inner line) and "semi-humid" (outer line) subperiods at Ouagadougou. The humid subperiod is determined by the probability AET/MET > 0.90. The "semi-humid" subperiod is determined by the probability AET/MET >0.50. AWC is 50 mm: the favorable planting period is only 20 days (J2+J3) and the probabilities of fitting the flowering and fruiting phases do not exceed 0.38 and 0.42, respectively.

the temperature conditions at Ouagadougou, or a relatively photosensitive cultivar, also of 100 days, are sown on the same date, the duration and crop coefficients would be:

(0.50-0.55-0.60) (0.80-1.00-1.10-1.10) (0.90-0.70-0.50).

The flowering phase of 40 days is the most critical period for yield in relation to water availability. It should be fitted to the highest probability within the humid subperiod (Fig. 5 inner line). This probability is:

0.70 (on 1 Aug) x 0.54 (on 10 Sept) = 0.38

For this apparently optimum adjustment of the flowering phase, the cultivar should be sown in the first 10-day period of July (Jy 1). But it is not possible to plant a cultivar during the same 10-day period each year. This interval shou'd be made more flexible and increased to 20 to 30 days. If the flowering phase is moved back one, two, or three 10-day periods, corresponding to sowings in J3, J2, and J1, the probabilities of fitting the flowering phase would be 0.34, 0.31, and 0.12, respectively. Since the last probability is very low, the planting period would cover three 10-day intervals—J2+J3+Jy1. As the flowering phase would then coincide with maximum rainfall, the cultivars should also be resistant to pests and diseases.

The conditions for fitting the fruiting phase (30 days) also need to be examined in relation to probabilities associated with the "semi-humid" subperiod (the line on the right side of the outer curve, Fig. 5). For the fruiting phase, the probability of success is very low (on 10 Oct) for a sowing in Jy1; it is 0.12 (on 30 Sept) for a sowing in J3; and 0.42 (on 20 Sept) for a sowing in J2. Lastly, the appropriate interval for sowing is reduced to two 10-day periods: J2+J3.

This interval is essential for obtaining stable and high yields. If the planting date is simulated as in the case of a completely photosensitive cultivar (see

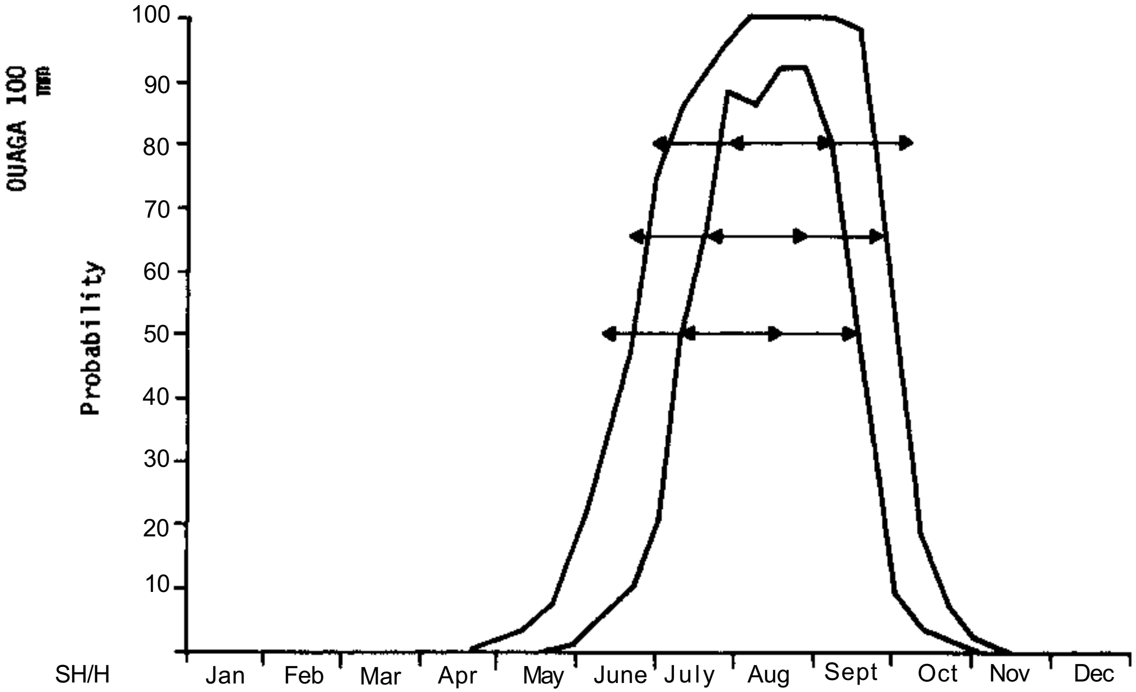

Figure 6. Same as Figure 5, but AWC = 100 mm: the planting period extends over 30 days(J2+J3+Jy1) and the probabilities of fitting the flowering and fruiting phases are 0.70 and 0.98, respectively.

earlier section), then the frequency distribution of Y/100 can be compared, using the formula

$$Y/100 = (A\bar{E}T/M\bar{E}T)_1^{0.5} \cdot (A\bar{E}T/P\bar{E}T)_2^{1.5} \cdot (A\bar{E}T/P\bar{E}T)_3^{0.5} \qquad (10)$$

applied to the simulated water balances-

- for planting during the J2 10-day period;
- for any plantings from M1 to Jy1.

These frequency distributions are given in Table 2.

If the same cultivars are grown on a soil with a moisture-retention capacity of not 50 mm but 100 mm, it is evident from Figure 6 that the interval suitable for planting increases from 20 to 30 days (J2+J3+Jy1) also considerably increasing the probabilities for fitting the flowering and fruiting phases.

Table 2. Frequency distribution of relative yield for plantings in different 10-day periods.

Y/100	Any planting (M1-Jy2)	Planting in J2
0.21 -0.30	II	
0.31-0.40	III	
0.41-0.50	IIII	
0.51 -0.60	IIIII	
0.61-0.70	IIIIIIIIIII	IIIIII
0.71-0.80	IIIIIII	III
0.81 -0.90	IIIIIIIIIII	IIIIIIIIIIIIIIIIIIIII
0.91 -1.00	IIIIIII	IIIIIIIIIIIIIIIIIIII

Conclusion

A photoinsensitive or relatively photosensitive cultivar has greater flexibility for fitting than a completely photosensitive cultivar, particularly if it is grown on a soil with adequate water-holding capacity. However, this character must be combined with good pest resistance, since the flowering and fruiting phases are not fixed in time and may occur during the heavy-rainfall period.

Acknowledgment

I am grateful to Messrs. Clement, Perret, et al., who collected the millet samples from Upper Volta, and

to the ICRISAT Upper Volta program for the observations on flowering of these samples.

Annexure

Length of the Vegetative Phase and Number of Internodes

In a completely photoinsensitive plant, the duration d of the vegetative phase depends solely on temperature, under light saturation conditions, according to the equation:

$$d(\bar{T}_i - T_o) \simeq \Sigma(T_i - T_o) \simeq K \tag{A1}$$

where T_i is the mean temperature (at night, for a short-day plant) on the day i; To, the base temperature and K, a constant for the variety.

in a completely photosensitive plant, the duration d is determined by both the photoperiod and temperature, according to the equation:

$$d(\bar{T}_i - T_o) \simeq \Sigma(T_i - T_o) \simeq k_o + \frac{\pi m}{2a} \left[1 + tg^2\left(\frac{\pi}{2} \; \frac{N_o/H_o}{\bar{N}_i/\bar{H}_i}\right)\right] \tag{A2}$$

This result, for a short-day sorghum or millet plant, is based on the following principles. The plant is regulated by a circadian rhythm consisting of two periods of 24 h, one of daylight sensitivity of duration H_o, the other of darkness sensitivity of duration No ($H_o + N_o = 24$). The oscillations of the endogenous system No /Ho form the basis to which the exogenous oscillations N_i / H_i of actual day and night lengths are compared by means of the phytochrome. This information on the "imposed" fluctuation N_i / H_i (in relation to the "own" fluctuation No /Ho) can be effectively introduced in the differential equation of a forced harmonic oscillator set off by friction of day/night alternance:

$$u'' + cotg^2\left(\frac{\pi}{2} \; \frac{N_o/H_o}{N_i/H_i}\right)u' + \left(\frac{\pi}{N_o/H_o}\right)^2 u = a(T_i - T_o)\frac{1}{N_i/H_i} \sin\left(\frac{\pi}{N_i/H_i} h\right) \tag{A3}$$

The integration, in relation to h (h = t / [24-t], 0 ⩽ t ⩽ 24) of heat excitation related to a (T. - To)—excitation with a minimum threshold m for floral induction—leads to equation 2, in which a and m are parameters.

The number n of nodes or leaf internodes at floral initiation depends on the photoperiod and temperature according to the equations:

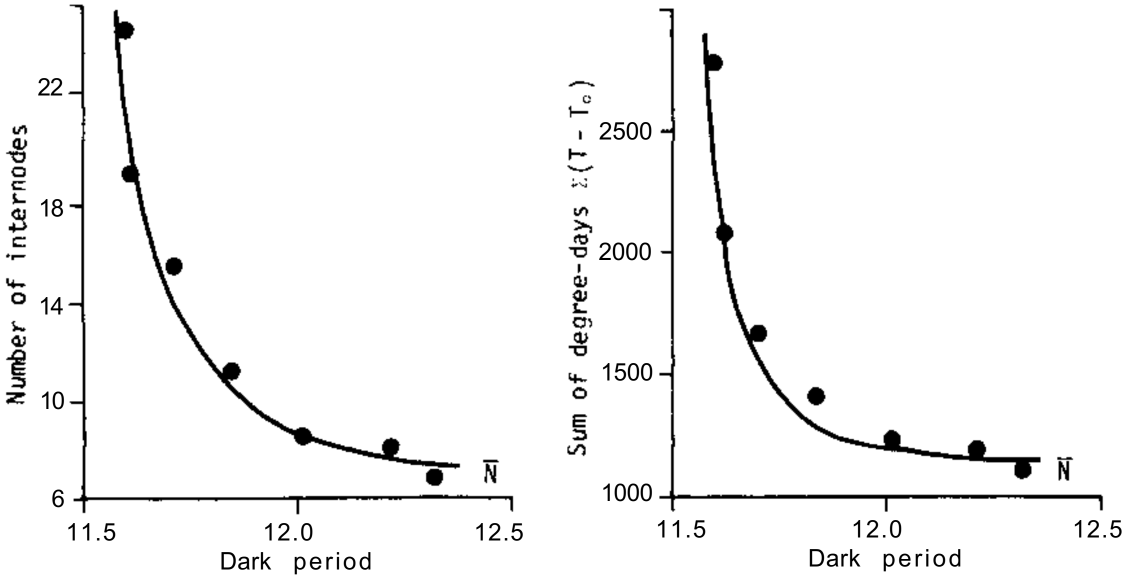

Figure 7. Data on a sorghum variety grown in Chad in farmers' fields. Right: fitting of equation A2 in Annexure 1 to the sum of degree-days Σ (T_i-T_o) according to the average dark period $\bar{N}_i$; left: fitting of equation 4 to the number of stem nodes according to the average dark period $\bar{N}_i$.

$$n = n_o + \alpha m tg^2\left(\frac{\pi}{2}\ \frac{N_o/H_o}{\bar{N}_i/\bar{H}_i}\right) \quad (A4)$$

$$n = n_o + \alpha\frac{2a}{\pi}\ \sin^2\left(\frac{\pi}{2}\ \frac{N_o/H_o}{\bar{N}_i/\tilde{H}_i}\right)\Sigma\ (T_i - T_o) \quad (A5)$$

where ko represents the sum of temperatures and n_o the total number of nodes in the "juvenile" phase; $\pi m/2a$ can be reduced to a single parameter, k; thus ko + k = K, k being the sum of temperatures between two nodes.

These equations have been confirmed for sorghum cultivars, as can be seen from the statistical fitting of equations 2 and 4 (Fig. 7).

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Some Agroclimatic Aspects of the Sorghum Crop in India

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Abstract

This paper deals with the general climatic features of the sorghum belt in India, crop-weather relationships, and analysis of evapotranspiration data.

The climate, mean rainfall, temperature, humidity, sunshine, and their variability are considered during different phytophases of the sorghum crop; the minimum assured rainfall and moisture availability index suggest that sowing should be shifted to an earlier date. Three methods have been used for statistical analysis of crop-weather data: (1) *Fisher's response curve technique establishes the influence of meteorological parameters on yield;* (2) *the selected period method identifies critical periods for different parameters;* (3) *curvilinear analysis shows the optimum values of different parameters for maximum yields.*

The analysis of evapotranspiration data identifies critical periods for peak water consumption and shows that hybrid sorghum does not exhibit any physiological drying up during maturity. It is concluded that sowing sorghum 2 months earlier in a particular area would help avoid the stress period and thus give better and more stable yields.

Résumé

Quelques aspects agroclimatiques de la culture du sorgho en Inde : Cette communication porte sur divers aspects climatiques de la région productrice de sorgho en Inde, les relations entre les cultures et le climat et l'analyse des données sur l'évapotranspiration.

Le climat, la pluviométrie moyenne, la température, l'humidité, l'ensoleillement et la variabilité de ces facteurs sont étudiés pour différents stades d'une culture de sorgho. La disponibilité minimale de précipitations stables et l'indice d'humidité utilisable indiquent qu'il faudrait avancer le semis. Les méthodes utilisées pour l'analyse statistique des données sur les cultures et le climat sont : (1) la technique des courbes de réponse de Fisher pour déterminer l'influence des paramètres météorologiques sur le rendement; (2) l'étude de différentes périodes pour définir les périodes critiques pour différents paramètres; (3) l'analyse curvilinéaire pour établir les valeurs optimales de différents paramètres pour obtenir un rendement maximum.

L'analyse des données sur l'évapotranspiration a permis de déterminer les périodes critiques de consommation maximale d'eau. On a alors constaté que les hybrides de sorgho ne manifestent aucune dessication physiologique à la maturité. Dans certaines régions, un semis du sorgho avancé de deux mois permettrait d'éviter la période de stress hydrique et d'obtenir de meilleurs rendements.

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Weather, climate, and soil primarily determine the crop potential of an area; while the climate determines the crop, variety, and normal growing season, the behavior of the weather during the growing season in a particular year will determine the various cultural operations needed to benefit from the good weather and to minimize the loss from adverse weather.

In the semi-arid tropics of the dry-farming tract, crop production is normally low and unstable. To stabilize food production at a certain level, scientific agricultural planning, in terms of basic climatology, is called for. Agroclimatic studies not only help find the optimum climate for a particular crop but are also important to identifying the ecological zones where this crop could be successfully introduced. Such studies also reveal chronic climatic hazards such as drought, so that suitable drought-resistant varieties can be evolved by the plant breeders.

In this paper we examine some of the agroclimatic aspects of the sorghum-growing areas in India. The sorghum belt in India is mainly confined to the Deccan plateau (Fig. 1), where the crop is grown during the *kharif* (rainy) and *rabi* (postrainy) seasons. Under the auspices of the All India Coordinated Crop Weather Scheme, the India Meteorological Department has collected data on sorghum growth and yield for the last 20 to 25 years from seven experimental farms where, simultaneously, meteorological data have also been recorded from sowing to harvest. Additionally, lysimetric data on daily evapotranspiration loss from hybrid sorghum during the rainy season have been recorded during the last 4 years at three of these farms and have also been used here.

Section 1 of this paper examines several climatic elements in the sorghum belt and their variation during the different crop phytophases. Mean yield and year-to-year variability are also considered.

Section 2 deals with the statistical analysis of crop-weather data by three methods: Fisher's response curve technique; the selected period method; and curvilinear analysis. The first is used to examine the influence of distribution of each meteorological variable on sorghum yield; the second, to identify some critical periods and to work out regression of yield with the meteorological elements at critical periods; the third, to obtain optimum values of meteorological parameters.

Section 3 analyzes experimental data on evapotranspiration from three stations, recorded from sowing to harvest. An indication is obtained of the total water requirement of hybrid sorghum. The weekly distribution of the ratio of evapotranspiration to evaporation identifies the critical period of peak water consumption. From this analysis and a probability analysis of weekly rainfall, it appears that sowing a few weeks earlier in a particular area might give better yields.

Climatology of the Sorghum Belt in India

The data used in this study were collected from seven crop-weather observatories in the Deccan Plateau—four kharif and three rabi—in the states of Maharashtra and Karnataka (Table 1). Average yields of different cultivars are also shown in Table 1. The performance of a cultivar varies from station to station; however, the highest kharif yield is in Dharwar—almost three times that in Jalgaon and Parbhani and one and a half times that in Akola. The highest rabi yield is in Raichur—almost double that in Hagari and Sholapur—and although total rainfall is highest at Sholapur, yields are the lowest. The rainfall figures indicate that the total rainfall during the life cycle of the crop does not appear to have any correlation with the final yield. However, the varieties under study are old varieties and the yields are generally lower than those of the recent hybrid varieties.

Important Phytophases

For convenient study, the life cycle of the crop has been divided into three phases: (1) from sowing to commencement of elongation; (2) elongation and ear emergence; and (3) flowering to harvest. Table 2 gives the standard weeks of sowing, elongation, flowering, and harvest; total duration is 24 weeks for the kharif crop and 20 weeks for the rabi crop.

Climatic Parameters

Climatic parameters for each crop phase at the kharif and rabi stations are shown in Table 3. The week-by-week distribution of these climatic variables (total for rainfall and means for other elements) is also shown for two typical stations (Figs. 2 and 3) by a set of histograms, which also show the standard deviation between years of each week, to indicate the variability.

Kharif Season

Rainfall. The average total rainfall during phase 1 is about 200 to 280 mm; during phase 2,260 to

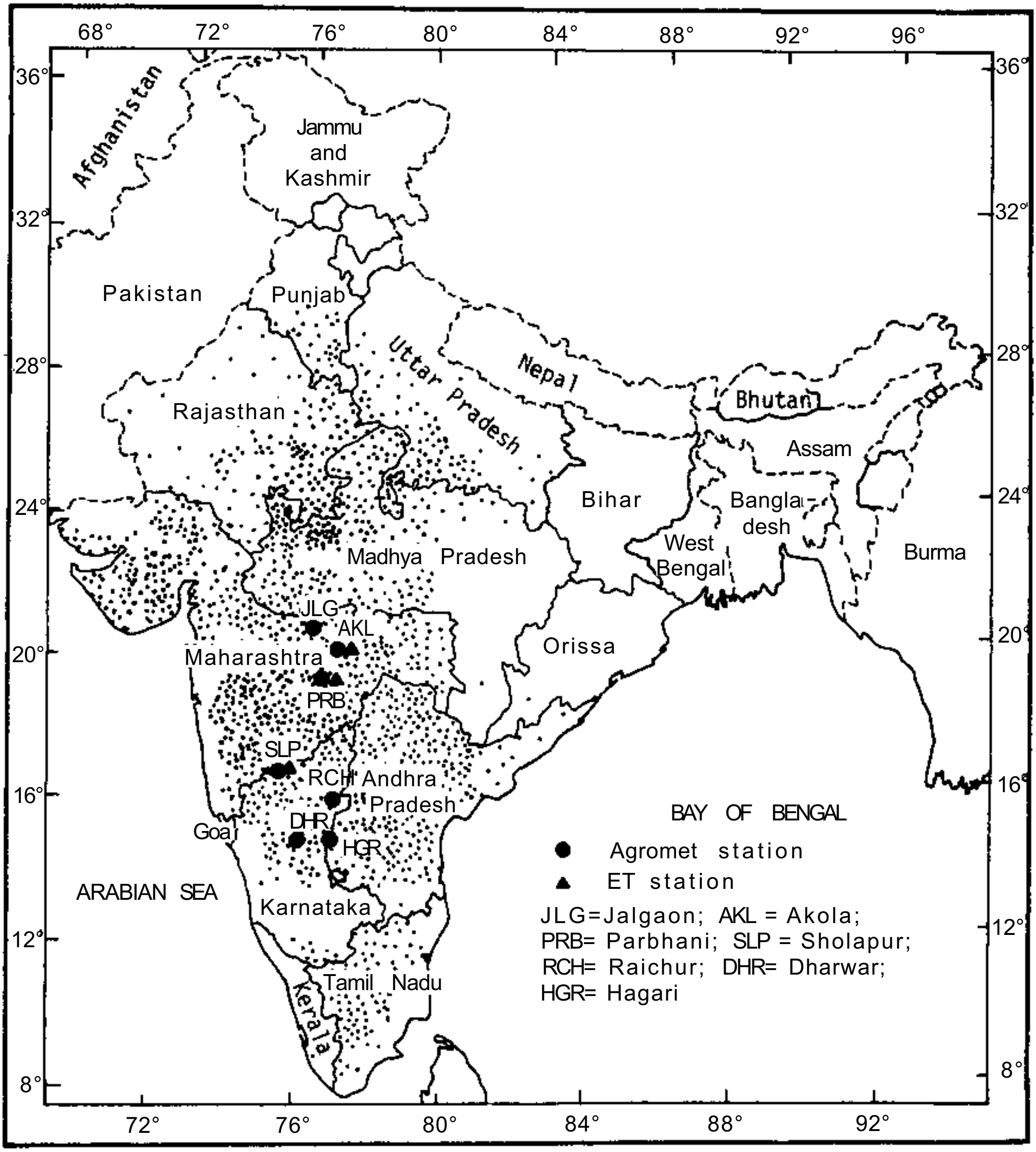


Figure 1. Sorghum-growing regions of India.

420 mm; and during phase 3, only 20 to 80 mm. The variability is appreciable throughout, and there are also wide differences between one station and another.

As there is marked fluctuation from year to year also, it would be desirable to do any planning on the basis *of* dependable, rather than average, precipitation.

Temperature. While rainfall fluctuates widely, temperatures, both maximum and minimum, show little variability either between years or during each

Table 1. Average sorghum yields and total rainfall during crop life cycle at seven stations in Karnataka and Maharashtra. India.

	Kharif (rainy-season) crop							
	Jalgaon		Akola		Parbhani		Dharwar	
	Var Aispuri	Var Godgarya	Var Saona	Var Dukri	Var PJ-1K	Var PJ-4K	Var Pulnar white	Var Nandyal
Average yield (kg/ha)	847	569	1295	1271	587	559	1938	1995
SD between years	417	276	535	556	541	589	643	753
Total rainfall during crop cycle (mm)	510		510		720		370	
SD between years	150		200		220		150	

	Rabi (postrainy-season) crop					
	Raichur		Hagari		Sholapur	
	Var M-35-1	Var PJ-UK	Var M-47-B	Var H1	Var M-35-1	Var ND-15
Average yield (kg/ha)	1010	785	605	432	414	314
SD between years	416	410	379	329	142	130
Total rainfall during crop cycle (mm)	390		330		420	
SD between years	160		140		160	

Table 2. Important phytophases[1] of the sorghum crop at seven stations in Maharashtra and Karnataka, India.

	Kharif crop			
	Jalgaon	Parbhani	Akola	Dharwar
	Standard week[2]			
Sowing	26	27	29	29
Elongation	32-40	33-41	34-42	34-41
Flowering	41-43	40-42	42-43	42-44
Harvest	50	51	1	50

	Rabi crop		
	Raichur	Sholapur	Hagari
	Standard week		
Sowing	40	40	40
Elongation	47-1	47-52	47-4
Flowering	51-2	51-1	52-2
Harvest	8	7	8

1. Phase 1 = sowing to commencement of elongation; phase 2 = elongation and earhead emergence; phase 3 - flowering to harvest.
2. Weeks are numbered consecutively through the year, standard week 1 being the first week of January.

phase. The average weekly maximum during phase 1 is 27 to 33°C; during phase 2, 29 to 33°C; and during phase 3,30 to 33°C. The general pattern of distribution week by week during the life cycle of the crop is more or less similar. Dharwar, a station at a higher altitude (678 m), is somewhat cooler, the day temperature rarely going above 30°C.

The average weekly minimum temperature during phase 1 is 21 to 24°C; during phase 2, 20 to 21 °C; and during phase 3,11 to 14°C. The general pattern of distribution of night temperature week by week remains more or less the same (22-23°C) up to week 40 (beginning of October, end of elongation phase); thereafter, as winter approaches, the temperature falls, reaching a minimum of 12 to 13°C at harvest time.

The variability between years is negligible and is within half a degree up to week 37 (vegetative phase); thereafter, it is of the order of 1 to 3°C.

Sunshine. The average daily sunshine is 2.5 to 4.4 h during phase 1; 5.7 to 7 h during phase 2; and 8.6 to 9.5 h during phase 3. Normally, sunshine increases from the beginning of the season (4-5 h) until week 41 (beginning of October), when it reaches a value of 9 to 10 h, and then remains practically the same until harvest. At Dharwar (678

Table 3. Meteorological parameters during different phytophases of the sorghum crop at seven stations in Maharashtra and Karnataka, India.

	Kharif crop				*Rabi* crop		
Parameter	Jalgaon	Dharwar	Parbhani	Akola	Raichur	Sholapur	Hagari
Phytophase 1							
Average rainfall (mm)	197	276	283	222	377	416	321
SD	132	107	119	68	159	156	145
SE	28	24	27	15	38	33	35
Lowest temp (°C)	23.4	20.3	22.0	22.7	17.1	16.0	17.2
Average minimum temp (°C)	24.2	20.6	22.6	23.3	20.5	19.1	20.5
Highest temp (°C)	36.1	28.5	34.0	33.2	33.4	33.5	33.9
Average maximum temp (°C)	33.1	26.8	31.9	31.2	31.5	32.1	31.7
Average sunshine (h)	4.3	2.5	4.4	3.2	8.1	7.9	7.0
Relative humidity (%)	62	78	63	67	45	39	45
Phytophase 2							
Average rainfall (mm)	262	273	423	257	8.0	0	10
SD	73	82	200	202	15	0	18
SE	15	18	46	44	4	0	4
Lowest temp (°C)	14.5	17.2	18.3	14.8	14.5	11.3	11.3
Average minimum temp (°C)	21.5	19.6	21.1	20.8	16.7	14.4	14.6
Highest temp (°C)	35.9	31.0	33.9	34.4	30.8	31.0	31.7
Average maximum temp (°C)	32.9	28.7	31.6	32.0	29.5	30.2	30.3
Average sunshine (h)	6.9	57	6.6	6.7	9.1	9.4	9.0
Relative humidity (%)	50	63	55	53	41	32	31
Phytophase 3							
Average rainfall (mm)	83	26	17	29	0	0	0
SD	95	29	21	52	0	0	0
SE	20	6	5	11	0	0	0
Lowest temp (°C)	10.6	11.0	8.9	6.8	15.6	12.7	13.9
Average minimum temp (°C)	13.9	14.3	13.5	11.1	17.2	15.0	15.9
Highest temp (°C)	33.5	30.1	32.6	32.9	34.4	33.9	34.7
Average maximum temp (°C)	31.7	29.1	30.1	30.5	32.1	32.1	33.3
Average sunshine (h)	9.5	8.6	9.5	9.5	10.1	10.1	10.0
Relative humidity (%)	27	43	34	31	34	24	24

m), sunshine periods average 1 to 2 h less than at the other stations. The standard deviation between years is 1 to 2 h/day.

Relative humidity. The afternoon relative humidity during phase 1 is about 65 to 70%; during phase 2, 50 to 60%; during phase 3, 30 to 40%; Dharwar averages about 10% higher at all times. Standard deviation between years is less than 10%.

Rabi Season

Rainfall. The average total rainfall during phase 1 is 320 to 420 mm; during phases 2 and 3, rainfall is practically nil. Year-to-year variability is very high, so that agricultural planning on the basis of dependable precipitation is needed. At all three rabi stations, the sorghum crop faces water stress even in phase 2—elongation and ear emergence—but the average weekly rainfall distribution during weeks 33 to 40 suggests that this stress could be avoided by sowing the rabi crop earlier—say, the end of August or early September, instead of early October.

Temperature. The average maximum temperature during phase 1 is 32°C; during phase 2, it is 30°C, but goes up again to 32°C during phase 3. The general pattern of week-by-week distribution is similar at all the stations. The standard deviation between years is 1 to 2°C.

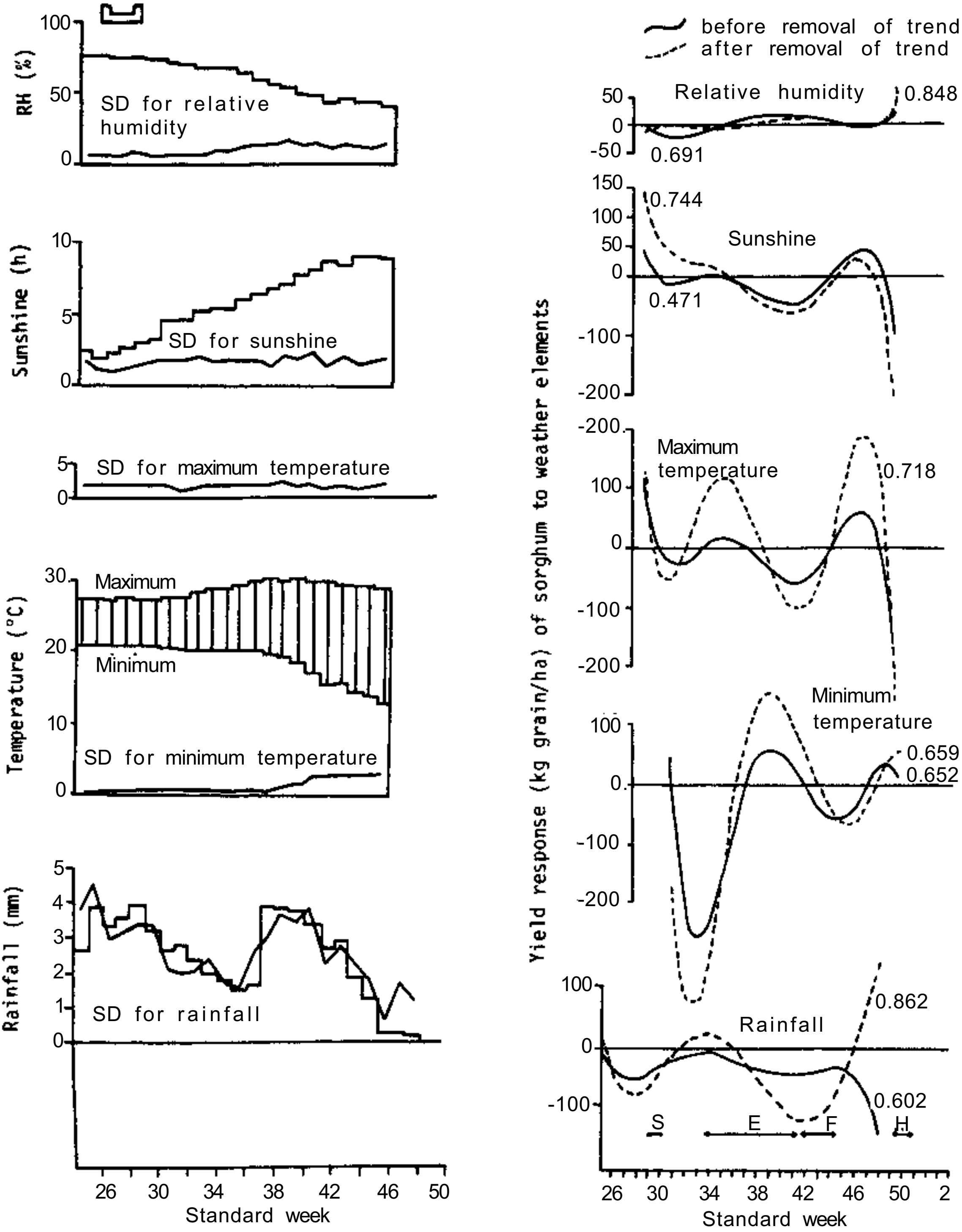


Figure 2. Weather elements (a) and yield response to them (b) of *kharif* sorghum (var Nandyal) at Dharwar, Karnataka, 1946-65. S = sowing; E = elongation; F = flowering; H = harvest. Values given with response curves are multiple correlation coefficients.

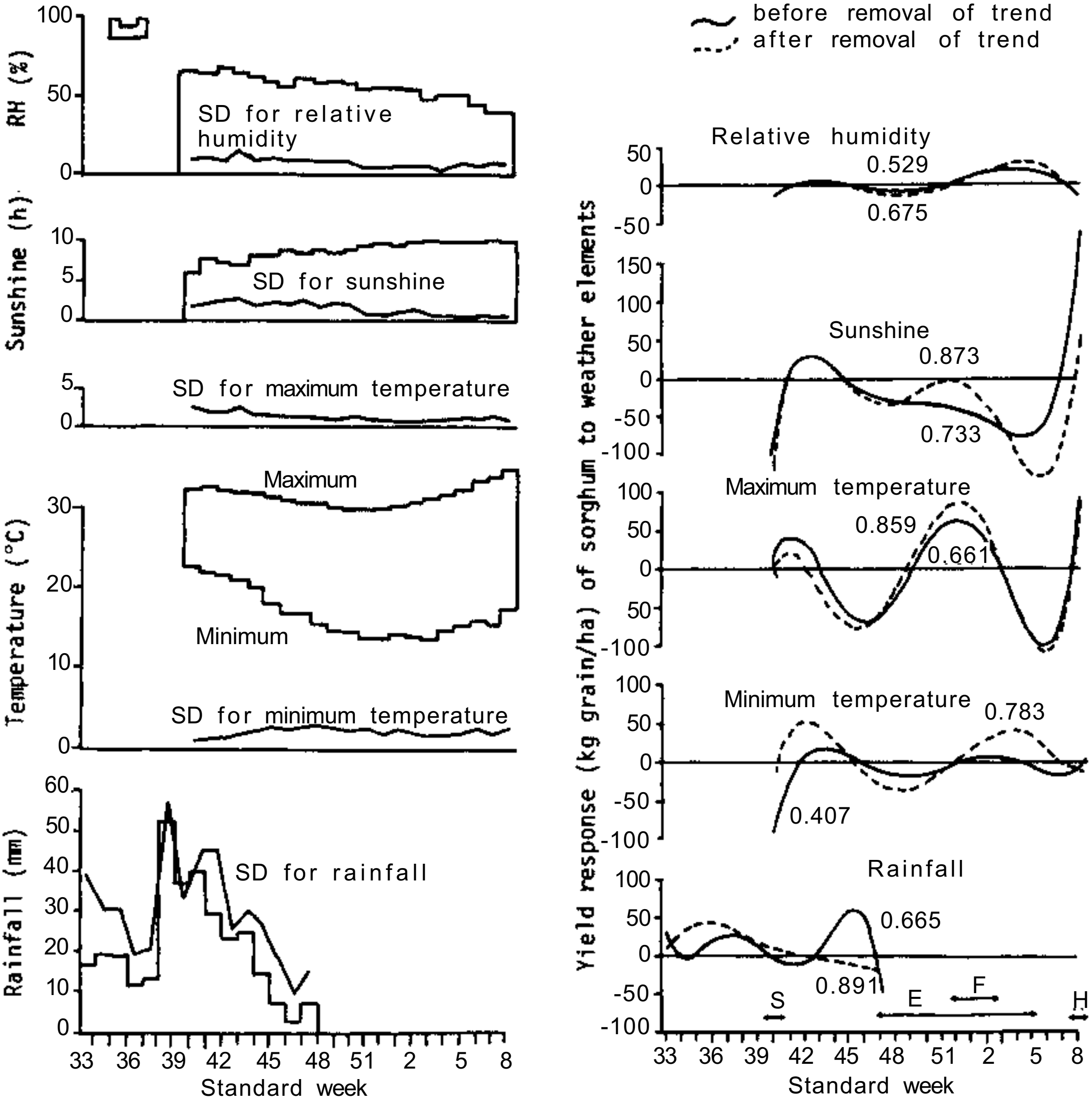


Figure 3. Weather elements (a) and yield response to them (b) of *rabi* sorghum (var M-47-3) at Hagari, Karnataka, 1948-65. S = sowing; E = elongation; F = flowering; H = harvest. Values given with response curves are multiple correlation coefficients.

The average minimum temperature is 19 to 20°C during phase 1,15 to 16°C during phase 2, and 15 to 17°C during phase 3. The standard deviation of night temperature between years is 1 to 2°C.

Sunshine. The average daily sunshine is 7 to 8 h during phase 1; 9 h during phase 2; and 10 h during phase 3—a pattern that is similar at all stations. The standard deviation between years is 1 to 2 h per day.

Relative humidity. The average afternoon relative humidity is of the order of 40 to 45% during phase 1; 32 to 40% during phase 2; 24 to 34% during phase 3.

There is a gradual decrease in relative humidity from sowing to harvest at all stations, but this decrease is most marked in Sholapur. The standard deviation between years is 5 to 10%.

Minimum Assured Rainfall

The rainfall in the region is highly variable; thus agricultural planning should not be done on the basis of average rainfall—seasonal, monthly, or even weekly. It should be done on the basis of minimum assured rainfall at suitable probability levels, depending on the duration and the type of crop. Virmani (1975) and Hargreaves (1975) considered 75% probability as an acceptable risk value for most conditions on a monthly basis. Sarker et al. (1982), Biswas and Sarker (1978), and Biswas (1980) considered 50% probabilistic rainfall as dependable precipitation on a weekly basis. It was also shown by Sarker and Biswas (1982) that a 50% value on a weekly basis is almost equivalent to a 60% value on a fortnightly basis.

In Tables 4 and 5 we give the minimum assured rainfall figures computed by incomplete Gamma distribution at 50% and 70% probability levels from week 25 to week 42.

We consider that in the semi-arid tropical belt a short-duration crop of 10 to 12 weeks will require about 250 mm of assured accumulated rainfall (AAR); a medium-duration crop of 12 to 16 weeks will require about 350 mm; and a long-duration crop of 16 weeks or more will require about 400 mm. Also the potential evapotranspiration value in the region is about 5 mm/day during the rainy season; and around 8 to 10 mm/day in rainless periods. Based on these observations we would suggest that at least 20 to 25 mm of dependable weekly rainfall be adopted as a criterion for effective rainfall during the kharif season, rather than the 10 mm suggested by Virmani (1975).

As Table 6 shows, the minimum assured weekly rainfall is well distributed from week 25 to 39 (mid-June to end September) at 50% probability level for all the kharif and rabi stations, except Hagari (Bellary). The Sholapur values are also lower. But at 70% probability level (Table 6), the chances of meeting the criterion are limited, particularly beyond week 32 (from mid-August), even if we accept the lower value of 10 mm proposed by Virmani (1975).

In any case, the kharif crop could be success-

Table 4. Assured weekly precipitation (mm) at 50% probability level at seven experiment stations in Maharashtra and Karnataka, India.

	Standard week																	
Station	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Dharwar	14	22	28	32	29	34	29	21	17	20	11	7	8	19	27	26	25	15
Raichur	17	19	19	17	20	21	17	13	20	16	19	16	20	30	30	14	6	3
Bellary (Hagari)	1	5	4	5	5	3	3	2	6	4	5	4	10	25	27	20	11	9
Jalgaon	20	37	43	41	41	37	41	30	18	23	18	25	13	12	7	0	0	0
Akola	30	38	40	35	36	39	40	19	17	19	22	23	19	22	9	0	0	0
Parbhani	37	30	37	31	30	39	29	23	22	27	25	38	25	32	25	7	0	0
Sholapur	19	18	16	15	21	20	13	8	15	13	16	18	24	31	28	11	3	2

Table 5. Assured weekly precipitation (mm) at 70% probability at seven experiment stations in Maharashtra and Karnataka. India.

	Standard week																	
Station	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Dharwar	7	10	17	16	16	20	17	13	8	10	5	2	2	7	11	10	10	4
Raichur	8	9	9	8	9	9	7	5	8	5	7	5	7	13	15	3	0	0
Bellary (Hagari)	0	1	0	1	1	0	0	0	0	0	0	0	0	9	11	7	0	0
Jalgaon	6	17	25	23	23	20	21	16	7	9	7	9	0	2	0	0	0	0
Akola	11	19	22	17	20	21	20	9	5	6	8	8	0	7	0	0	0	0
Parbhani	20	13	18	16	13	21	12	12	9	12	8	17	9	15	5	0	0	0
Sholapur	9	7	6	6	9	9	6	0	5	9	3	6	7	13	10	0	0	0

Table 6. Agroclimatic classification of sorghum zones based on moisture availability index (MAI), potential evapotranspiration (PET), assured accumulated rainfall (AAR), and stored soil moisture (SSM).

	No. of weeks MAI				AAR (mm)	PET (mm)	SSM (mm)	Classification
	⩾ 0.3	⩾ 0.5	⩾ 0.7	⩾ 0.9				
					At 50% probability			
Jalgaon	14	11	9	6	401	476	44	G1
Akola	16	14	9	6	422	532	123	G1
Parbhani	15	15	14	6	449	515	63	G1
Sholapur	17	7	4	2	309	573	0	F1
Raichur	18	17	14	5	323	428	2	G1
Bellary (Hagari)	6	3	3	1	103	179	0	D1
					At 70% probability			
Jalgaon	9	6	1	0	170	307	0	
Akola	6	4	0	0	118	204	0	
Parbhani	11	3	0	0	169	381	0	
Sholapur	2	0	0	0	23	59	0	
Raichur	12	2	0	0	106	276	0	
Bellary	2	0	0	0	21	62	0	

fully raised in the area (at least once in 2 years, if not more often).

The same cannot be said for the rabi crop, which is sown at week 40. By this time the rain stops, and the crop thrives on stored moisture; however, this is not available in any of the rabi stations at 50% and 70% probability levels.

A rethinking appears desirable for continuing rabi cropping. We must at least consider sowing for the rabi crop a few weeks earlier.

Moisture Availability Index and Agroclimatic Classification

The moisture availability index (MAI) is defined as the ratio of dependable precipitation to potential evapotranspiration. Hargreaves (1975) considered 75% probability monthly rainfall as dependable precipitation. Biswas and Sarker (1978) and Biswas (1980) considered weekly rainfall and defined the criteria of MAI for various probability levels—30,40, 50,60, and 70%; the agroclimatic classification, however, was made on the basis of MAI for 50% probability weekly rainfall.

The MAI and assured accumulated rainfall (AAR) for the weeks with MAI ⩾0.3 and the stored moisture are given in Table 6 for kharif and rabi stations for 50% and 70% probability levels. Stored moisture is computed by the formula:

Stored Moisture = AAR-0.75 PET

where PET is the potential evapotranspiration.

The dry-farming tract of India was divided into agroclimatic zones according to the number of weeks where MAI is 0.3 and 0.7, at 50% probability.

Classification	No. of weeks where MAI at 50% level is	
	0.3	0.7
D	< 10	< 1
E	10-11	1-4
F	11-14	4-7
G	⩾ 14	⩾ 7

These zones were further subclassified according to the length of the moisture-stress period. Superimposition of a map of the sorghum-growing areas of India on this map shows that the sorghum belt can be classified as E, F, and G, with a few pockets of D.

Zone D has low potential for crop production, and could be identified as a drought-prone area where growing crops without irrigation is highly risky.

Zone E is an area of fairly good crop potential. The MAI is normally more than 0.3 for 10 to 11 weeks and more than 0.7 for 1 to 4 weeks. The AAR varies from 200 to 350 mm. A short-duration crop may be raised.

Most of the sorghum belt falls under zones F and G. Zone F has good crop potential. There is hardly any water-stress period and AAR ranges from 250 to 450 mm. A medium-duration crop (3-3.5 months) may be successfully raised once in 2 years over most of this zone.

Zone G has the highest crop potential in the sorghum belt. In most stations in this zone, MAI is normally more than 0.3 for 14 to 19 weeks and more than 0.7 for 7 to 13 weeks, and AAR ranges from 330 to 480 mm. Some stored moisture will also be available at some of the stations. A crop of 13 to 18 weeks' duration may be raised in this region under rainfed conditions once in 2 years.

It has also been seen that AAR at 70% is of the order of 200 to 250 mm at a number of locations. A short-duration crop may therefore be raised at these places in 7 out of 10 years.

It can be seen from Table 6 that the stored moisture is either negligible or absent. This again raises some doubt about growing rabi sorghum, although the prospect of a kharif crop is quite good.

Statistical Analysis of Crop-Weather Data

The crop-weather data collected at the seven experimental farms were analyzed to estimate the influence of various meteorological parameters on crop yield. The three methods of statistical analysis used were: Fisher's response curve technique; the selected period method; and curvilinear analysis.

Fisher's Response Curve Technique

Fisher (1924) developed a method to examine the influence on yield of the distribution of a meteorological parameter throughout the crop life cycle. The response curve depicts the gain or loss in yield per unit increase in the parameter above its normal value at any point of time, thus showing when this parameter will have a beneficial effect and when an adverse effect. In Figures 2 b and 3 b typical response curves for sorghum are shown both before and after removal of trends for two stations.

Multiple correlation coefficients were significant, except in a few instances; for example, for the kharif crop the multiple correlation coefficients were 0.70 to 0.90 for rainfall, showing that 50 to 80% of the variation in yield could be explained by distribution of rainfall alone.

The influence of sunshine and maximum temperature could also be established for the kharif crop, but the influence of minimum temperature and relative humidity could not.

Similarly, for the rabi crop, the influence of rainfall, sunshine, and maximum temperature could be established, but that of minimum temperature and relative humidity could not.

From this analysis we could deduce that more rainfall is beneficial during germination. Both during the elongation phase and during the flowering and ripening stages, average rainfall seems sufficient; any addition would have a detrimental effect on yield.

Increase in maximum temperature during the germination and elongation phases has, in general, a beneficial effect on yield; during the grain-formation and ripening stage, however, higher maximum temperatures depress yield at the kharif stations, except Dharwar, where day temperature is lower (30°C) and the crop may therefore benefit from a higher maximum temperature.

No consistent yield response can be attributed to the influence of sunshine; hence no general statement is possible.

During the rabi season, although the significant multiple correlation coefficient confirmed the influence of rainfall on yield, it is difficult to make a proper interpretation. Rabi stations get good rainfall during August and September; yet rabi sowing is done only in the first week of October. By the time the crop enters the elongation phase in the middle of November, rainfall ceases completely. Thus valid statistical results are difficult to obtain.

The influence of sunshine and maximum temperature is more or less similar: an increase in these parameters during the period from sowing to commencement of elongation will have a beneficial effect on yield. In the early phase of elongation, the effect is adverse, but towards the end of elongation and during flowering and grain formation, increased sunshine and higher maximum temperatures are beneficial.

Selected Period Method

This method assumes a differential effect of weather during certain critical phytophases rather than a continuous general effect. These critical periods were determined by systematically working out correlation coefficients during periods ranging from 1 to 8 weeks. Significant correlation coefficients were chosen to identify critical periods and regression equations worked out. Deleting the factors that were not partially significant, a final regression was obtained.

Results based on the regression equations are discussed below and compared with results obtained from Fisher's response curve technique.

Kharif Season

Rainfall. From the partial regression coefficients of Table 7 and other equations, it is evident that average yield increases with increased rainfall up to 2 weeks after sowing. However, rainfall occurring 1 week after commencement of elongation (week 33-34) reduces yield. These conclusions are similar to those obtained with the Fisher's response curve method.

For the hill station Dharwar, rainfall during flowering and ripening (weeks 41 -48) depresses yield. The response curve for Dharwar also leads to the same conclusion, that additional rainfall above the average during the flowering phase depresses yield.

Maximum Temperature. The critical period for maximum temperature could be determined at only two of four stations. For maximum temperature and sunshine the selected period method gave inconclusive results. It appears that sunshine at some point in the elongation phase depresses yield; however, because of variation between stations, no conclusive result could be obtained.

Rabi Season

Rainfall. The critical periods identified are presowing, sowing, and sowing to commencement of elongation. Rainfall during the first two is beneficial; during the third, detrimental. However, because of odd distribution of rainfall, the last inference from statistical results is somewhat doubtful.

Maximum Temperature. In general, higher day temperatures and sunshine for 4 to 5 weeks after sowing will increase yield. During the early elongation phase high day temperatures are detrimental but are again beneficial during later elongation and during ripening. The effect of sunshine is similar to that of maximum temperature.

The Fisher's response curve for these parameters also led to similar conclusions.

Curvilinear Technique

This technique is a powerful tool for determining nonlinear relationships between crop growth and weather. The method is essentially a graphical one, and the relationships between yield and various meteorological factors could be used to predict yield. Unlike the two methods described so far, the curvilinear technique can be used to find the optimum value of a weather parameter for crop growth and yield. Sreenivasan and Banerjee (1973) used this method to study rabi sorghum at Raichur (Fig. 4).

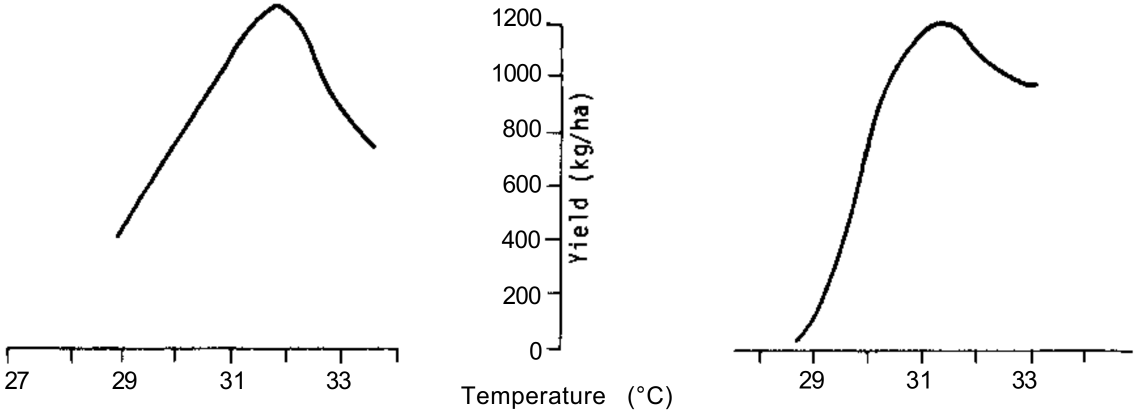
Relationships were obtained for (1) rainfall and rainy days, beginning 8 weeks prior to sowing, and

Table 7. Regression equations of yield on individual meteorological parameters by selected period method.

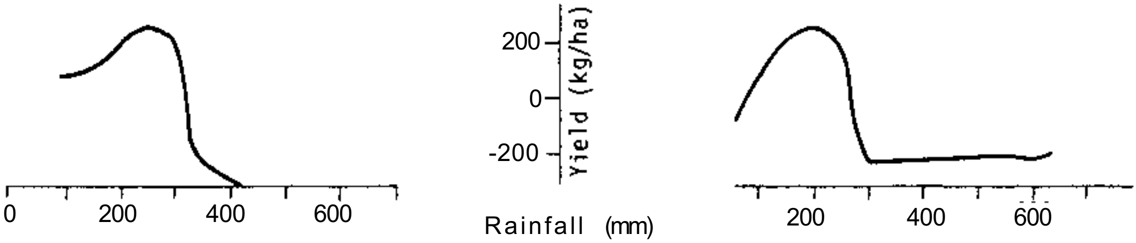
Station	Sorghum variety	Meteorological parameter	Regression equation	MCC
Kharif crop				
Jalgaon	Aispuri	Rainfall	$Y = 745.26-32.02\text{ (week 33-34)}+73.31\text{ (week 28)}$	0.772***
Akola	Dukri	Maximum temperature	$Y = 5332.24+207.93\text{ (week 29)}$	$r = 0.536$*
Parbhani	PJ-UK	Sunshine	$Y = 6402.55-1289.43\text{ (week 39)}-472.34\text{ (week 50-51)}$	0789**
Rabi crop				
Hagari	H1	Rainfall	$Y = 69.37+23.57\text{ (week 33-35)}+30.33\text{ (week 41-43)}$	0.701**
Sholapur	No.15	Maximum temperature	$Y = 9018.44+37.16\text{ (week 43-44)}+95.58\text{ (week 5-7)}$	0.690**
Raichur	PJ-4R	Sunshine	$Y = 357.029+135.93\text{ (week 44)}$	0.667**

* Significant at $P = 0.05$; ** significant at $P = 0.01$.

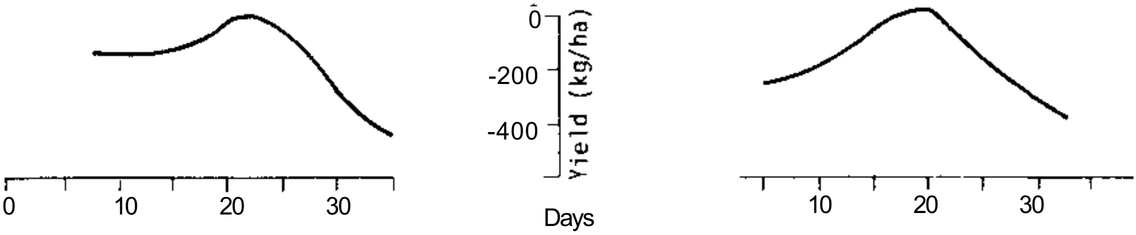
a. Yield estimated from maximum temperature



b. Yield correction (kg) for rainfall amount



c. Yield correction (kg) for no. of rainy days



d. Yield correction (kg) *for* minimum temperature

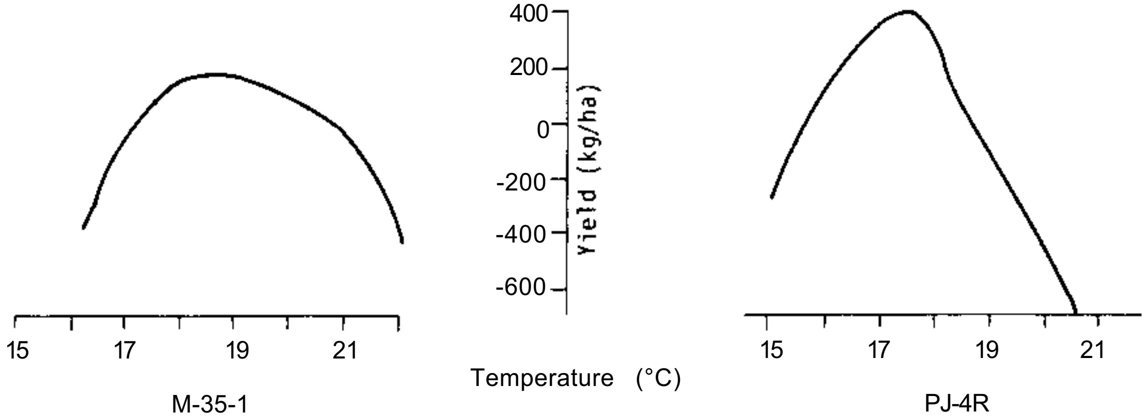


Figure 4. Curvilinear relation of yield of *rabi* sorghum (var M-35-1 and varPJ-4R) to weather elements at Hagari, Karnataka.

(2) maximum and minimum temperatures during the growth period.

Figure 4 shows, for variety M-35-1, the optimum values of rainfall (275 mm), rainy days (20), and maximum and minimum temperatures for maximum yield (31 and 17.5°C). The corresponding figures for variety PJ-4R are 200 mm, 20 days, 31.5°C, and 18°C, respectively. The two varieties show a differential response to variation in weather, but for both varieties, temperature appears to exert greater influence than rainfall. A comparison with a similar study on wheat at Dharwar by Ramamurti and Banerjee (1966) reveals that winter sorghum is perhaps better suited than wheat for the semi-arid tracts with somewhat higher temperatures.

Evapotranspiration in Sorghum

For the last few years daily evapotranspiration data have been recorded by lysimeter for hybrid sorghum crops from sowing to harvest at three experiment stations. We present here the analysis of these data in relation to rainfall, evaporative power of air, and crop stage.

The three stations are Akola (21 °N latitude; 77°E longitude), Parbhani (19°N, 77°E), and Sholapur (18°N, 76°E). The varieties grown at these stations are, respectively: CSH-1, of 3 months' duration; CSH-6, of 3.5 months' duration; and Maldandi, of 4.5 months' duration, which is raised as a rabi crop. The weekly values of AE:EP (ratio of evapotranspiration to evaporation) for these stations are given in Figures 5 to 8, which also show the weekly rainfall amounts.

Akola

In 1974 the main features of weather were the lack of rainfall from the beginning of the third week of August to the end of the third week of September, necessitating two light irrigations in September to keep the crop alive (Figure 5). The AE:EP ratio rose from 0.45 to 1.15 until week 34 (third week of August), after which it dropped to 0.2 during the water-stress period of weeks 35 to 42. Rains from week 40 helped the crop recover, and the water consumption remained high even at harvest, as evidenced by the AE.EP ratio of 0.95. Evaporation was quite high, 8 to 11 mm/day; total rainfall was 430 mm, and the grain yield of 2702 kg/ha was quite low. This is due to the low potential consumption, especially during weeks 33 to 40.

In 1975 the rainfall distribution was very good, except for the second half of August. The AE:EP ratio gradually rose and remained around 1.0 from mid-August to the end of September. The decline started from week 39, as the crop matured, even though the value remained near 0.9 at harvest. The evaporation was on an average 5 mm/day and never exceeded 8 mm/day. The total rainfall was 603 mm and total ET 336 mm. The yield was maximum this year, i.e., 6500 kg/ha.

In 1977, as in 1975, rainfall was good throughout; however, the total rainfall was less—429 mm. There was no appreciable decline in AE:EP ratio during maturity. The evaporation was on an average 5 mm/day.

The years 1976, 1979, and 1980 were more or less comparable. Both in 1976 and 1979, rainfall distribution was good, except during the last 4 weeks, when there was no rain. Evaporation was on an average 5 mm/day. Rainfall was 468 mm and 493 mm respectively. AE:EP ratio dropped to between 0.2 and 0.4 in the last 4 weeks. In 1980 the crop suffered water stress in the last 2 weeks, when the AE.EP ratio declined to 0.6.

From this analysis of the Akola case, we may conclude that: (1) the period from commencement of flowering to grain hardening is critical, when water consumption is at its peak, and any soil moisture deficiency during this period will reduce yield. The crop must either have adequate stored soil moisture or very well-distributed rainfall in the period from a month after sowing to maturity stage. (2) Hybrid sorghum does not seem to have any marked physiological senescence and reports of reduced wafer consumption during maturity seem to be due to soil moisture inadequacy only. (3) The yield and total ET in 1975 would suggest that the optimum water use by CSH-1 sorghum would be about 330 mm or more.

Parbhani

The CSH-6 variety grown at this station is of 3.5 months' duration. In 1980 and 1981, rainfall distribution was quite good from sowing in week 26 (end of June) to week 37 (mid-September) a period that coincides with the milk stage.

The total yield of grain in both years was comparable; i.e., 5029 and 4882 kg/ha. The total rainfall was 547 and 552 mm, and the total ET 345 and 348 mm, respectively. The average evaporation values were also comparable.

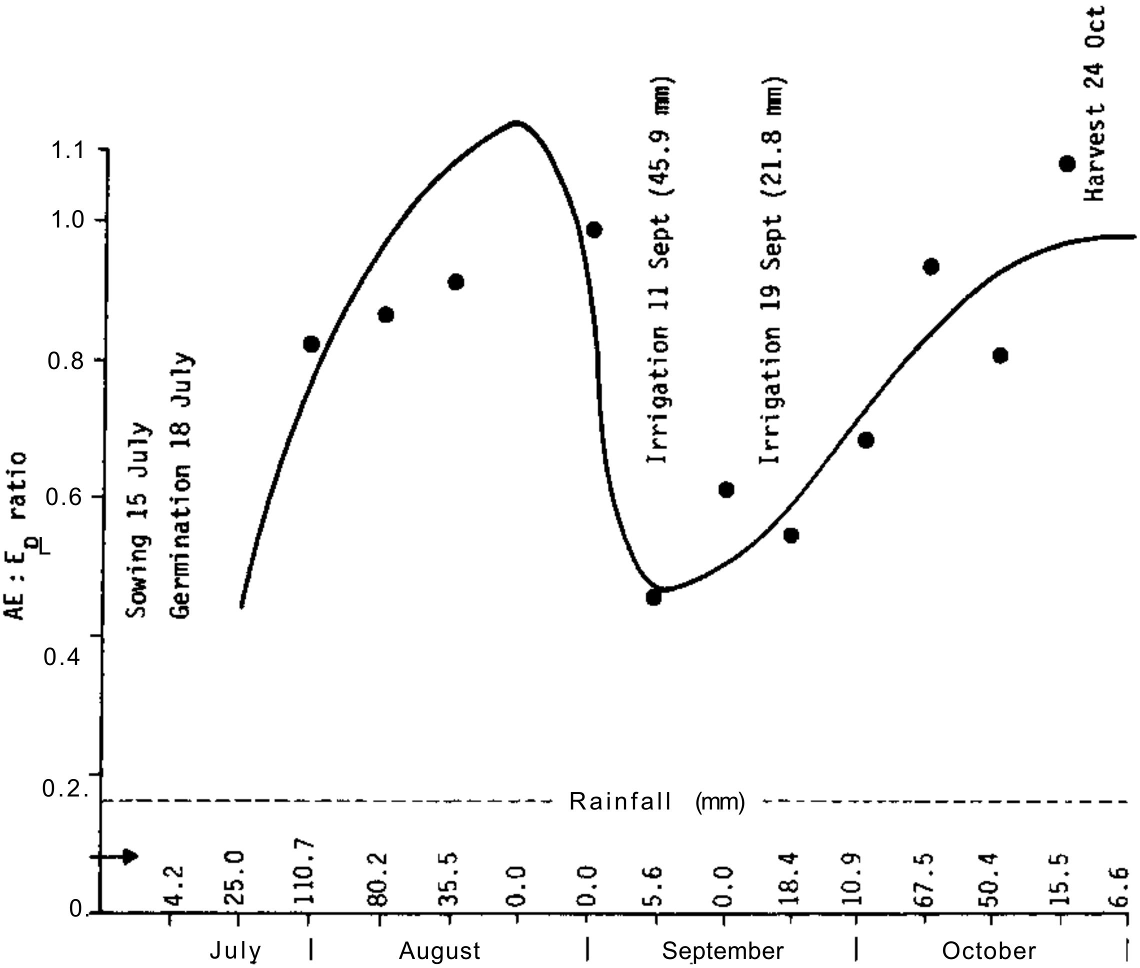


Figure 5. Relationship of rainfall distribution and AE:EP ratios to grain yield of *kharif* sorghum at Akola, Maharashtra, in 1974, a bad year with poor rainfall distribution, and no rain at critical growth stages; yield: 2702 kg/ha.

From AE:EP values, it is seen that the critical period is from 1.5 months after sowing until the milk stage, and perhaps even up to maturity. In 1980 there was no rain for the last 5 weeks of the season and the AE:EP ratio declined to between 0.1 and 0.3 at harvest. In 1981, however, there was no significant fall in the AE:EP ratio. Thus the conclusions drawn for CSH-1 at Akola seem to be valid for CSH-6 at Parbhani also, except that the water use might be slightly higher.

Sholapur

The variety grown most commonly in Sholapur is the long-duration (4.5 months) Maldandi, sown in early September. In 1978/79 the rainfall at the station was normal; that is, it was good from sowing on 8 September up to the middle of November. But after that there was no rain at all till harvest and the crop suffered water stress continuously for 9 weeks. This is a normal feature at Sholapur if the crop is sown in early September and harvested in the third week of January. Average evaporation was 5 mm/day. The AE:EP ratio started declining from week 48 (end of November) until harvest, when the value was 0.11. The critical period appears to be from 1 month after sowing until the milk stage. The total grain yield was 3330 kg/ha;

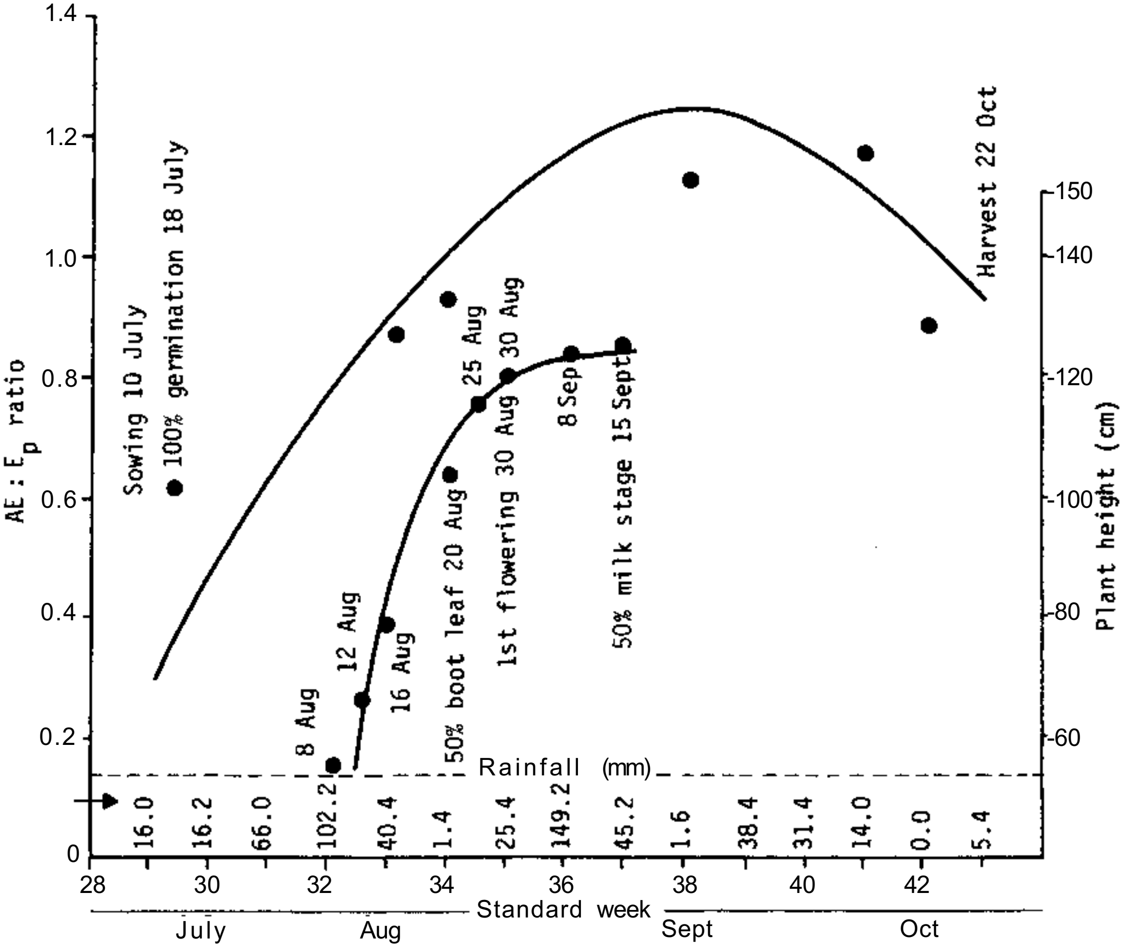


Figure 6. Rainfall and AE:Ep ratios during various phytophases and their relationship to grain yield of *kharif* sorghum at Akola, Maharashtra, 1975. This was a good year with even rainfall distribution over the season; yield: 6600 kg/ha. Compare Figure 5.

the total rainfall, 310 mm; and the total ET, 436 mm. Thus the extra water use was obviously from stored soil moisture.

In 1979/80, rainfall distribution was very uneven. There was good rain in September, no rain in October, good rain in November, and no rain at all for the next 2 months, until harvest. Evaporation was also high (7 mm/day) during October. The AE:EP ratio declined to about 0.3 during the critical period of October and also during the milk stage and grain hardening in December. Although the total rainfall was 420 mm (quite high compared with 1978/79) and water use 400 mm, the yield was over 20% lower than in 1978/79, because of the water stress in October.

In 1980/81 the sorghum crop at Sholapur suffered moisture stress throughout the season. From the fourth week after sowing, there was no rain at all until harvest, except in weeks 46, 47, and 3. AE:EP ratio was less than 0.4 throughout the season; evaporation was considerably higher than in the 2 previous years. Considering that total rainfall was only 82 mm and total ET 280 mm, the grain yield of 2280 kg/ha appears good.

From the 3 years' data, it is concluded that: (1) the critical period is from 1 month after sowing until the milk stage; (2) there is no way of suggesting that the crop does not show any physiological senescence; (3) Sholapur is a typical case where an alternative sowing date should be tried. We have

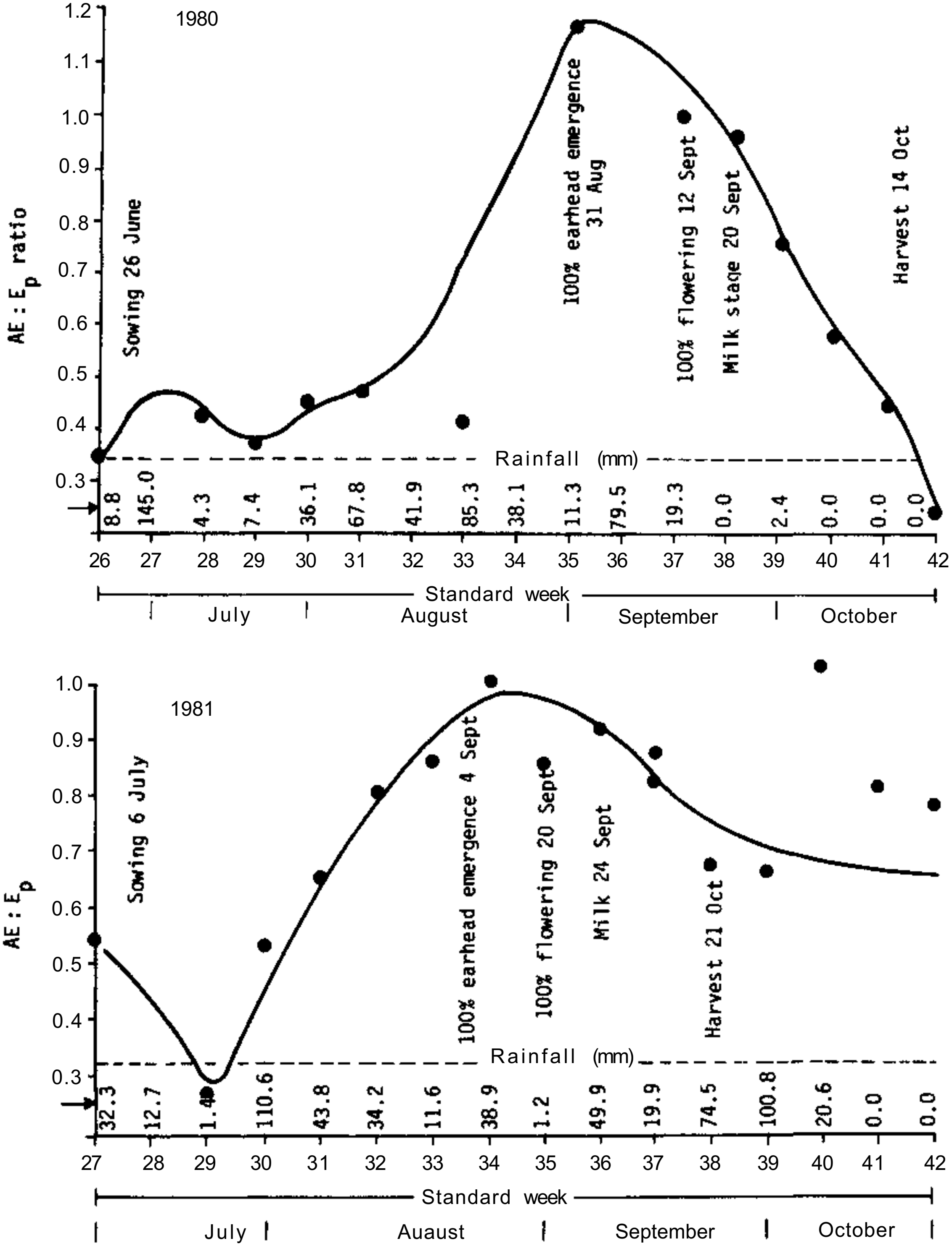


Figure 7. Relationship of rainfall distribution and AE : EP ratios to grain yield of *kharif* sorghum CSH-6 at Parbhani, Maharashtra. Conditions in 1980 and 1981 were comparable, giving similar grain yields of 5029 and 4882 kg/ha, respectively.

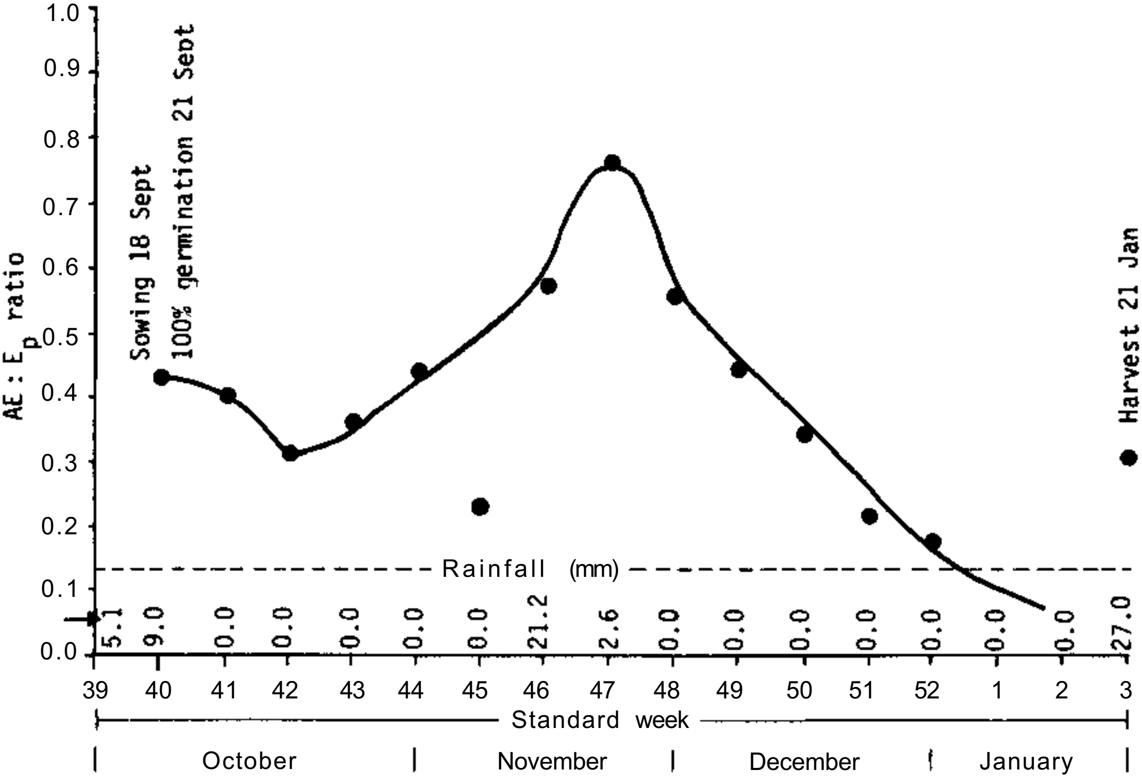


Figure 8. Rainfall distribution and AE:Ep ratios during the *rabi* sorghum season at Sholapur, Maharashtra, 1980/81. Sowing a few weeks earlier would help the crop avoid moisture stress at critical stages.

seen earlier that there is practically no rain at all beyond week 42.

A study of minimum assured rainfall by Sarker et al. (1982) shows that at Sholapur assured rainfall at 50% probability level is practically nil beyond week 42 (mid-October). But it is very good (15-20 mm/week) during weeks 25 to 40. Similar figures at 70% probability level are 8 to 13 mm/week. This would suggest that shifting of sowing to an earlier date by a few weeks will yield better results by reducing the water-stress period.

It might be worth examining whether a kharif crop would be more profitable than a rabi one, taking into consideration other practical aspects, such as soil conditions, etc.

Conclusion

This paper has dealt with some of the agroclimatic and agrometeorological aspects of the sorghum-growing belt in India. However, the role of the soil has not been considered, which constitutes a limitation of the inferences drawn. Salient features of climatic requirements of the sorghum crop have been brought out. An extension of this study will be to identify homoclimes of the sorghum belt so that production can be increased by extending the crop to new areas.

Derived parameters such as dependable precipitation and moisture availability index identify the growing season. The beginning and end of the crop season should match this available length of growing season; production could then be stabilized on the basis of rational agricultural planning. Agroclimatic classification identifies areas of crops of different durations and different stress periods. This may give a partial answer to two questions: (1) which variety of hybrid an agronomist should choose for his area and (2) what type of hybrid a plant breeder should develop to suit his soil-climate environment.

como un todo, sino tomando en cuenta los parámetros componentes de ese medio y su presencia en las cantidades requeridas en las diferentes etapas fenológicas del cultivo y que involucran también al suelo.

Conocer, comprender, analizar y manejar los factores agroclimáticos, nos permitirá un conocimiento más amplio de nuestros territorios y de esta manera podemos dar una mejor utilización a nuestros recursos naturales y mediante la agroclimatología, obtener la delimitación de áreas óptimas para la producción, así como de aquellas que pueden ser incorporadas a los cultivos.

En México y mundialmente, encontramos una gran diversidad de agroclimosistemas con áreas muy variables, debido a los efectos combinados del clima, del suelo y de las características orográficas, así como a la variabilidad de la precipitación pluvial y a la temperatura, por lo tanto, se desconoce en su mayoría los óptimos parámetros agroclimatológicos que inducen a los cultivos a mayores rendimientos, dado que generalmente solo se cuenta con conocimientos bioclimáticos, donde prosperan una serie de especies vegetales, pero no el de las áreas verdaderas de adaptabilidad agroclimática de las especies cultivadas.

La tierra presenta una gran variedad de microclimas y suelos, lo que hace que se pueda comparar con un mosaico de bio y agroclimosistemas, de superficies muy variables que hacen que la investigación y tecnología sean difíciles de generalizar; esto implica mayores esfuerzos y elementos que mediante la agroclimatología podrían reducirse, ya que esta ciencia estudia las necesidades de los parámetros climáticos, edáficos, hídricos de las plantas, su balance y relaciones para obtener el máximo rendimiento con la utilización eficiente de ellos.

La Secretaría de Agricultura y Recursos Hidráulicos en México, a través del Instituto Nacional de Investigaciones Agrícolas, había estado considerando fundamentalmente los factores agua, suelo, planta y algunos elementos del clima como temperatura, precipitación pluvial y altitud sobre el nivel del mar, utilizando en gran escala datos de estaciones meteorológicas que no han sido instaladas exprofeso para estudios agroclimáticos, faltando el estudio acucioso de las necesidades mínimas de los cultivos y las interrelaciones de los limitantes de los factores climáticos como son los fenómenos derivados de la radiación solar, la temperatura, humedad ambiental y del suelo, así como sus relaciones con los aspectos fenológicos de la planta.

El Programa de Agroclimatología del INIA, ha emprendido proyectos de investigación en el campo, en los cuales se llevan a cabo estudios fenológicos de los cultivos conjuntamente con observaciones de los datos que se obtienen de las Estaciones Agroclimatológicas para valorar las disponibilidades agroclimáticas de cada región. Para poder llevar a cabo este Programa, se ha previsto y se está llevando a cabo, la instalación de una red de estaciones agroclimatológicas con un equipo e instrumentos científico-agroclimáticos adecuados para el enfoque diferente que le hemos dado a nuestras investigaciones.

Con el objeto de entender en forma precisa el enfoque que nuestras investigaciones le han dado al Programa de Agroclimatología, es necesario identificar claramente lo que para nosotros significa Agroclimatología: Es la ciencia que estudia la relación óptima de los factores clima-suelo-agua a través de cada etapa fenológica durante el ciclo vegetativo del cultivo, buscando que se combinen adecuadamente en frecuencia, intensidad, duración y época de ocurrencia, para obtener los mejores rendimientos óptimos-económicos. No así la bioclimatología que estudia las necesidades y exigencias mínimas de los vegetales de elementos bioclimáticos en relación con su ciclo de vida, es decir, hasta que la planta complete su ciclo reproductivo, sin hacer énfasis en óptimos rendimientos.

En México, los estudios y clasificaciones climáticas realizadas hasta hoy, han sido de un valor relativo para fines de investigación agrícola, pues han considerado el clima como un todo relacionado con los cultivos y para ellos se toman promedios mensuales y anuales de temperatura, precipitación y evaporación que son de poca utilidad, puesto que la planta tiene necesidades diferentes en cada etapa fenológica y que no se reflejan en los promedios mensuales y anuales de precipitación y temperatura que se han venido manejando para estudios y clasificaciones climáticas.

Por tal motivo, el Programa de Agroclimatología en México se ha fijado los objetivos fundamentales que son:

1. Determinar los requerimientos mínimos (bioclimáticos) y óptimos (agroclimáticos) de los cultivos requeridos en sus diferentes etapas fenológicas a través de los experimentos e

investigaciones de campo.

2. Obtener un inventario de las condiciones y disponibilidades bio y agroclimaticas de un lugar, mediante la red de estaciones agroclimatologicas que ya se instalan en 55 Campos Agricolas Experimentales y que cubren todo el Territorio Mexicano.

Debido a lo anterior, es necesario estudiar mas detalladamente el aspecto de los parametros dentro del clima-agua-suelo-planta y las relaciones entre ellos. Para lograrlo se necesitan llevar registros adecuados y no manejar el clima como un todo, separando cada uno de los parametros que intervienen en la produccion. Asi pues, se debera estudiar ademas de la temperatura y la precipitacidn, la radiacion solar (fotoperiodo, insolacion, luz difusa, reflejada, albedo), asi como los componentes del espectro solar en sus diferentes longitudes de onda y la evapotranspiracidn, humedad y temperatura del suelo y algunos otros que tienen influencia decisiva en el crecimiento, fructificacion y rendimientos obtenidos y en esta forma, poder interrelacionar los factores clima-agua-suelo y manejo con cada etapa o fase fenologica del cultivo.

En base a esto, se proporcionara una mejor orientacidn a los fitomejoradores en la obtencion de mejores variedades que se adapten a fenomenos meteorologicos y bioclimaticos que restringen su produccidn. De igual manera, estas investigaciones seran determinantes para el combate y control de plagas y enfermedades, mediante la probabilidad de ocurrencia de los fendmenos meteoroldgicos que inciden la produccidn agricola y asi lograr una planificacion de mayor confiabilidad, utilizando eficientemente la interrelacion de los factores y parametros y a la vez delimitar las areas optimas para la produccion agricola, ya que existen areas susceptibles de incorporarse a la produccion agropecuaria. Es de vital importancia que ese recurso sea correctamente definido y, en base al marco de referen--a, se canalice su uso, el cual nos brindara rendimientos optimos, productivos y economicos, de tal forma que nos permita evitar errores que vayan a significar una destruccion del medio ecoldgico o la degradacion de ecosistemas actualmente estables o en proceso de estabilizacion.

Esto se puede lograr efectuando un analisis concienzudo de la situacion actual, evaluando el recurso que se pretende sustituir, asi como del que se pretende implantar. Realizarlo significa una ardua labor en el aspecto cientifico y tecnico, ya que habra que considerar todos los factores y parametros de la produccidn y hacer un analisis de probabilidad de adaptacion a la zona de algun cultivo pretendido.

Por otro lado, en funci6n de las estadisticas agroclimatologicas, se puede determinar en base a los requerimientos optimos y/o minimos agroclimaticos de los cultivos, sus factibilidades de desarrollo en una determinada area y seleccionar entre ellas las que alcancen las mas altas probabilidades de ver satisfechas sus demandas.

El Programa de Agroclimatologia pretende apoyar y retroapoyarse de los grupos Interdisciplinarios, es decir, que haya una participacion de todos en donde habra beneficio mutuo. Consideramos este Programa de capital importancia para la creacidn de tecnologia y produccidn de materiales que puedan prosperar en diferentes ambientes.

Por lo anterior, cualquier programa de fitomejoramiento tendra como objeto crear plantas para los diferentes ambientes y no ambientes para la planta y consecuentemente con nuestros trabajos de investigacidn interdisciplinaria conociendo-los requerimientos de cualquier especie vegetal en sus diferentes etapas y estados fenoldgicos, estaremos en posibilidad de ubicarlos en las areas dptimas en que puedan expresar su maximo rendimiento y esto permitira un intercambio de materiales fitogeneticos a nivel mundial, si en otros pafses le dap el mismo enfoque que nosotros le damos a sus Programas de Investigacidn Agrfcola y Pecuaria.

La superficie destinada al cultivo de sorgo para grano en Mexico ha tenido un desarrollo impresionante en los ultimos 20 anos, en virtud de que de las 116,000 hectareas que se sembraban en 1960, se incrementaron a 1,500,000 en 1980 debido a los trabajos de introduccidn de variedades y fitomejoramiento y otras practicas culturales para ubicarlas en diferentes regiones de nuestro pafs tomando en cuenta la gran demanda de este grano por parte de la industria pecuaria, considerando que actualmente de las 6,500,000 toneladas requeridas, nuestra produccidn solamente se satisface en un 70% y el 30% restante requiere de importacidn, incrementandose los rendimientos por unidad de superficies en un 67%, ya que de 1.8 toneladas que se obtenfan en 1960, se pasd a 3.0 toneladas en 1979. Este incremento se debe en gran parte, como se ha indicado, a los trabajos de investigación agrícola que han permitido recomendar para cada región mejores híbridos, mejores prácticas de cultivo, fertilización óptima, fecha de siembra adecuadas y las indicaciones para lograr un mejor control de plagas y enfermedades y malas hierbas, ocupando este cultivo actualmente el tercer lugar en cuanto a superficie de siembra, después del maíz y del frijol y las entidades productoras más importantes por superficie sembrada, cubren el 85% de la superficie y de la producción nacional de sorgo, siendo éstas: Tamaulipas, Guanajuato, Jalisco, Sinaloa y Michoacán.

El mejoramiento genético del sorgo se hace principalmente en tres regiones : El Bajío, el Golfo Norte y los Valles Altos Centrales. Es así como el INIA ha liberado, hasta la fecha, 40 sorgos híbridos y tres variedades de polinización libre de las cuales sobresalen 16 y de éstas, 10 han tenido una mayor aceptación.

Con base en la problemática aludida, el enfoque primordial ha sido la formación y evaluación de sorgos híbridos y variedades adaptadas a las diferentes condiciones ecológicas de nuestro país, para obtener una mayor producción de grano con mejor calidad, con precocidad y resistencia a sequía, a plagas, a enfermedades, al acame y al desgrane y que se adapten a la recolección mecanizada.

Actualmente el programa evalúa en varias localidades del país alrededor de 300 nuevos sorgos híbridos mexicanos, con resistencia a mildiú velloso y con una capacidad de rendimiento superior a los recomendados; algunos de éstos se liberarán en uno o dos años más. Para los Valles Altos se han seleccionado alrededor de 30 líneas precoces que se evalúan bajo condiciones de temporal.

En el Campo Agrícola Experimental del Valle del Mayo, en el Estado de Sonora, el grano de sorgo tiene una gran demanda para la elaboración de alimento para consumo animal. Se ha detectado que la poca disponibilidad de agua en este Campo Agrícola Experimental es el factor limitante, por lo cual la producción de grano hasta ahora ha sido deficitaria. Las investigaciones por lo tanto se han concentrado en la producción de grano en zonas agrícolas de temporal, siendo una de ellas en Alamos, Sonora, donde se siembran anualmente 4,000 hectáreas de sorgo para grano.

En cuanto a nuevas prácticas agronómicas, en 1980 se constató que es conveniente hacer una siembra escalonada, dividiendo las épocas de siembra en tres etapas o tercios: en la primera se siembran híbridos tardíos, en la segunda híbridos intermedios y en la tercera o último tercio, híbridos precoces. De esta manera se tienen más probabilidades de cosechar el grano de sorgo antes del inicio de la temporada de lluvias y así escapar al ataque de la mosca "midge".

Se ha comprobado también que las bajas densidades de población son inconvenientes pues causan una disminución en el rendimiento de las plantaciones por la proliferación de tallos secundarios o "hijos" lo cual induce un período de floración mas largo. En consecuencia, habrá una mayor exposición de panojas a la infestación de la mosca "midge".

En el Istmo de Tehuantepec, en el Estado de Oaxaca, el sorgo es un cultivo de introducción reciente y cuya mayor superficie se siembra dentro del Distrito de Riego No. 19. Actualmente este cultivo se perfila como una excelente alternativa para sustituir al maíz en aquellas áreas cuyas condiciones climáticas (como los vientos fuertes y la escasa e irregular precipitación pluvial), no permiten al cultivo del maíz tener un desarrollo adecuado. Las dosis económicas de fertilización para el sorgo en esta región, en cultivos de bajo riego, se han determinado en 120 kgs. de nitrógeno por hectárea y 40 de fósforo, con una población de 320 mil plantas por hectárea.

Los trabajos de investigación realizados en el Campo Agrícola Experimental de Chetumal, en el Estado de Quintana Roo, han mostrado que el sorgo se puede producir favorablemente bajo condiciones de humedad residual, después del cultivo de arroz, en los suelos negros pesados y en los suelos semipesados y en condiciones de temporal con poca precipitación, después de la cosecha de maíz.

Se espera que en un futuro próximo el cultivo del sorgo llegue a tener mayor importanica en esta región para satisfacer las necesidades locales de grano, ya que requieren alrededor de 55 mil toneladas anuales de grano de sorgo para satisfacer la necesidad de elaborar alimentos para ganado; hasta el presente esta demanda ha sido cubierta por otras zonas productoras de sorgo del país.

En el Campo Agrícola Experimental de Zacatecas, en el Estado de Zacatecas, el sorgo ha sido un mecanismo para buscar una opción de producción de granos con el propósito de reducir las importaciones del mismo, dada la demanda de materia prima para elaborar alimentos para la actividad ganadera de esa región.

Aún cuando el sorgo se desarrolla y produce grano en forma eficiente desde alturas al nivel del mar hasta los 1,800 mts. altura que se considera como el límite seguro para su coltivo, en el Altiplano de Zacatecas, bajo condiciones de riego y con altura promedio de 2,200 msnm, se han encontrado variedades que tienen buena adaptación a las condiciones ecológicas de la región.

Uno de los grandes limitantes de las variedades de sorgo que se tenía en México se debía a que éste no producía grano en alturas mayores de los 1400 msnm, por lo que a través de la introducción y fitomejoramiento de nuestras variedades y otras obtenidas, es posible llegar a alturas superiores que lleguen hasta los 2800 msnm.

Así, la superficie sembrada con sorgo en el Altiplano de Zacatecas, es factible de aumentarse cos los híbridos generados por el INIA, considerando que los rendimientos se pueden incrementar significativamente.

El Programa de Mejoramiento Genético de Sorgo para los Valles Altos de México se inició con el propósito de lograr la adaptabilidad de variedades a nuevas áreas. Así, en este Campo Agrícola Experimental se han obtenido, mediante cruzamientos dirigidos, los genotipos tolerantes al frío, algunos de ellos con buena adaptación a aquellas alturas que oscilan entre los 1800 y los 2800 msnm.

Originalmente, antes de que el sorgo ocupara una importancia nacional para la alimentación del ganado, grandes cantidades de maíz se utilizaban para la alimentación del mismo y consecuentemente, con la demanda de maíz para la fabricación de tortillas y otros alimentos dentro de las costumbres mexicanas, se reducía considerablemente la disponibilidad de maíz. Actualmente el uso de este cereal ha originado, independiente de la sustitución del maíz por el sorgo, el hacer mezclas hasta del 10% sin afectar el sabor de la tortilla.

Otras pruebas se han hecho también en mezclas de harina de trigo y triticale en forma muy satisfactoria. Se ha tratado de eliminar hasta donde sea posible ciertas cantidades de maíz sustituyéndolas por el sorgo, consiguiéndose que las cantidades requeridas de maíz disminuyan para la dieta humana.

En 1980 se liberaron 3 variedades que se encuentran en proceso de multiplicación y que tienen buenas características agronómicas y sus rendimientos potenciales son de 8.5, 8.0 y 8.0 toneladas por hectárea, respectivamente. En parcelas de una hectárea de superficie, se han obtenido rendimientos comprobados de 6.3, 5.4 y 5.3 toneladas por hectárea, respectivamente. Ambos niveles de rendimientos se obtuvieron en siembras de punta de riego, en una región de temporal que tiene buena disponibilidad de humedad en el ciclo agrícola, mientras que en condiciones de temporal crítico, el rendimiento experimental obtenido fué de 3.5, 3.0 y 2.9 toneladas por hectárea, respectivamente, con las mismas variedades. Estas tres primeras variedades de sorgo con adaptación a las zonas altas y con tolerancia al frío, constituirán una nueva opción, ya que con estas tecnologías y otras ya disponibles en cuanto a fertilización y a combate de malezas, es posible establecer cultivos de sorgo que sean redituables para los productores agrícolas.

Se ha observado a través de nuestras investigaciones, que las plantas de sorgo contienen una cantidad apreciable de fósforo e indudablemente está íntimamente-relacionado con su resistencia al frío y a la sequía, por lo que ese factor se ha buscado en el caso particular del maíz, habiéndose conseguido algunas variedades resistentes a heladas y sequía.

El nombre de Mijo es aplicado a diversas gramíneas que producen granos pequeños y redondos, en espigas de forma diversa, según la variedad de que se trate. Son plantas de caña delgada que suelen alcanzar una altura máxima de un metro.

En las condiciones agroecológicas y climáticas del norte de México, se siembra la variedad "Alemana", utilizándose únicamente como pastura verde y su grano para la alimentación de las aves de corral.

La gran ventaja de los mijos consiste en su precocidad, ya que mes y medio después desembrarlos pueden cortarse, por lo que son insustituíbles como cosecha de emergencia.

El mijo es un cultivo que se siembra en varios países del mundo y se adapta fácilmente a condiciones agroecológicas y edáficas.

De los trabajos de investigación para fines pecuarios que se han hecho en México, destacan dos aspectos importantes: a). La introducción de variedades y b). Pruebas en diferentes condiciones bioclimáticas, así como las fechas de siembra adecuadas, la densidad de siembra y la época de corte mas apropiada, determinándose cómo varía la recuperación del cultivo al variar la época de corte.

Los datos que se tomaron en el experimento fueron: prueba de germinación de la semilla, emergencia, número de plantas por metro lineal en diferentes fechas, altura de las plantas en los diferentes estados de crecimiento, rendimiento por hectárea de forraje verde y seco, análisis bromatológicos en cada época de corte, amacollamiento, recuperación de los tratamientos en función de la época de corte.

Se encontró que la densidad de 40 kgs por hectárea fue la mejor que se comportó en cuanto a rendimiento de forraje.

En las épocas de corte la que dió mayores rendimientos de forraje verde y seco fue el corte en estado masoso del grano. Sin embargo, aquí el forraje era de mala calidad por el alto contenido de fibra y el bajo contenido de proteína.

En el corte de recuperación que se realizó a los 90 días de sembrado el cultivo y 20 días después del último corte (estado masoso del grano), se obtuvieron los mayores rendimientos de forraje en la densidad de 40 kgs.por hectárea, cuando el corte se realizó en estado de floración.

Se encontró también que la mejor combinación para cosechar el forraje fue con la densidad de 40 kgs.de semilla por hectárea y haciendo el corte en estado de floración completa, pues aquí se obtienen 4327 toneladas de forraje seco por hectárea, con un buen contenido nutritivo y poca fibra; por lo que se concluyó también que en 92 días se pueden obtener dos cortes de forraje con las características anteriores.

El Instituto Nacional de Investigaciones Agrícolas de la Secretaría de Agricultura y Recursos Hidráulicos de México, tiene como mandato principal procurar el aumento de la producción y productividad agrícola. Sin embargo, uno de los objetivos primordiales se refiere a la obtención de un mejor perfil nutricional de los cultivos mas importantes en el país, así como generar la tecnología adecuada en las diferentes zonas agroecológicas, tomando en cuenta los intereses, los requerimientos y las condiciones socio-económicas de los productores, debido a que la agricultura es la actividad básica en México y en la gran mayoría de los países del mundo.

Agroclimatic Research to Delimit Optimal Areas for Grain Sorghum and Millet Cultivation

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Abstract

Research under the Agroclimatology Program at the National Institute for Agricultural Research (NIAR) in Mexico has two basic objectives: (1) to determine the minimum (bioclimatic) and optimal (agroclimatic) requirements of the crops at different phenological stages and (2) to draw up an inventory of the bio- and agro-climatic conditions and possibilities of a given location by using the network of stations already installed across Mexico.

Suitable sowing dates have already been determined for Mexico for grain sorghum and millet, according to variety and region. At present 40 released hybrids and 3 varieties have been covered, in addition to the commercial varieties that have been tested in the experimental fields of the NIAR and for which recommendations already exist for suitable sowing dates and regions.

Over the last 20 years, grain sorghum has become a major crop in Mexico, and is third in area sown, next to maize and kidney beans. Research using different genetic materials and aimed at improving the phytomass has produced several varieties adapted to previously difficult conditions, especially high altitudes. This paper indicates the areas and conditions in Mexico in which this crop has been grown with highly satisfactory results.

Résumé

Recherche agroclimatique visant à délimiter les meilleures régions de culture du sorgho grain et du mil : La recherche effectuée dans le cadre du Programme d'agroclimatologie de l'Institut de recherche agricole du Mexique vise deux objectifs de base : déterminer (1) les besoins minimum (bioclimatique) et optimum (agroclimatique) des cultures aux différents stades phénologiques et (2) les conditions et possibilités bio et agroclimatiques d'un site donné, cela grâce au réseau de stations établies dans ce pays.

Les dates optimales de semis du sorgho grain et du mil ont déjà été déterminées en fonction des variétés et des régions. Quarante hybrides et trois variétés diffusés, ainsi que les variétés commerciales ont été évalués. Au cours des 20 dernières années, le sorgho grain est devenu une importante culture au Mexique; les superficies cultivées en sorgho suivent celles du maïs et du haricot. Des ressources génétiques variées sont utilisées dans le but d'augmenter la phytomasse. Les chercheurs ont créé des variétés adaptées à des conditions difficiles, surtout en haute altitude. Cette communication présente les régions du Mexique où le sorgho est cultivé avec succès et les conditions qui y prévalent.

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Note: This is an edited translation of the original Spanish paper immediately preceding.

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Agricultural production mainly depends upon the characteristics and effects of different factors that influence crop growth and the genetic capacity of plants to use them efficiently. Any deficit or excess of these factors is reflected in the yields obtained.

The technology produced by agricultural research is applied for the utilization and management of these factors—genetic, climatic, edaphic, cultural, economic, and social—and other crop-protection factors during the crop growing period.

For a crop to be successful, it should give the maximum yields according to its genetic ability and adequately use all the environmental factors. Consequently, the main objective of a crop improvement research program is to obtain plants that best use the environmental factors, and that also have resistance or tolerance to pests and diseases that occur under these conditions.

Agroclimatological research is of primary importance and considers the factors not as a whole, but studies the component parameters of the environment, including soil, and their availability at different phenological stages.

A proper understanding, analysis, and monitoring of the agroclimatic factors enable a better use of the natural resources. Agroclimatological research also enables us to delimit the optimal areas for agricultural production, particularly crop production.

The great diversity of agroclimatic systems of variable area found in Mexico and throughout the world is due to the combined effect of climate, soils, and orographic characteristics, as well as variations in rainfall and temperature. It is not possible to know all the optimum agroclimatic parameters for obtaining high yields, because we only have bioclimatic data about areas where the different crops thrive, but not the actual areas of the agroclimatic adaptation of these crops. This diversity of bioclimatic and agroclimatic systems makes agroclimatological research difficult. The large number of existing parameters requires much work that can be reduced by agroclimatological studies. This science studies the climatic, edaphic, and water requirements of the plant and the balance and interrelationships of these factors, with the aim of obtaining the best results.

The National Institute for Agricultural Research (NIAR) of the Secretariat of Agricultural and Water Resources of Mexico mainly studies water, soil, crop, and climatic factors (temperature, rainfall, and altitude above sea level). The data are supplied by meteorological stations, but these stations were not established specifically for agroclimatological studies.

A more detailed study is required of the minimum crop requirements, including the interaction of various climatic factors such as solar radiation related phenomena, temperature, ambient moisture, and soils and their relationship to phenological factors.

The Agroclimatology Program of the NIAR conducts field research on crop phenology; it also examines data from the agroclimatological stations in order to understand the agroclimatic resources of each region. A network of agroclimatological stations was planned and established for this purpose. The stations are adequately equipped with scientific and agroclimatic instruments, to enable a different approach from the one adopted earlier.

In order to understand clearly the focus of research conducted by the Agroclimatology Program, it is necessary to know what we mean by agroclimatology. This is a science that studies the optimum relationships of climate, soils, and water for each phenological stage of the crop-growing period. It identifies the appropriate combinations in terms of frequency, intensity, duration, and time of occurrence in order to obtain the best economic results. Bioclimatology, on the other hand, studies the minimum bioclimatic requirements of the plant during its life cycle, i.e., until the plant completes its reproductive cycle, without emphasis on high yields.

In Mexico the climatic studies and classification carried out to date are not very useful to agricultural research. They consider climate as a whole in relation to crops. Monthly and yearly averages of temperature, rainfall, and evaporation are taken, but are of little use because plant requirements vary with each phenological stage. This is not reflected in the monthly and yearly averages of rainfall and temperature used for climatic studies and classification.

For this reason, the Agroclimatology Program in Mexico has proposed the following objectives:

1. To determine the minimum (bioclimatic) and optimum (agroclimatic) requirements of crops at different phenological stages through field experiments and research.
2. To obtain an inventory of the bioclimatic and agroclimatic conditions and resources of a location through a network of agroclimatological stations established in 55 agricultural experiment stations throughout Mexico.

The program will conduct detailed studies on the parameters of the climate-water-soil-plant continuum. For this purpose, proper records of data should be maintained and the climate should be studied not as a whole but based on different parameters that influence production. This requires the study of parameters other than temperature and rainfall, such as solar radiation (photoperiod, insolation, diffused radiation, albedo), the composition of the solar spectrum according to different wavelengths, evapotranspiration, soil moisture and temperature, as well as other factors that influence crop growth, production, and yields. Thus climate, water, and soil factors and their management can be related to time and management for each crop phenological phase.

This work would enable plant breeders to better orient the development of improved varieties suited to the agrometeorological and bioclimatic phenomena that limit production. This research will also be useful in controlling pest and disease incidence through a probabilistic analysis of the meteorological phenomena influencing agricultural production. Such work would provide for more reliable planning through an efficient use of the relationships of these factors and by delimiting the optimal areas for agricultural production. This potential should be correctly identified and exploited on the basis of benchmark locations to obtain optimum and economic yields. Moreover, this would help avoid mistakes that are harmful to the environment and that might lead to a degradation of the ecosystems that are stable or being stabilized.

The present situation should be analyzed by evaluating resources including those that need to be modified and the substitute proposed. This requires a large research effort, since all the production factors as well as the adaptability of a given crop to local conditions need to be considered.

Agroclimatological data can help determine the possibilities of growing a crop in a given area and in selection of plants with high yield potential on the basis of the optimum and/or minimum requirements of the crop.

The Agroclimatology Program supports and is supported by interdisciplinary teams that participate in work that is of common interest to all. This program is of primary importance for generating technology and producing material suited to different environments.

A crop improvement program aims at the development of varieties for different environments and not the creation of environments for plants. Therefore, our interdisciplinary research helps to understand the requirements of any crop species at different phenological stages. We shall soon be able to locate such crops in optimal areas where maximum yields can be obtained. This would facilitate exchange of germplasm at an international level among countries having the same focus for crops and livestock research programs.

During the last 20 years, the grain sorghum producing area in Mexico increased from 116000 ha in 1960 to 1.5 million ha in 1980. The introduction of new varieties and crop improvement work have largely contributed to this expansion as well as the development of cultural practices to enable their cultivation in different regions. There is a high demand for sorghum grain for livestock feed, and at present, Mexico can satisfy only 70% of the country's requirement of 6.5 million tonnes; the other 30% has to be imported. Yields per unit area have increased by 67%, from 1.8 tonnes in 1960 to 3 tonnes in 1979. This may be attributed to the recommendations made by agricultural research for each region concerning improved hybrids; better cultural practices; optimum fertilization; optimum date of planting; and efficient pest, disease, and weed control. This crop now ranks third after maize and beans in cultivated area. Eighty-five percent of the cultivated area is located in the states of Tamaulipas, Guanajuato, Jalisco, Sinaloa, and Michoacan.

Genetic improvement of sorghum is mainly carried out in three regions—El Bajio, Golfo Norte, and the Valles Altos Centrales. So far, NIAR has released 40 sorghum hybrids and 3 open-pollinated varieties, of which 16 were outstanding, including 10 that have been well accepted by consumers.

The main focus of this work has been the development and evaluation of sorghum hybrids and varieties adapted to various ecological conditions in Mexico in order to increase and improve grain production. The characteristics desired are easiness; drought tolerance; resistance to pests, diseases, lodging, and shattering; as well as characteristics suited to mechanized operations.

At present, the program is evaluating, at different locations, about 300 new Mexican sorghum hybrids with downy mildew resistance and high yield potential, to be recommended to farmers. Some of these will be recommended in a year or two. Thirty early lines were selected for the high-altitude valleys under rainfed conditions.

In the state of Sonora, there is a high demand for sorghum for animal feed. At the agricultural experiment station of the Mayo valley, it was observed that lack of water is a limiting factor responsible for the deficit in grain production. Research is therefore concentrated on grain production under rainfed conditions in Alamos and the state of Sonora, where 4000 ha are annually sown to grain sorghum.

In 1980, a staggered planting of the crop was carried out in a farming systems trial. The crop was planted at three intervals over one-third of the area—first, the late hybrids; second the intermediate hybrids; and last, the early hybrids. This way, the crops could be harvested before the start of the rainy season in order to avoid midge attack.

It was confirmed that low plant densities reduced crop yields, as abundant secondary tillering prolonged flowering. This exposes the panicles to midge attack.

In the isthmus of Tehuantepec (state of Oaxaca), sorghum has been introduced recently and is widely grown in Irrigation District No. 19. At present, it provides an excellent alternative to maize in areas where climatic conditions (strong winds, irregular and low rainfall) are not favorable for growing maize. The application rates determined for economically fertilizing sorghum crops grown in areas with irrigation (at sowing and crop germination) were 120 kg N/ha and 40 kg P/ha for a population of 320000 plants/ha.

Research results obtained at the agricultural experimental stations of Chetumal (state of Quintana Roo) have shown that sorghum grown after a rice crop produces well on residual moisture on heavy soils, and after a rainy-season maize crop on medium-heavy gray soils. Sorghum is expected to gain importance in this region in order to meet the local requirements for grain. Until now, the demand for about 55000 tonnes for animal feed has been satisfied by the other sorghum-producing areas of the country.

In the state of Zacatecas, considering the demand for animal feed, sorghum is grown as an alternative crop for reducing imports of this grain.

One of the drawbacks of sorghum varieties available in Mexico is that they cannot usually be grown at altitudes higher than 1400 m. But with the introduction and improvement of Mexican varieties and other accessions, sorghum can be grown up to an altitude of 2800 m and suitable varieties have now been identified for cultivation under irrigation in the plateau of Zacatecas (average altitude 2200 m).

The sorghum-cultivation area in the Zacatecas plateau can be extended by using new hybrids produced by the NIAR for substantially increasing yields.

The Sorghum Genetic Improvement Program for the high-altitude valleys in Mexico was established with the objective of developing new varieties suited to the new cultivation areas. Cold-tolerant genotypes, some of them suited to high altitudes ranging from 1800 to 2800 m, were obtained through directional selection.

Until sorghum became nationally important for animal feed, large quantities of maize were used for this purpose. The demand for maize for making tortillas and other local foods considerably reduced availability of maize. Apart from being used as a substitute for maize, sorghum is mixed (up to 10%) with maize for making tortillas.

In other trials, a mixture of wheat and triticale flour was successful. The objective was to substitute maize with sorghum as far as possible, so that more maize is available for human consumption.

Three new sorghum varieties were released in 1980 and are being multiplied. They have good agronomic characteristics, with a yield potential of 8.5, 8.0, and 8.0 tonnes/ha, respectively. Yields in 1-hectare plots were 6.3, 5.4, and 5.3 tonnes, respectively. These yield levels were obtained in a crop that was irrigated for seed germination in a region with normal conditions and good moisture availability during crop growth. Under more critical rainfall conditions, experimental yields were 3.5, 3.0, and 2.9 tonnes/ha respectively, for the same varieties. These three sorghum varieties that are cold-tolerant and adapted to high-altitude areas, provide a profitable new option when combined with other techniques for fertilization and weed control.

Our studies show that sorghum plants contain substantial quantities of phosphorus, known to be related to cold and drought tolerance. For example, when maize plants were selected for this character, several cold- and drought-tolerant varieties were obtained.

Millet

The term "millet" is applied to several Gramineae producing small round grains and earheads of varying shapes, depending on the variety. The thin stems are up to 1 m long.

The variety Alemana is grown in northern Mexico exclusively for pasture and its grain is used for poultry feed.

Millet has the advantage of being an early crop that can be cut 1.5 months after planting, so that it is hard to substitute it as a fast-growing cereal. Millet is grown in several countries of the world and is easily adapted to various agroecological and soil conditions.

Trials conducted for livestock research in Mexico highlighted two important aspects: (1) introduction of varieties, and (2) crop regrowth, which depends on the time of cutting according to trials conducted under different bioclimatic conditions for optimum date of planting, plant density, and optimum cutting time.

The aspects studied in this experiment were: seed germination, emergence, number of plants per meter at different dates, plant height at different crop stages, forage and fodder yields per hectare, bioclimatological chemical analysis for each cutting time, and tillering and crop regrowth for each date of cutting. The highest forage and fodder yields were obtained when the crop was cut at the seed-formation stage, but the forage had a high fiber and low protein content.

The crop is first cut for fodder 90 days after planting and the second cut follows 20 days later at the seed-formation stage. The best forage yields are obtained with a density of 40 kg seed/ha and when the crop is cut at flowering. This gives forage yields of 4327 tonnes/ha of good nutritive value and low fiber content. It is therefore possible to get two cuts in 90 days under these conditions.

The National Institute for Agricultural Research of the Secretariat of Agriculture and Water Resources of Mexico has the basic mandate of increasing agricultural production and productivity. An important objective is to improve the nutritive value of the country's main crops and to generate technology suited to different agroecological zones by considering the interests, requirements, and socioeconomic conditions of farmers, because agriculture is the basic activity in Mexico.

Influence du regime pluviometrique sur la fluctuation du rendement d'une culture de sorgho intensifiee

F. Forest-B. Lidon*

Résumé

Influence du régime pluviométrique sur la fluctuation du rendement d'une culture de sorgho intensifiée : A partir d'une série longue (1962–1981) de rendements observés sur une monoculture de sorgho fortement fertilisée en Haute-Volta (Station de Saria), les modalités d'influence du régime pluviométrique sur la fluctuation de la production de grain sont analysées à travers une modélisation du bilan hydrique.

Prenant en considération la demande évaporative, la pluviométrie journalière, la valeur de la réserve utilisable ainsi que les besoins en eau de la culture au cours de son cycle végétatif, le taux de satisfaction des besoins en eau ETR/ETM et un indice d'excédent hydrique sont calculés par périodes successives, depuis la date de levée générale de la culture, jusqu'à la période de récolte.

La fluctuation du rendement du sorgho grain, dans les conditions de l'essai, est principalement expliquée par trois composantes du bilan hydrique intervenant au cours de trois périodes du cycle végétatif :

- *L'excès d'eau (ruissellement et/ou drainage) au cours du premier mois est limitant pour le rendement. La qualité des façons culturales (labour + fertilisation organominérale forte) réalisées sur cet essai laisse présager l'hypothèse d'un drainage important impliquant un lessivage des éléments minéraux (réduction de l'activité du système racinaire).*
- *Le taux moyen de satisfaction des besoins en eau au cours des cinquante premiers jours à compter de la date de semis influence très significativement l'espérance de production.*
- *Le taux de satisfaction de besoins en eau au cours de la période de formation et de remplissage du grain qui intervient en général entre le 5 septembre et le 5 octobre pour les variétés de sorgho S29 et IRAT 56 (photosensibles) est apparu déterminant.*

Enfin 3 années sur 20, des événements pluviométriques exceptionnels ont considérablement affecté le rendement soit en interdisant la pollinisation (1963, grand nombre de jours de pluie consécutifs), soit en provoquant des dégâts au moment de la maturité (pluies élevées fin octobre, (1976–1978).

Introduction

Dans les regions semi-arides, le regime d'alimentation pluviometrique est frequemment le premier facteur limitant la production des cultures pluviales.

Dans le cas particulier de la region centre Haute-Volta, la culture du sorgho est très souvent pratiquée en monoculture sur des sols dont la capacité de stockage de l'eau est insuffisante pour assurer la continuité de la consommation en eau de la culture au cours des périodes de sécheresse intervenant au cours de la période de végétation.

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International Crops Research Institute for the Semi-Arid Tropics. 1984. Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics: Proceedings of the International Symposium, 15-20 Nov 1962, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

Au risque pedoclimatique s'ajoute une evolution defavorable des sols qui conduit a une baisse de la fertilite dont les consequences sur la production ont ete evaluees a travers un essai de longue duree "entretien de la fertilite" installe a la station agronomique de Saria depuis 1960.(J. PICHOT, M.P. SEDOGO, J. F. POULAIN, J. ARRIVETS, 1981).

A partir de la serie (1962-1981) de rendements disponibles correspondent a une monoculture de sorgho grain fortement fertilisee, et de la modelisation des termes du bilan hydrique (F. FOREST, J. M. KALMS, 1982), une premiere tentative de comprehension de la fluctuation du rendement est presentee dans cet article. Le choix du traitement experimental FMO est dicte par le souci d'isoler la composante hydrique dans l'elaboration du rendement du sorgho grain.

Cadre de l'etude

Localisation

Situee en zone centre Haute-Volta, la station agronomique de Saria est representative d'une region soumise a un climat de type soudanien. La pluviometrie moyenne est de l'ordre de 820 mm (Fig.1), la saison des pluies utiles s'echelonne entre le 15 juin et le 15 octobre. Le risque climatique y est eleve tant pour l'existence d'une grande variabilite de la ressource pluviometrique (Tab. 1a) que par la fr6quente apparition de jours successifs sans pluie (Tab. 1b).

Tableau 1a. Analyse fr6quentielle de la pluviometrie

ler janvier au 31 decembre		Pluviometrie en mm
Maximum		1 093.6
Quinquenale forte	0.2	966.1
Mediane	0.5	812.5
Quinquenale faible	0.8	711.2
Minimum		568.7
Du ler mai au 31 octobre		**Pluviometrie en mm**
Maximum		1 063.6
Quinquenale forte	0.2	914.2
Mediane	0.5	780.6
Quinquenale faible	0.8	686.6
Minimum		549.4

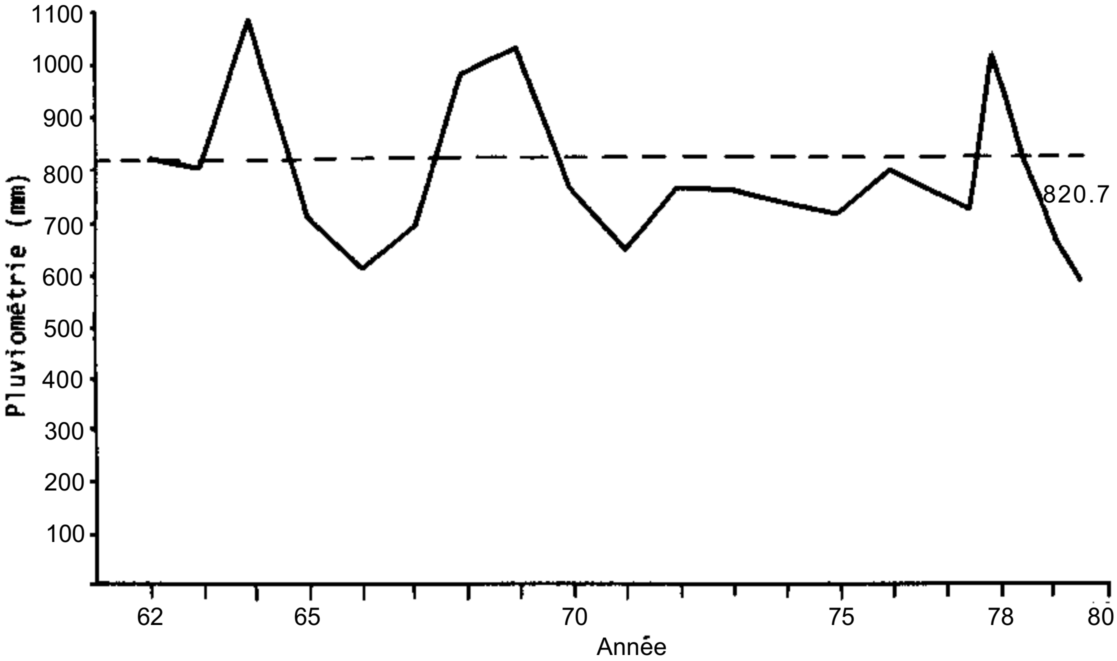

Figure 1. Variabilite interannuelle de la pluviometrie

Tableau 1b. Nombre de jours successifs sans pluie observes, station de Saria.

Duree	<5j	10j	15j	20j	25j	30j	35j	40j	45j	50j
1944	29	1	0	0	0	0	0	0	0	0
1945	26	3	0	0	0	0	0	0	0	0
1946	27	3	0	0	0	0	0	0	0	0
1947	26	3	1	0	0	0	0	0	0	0
1948	32	2	0	0	0	0	0	0	0	0
1949	27	1	0	1	0	0	0	0	0	0
1950	30	1	0	0	0	0	0	0	0	0
1951	27	1	1	0	0	0	0	0	0	0
1952	28	2	0	0	0	0	0	0	0	0
1953	26	1	2	0	0	0	0	0	0	0
1954	22	4	0	0	0	0	0	0	0	0
1955	29	1	0	0	0	0	0	0	0	0
1956	30	1	0	0	0	0	0	0	0	0
1957	26	5	0	0	0	0	0	0	0	0
1958	27	0	0	0	0	0	0	0	0	0
1959	19	2	0	0	0	0	0	0	0	0
1960	27	3	0	0	0	0	0	0	0	0
1961	24	2	0	0	0	0	0	0	0	0
1962	30	2	0	0	0	0	0	0	0	0
1963	26	2	0	0	0	0	0	0	0	0
1964	29	0	0	1	0	0	0	0	0	0
1965	31	2	0	0	0	0	0	0	0	0
1966	29	0	1	0	0	0	0	0	0	0
1967	27	1	0	1	0	0	0	0	0	0
1968	34	0	0	0	0	0	0	0	0	0
1969	31	1	0	0	0	0	0	0	0	0
1970	31	1	1	0	0	0	0	0	0	0
1971	29	0	1	0	0	0	0	0	0	0
1972	28	2	0	0	0	0	0	0	0	0
1973	24	4	0	0	0	0	0	0	0	0
1974	29	0	0	0	0	0	0	0	0	0
1975	25	1	0	0	1	0	0	0	0	0
1976	27	1	1	0	0	0	0	0	0	0
1977	25	2	0	0	0	0	0	0	0	0
1978	33	0	0	0	0	0	0	0	0	0
1979	28	2	0	0	0	0	0	0	0	0
1980	17	4	1	0	0	0	0	0	0	0
1981	29	1	1	0	0	0	0	0	0	0
Periode	27.5	1.6	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0

Periode: 15 juin - 15 octobre
Nombre d'annees: 38

Le sol sur lequel est effectue l'experimentation est de type ferrugineux tropical (JENNY, 1966), presentant une carapace induree limitant l'enracinement de la culture entre 0.70 m et I m de profondeur.

L'horizon superficiel (0-10 cm) est caracterise par une permeabilite elevee (Tab. 2), correspondant a une importance des sables fins et limons grossiers. L'horizon sous-jacent (20-40 cm) est nettement plus argileux.

La pente moyenne de l'ordre de 0,7% rend ces sols sensibles au ruissellement (Tab. 3).

Dans le cadre du traitement analyse, le ruissellement est pratiquement annule grace aux techniques cuiturales appliquees: culture attelee en traction bovine.

Tableau 2. Caracterisation pedologique parcelle "entretien de la fertilite".

Analyse Horizon	Argile	Limons fins	Limons grossiers	Sables fins	Sables grossiers
0-20 cm	9	5	22	33	31%
20-40 cm	28	5	19	24	21%
Densite apparente:					
Horizon cm :	2-12	15-25	30-40	50-60	90-100
Densite apparente	1.91	1.76	1.69	2.39	2.14

Tableau 3. Estimation d'un coefficient moyen de ruissellement.

		1977			1978		
		P	R	R/P%	p	R	R/P%
Avril	1	0.0	0.0		25.0	5.2	21
	2	0.0	0.0		3.0	0.0	0
	3	29.0	7.8	27	21.5	0.0	0
Mai	1	1.4	0.0	0	23.2	2.7	12
	2	10.2	1.6	16	18.0	3.5	19
	3	15.1	3.6	24	33.5	7.1	21
Juin	1	27.8	6.4	24	17.8	1.6	9
	2	31.0	49	16	24.7	0.0	0
	3	74.3	28.1	30	42.4	8.4	20
Juil.	1	4.4	0.0	0	35.8	14.3	40
	2	26.9	1.1	4	72.7	31.7	44
	3	29.8	3.9	13	129.5	72.2	56
Aout	1	75.1	8.9	11	44.7	16.3	36
	2	133.1	41.5	31	84.0	15.4	18
	3	132.3	41.8	32	125.4	65.8	52
Sept.	1	56.5	13.3	23	61.5	18.8	31
	2	12.0	-	-	70.5	362	51
	3	33.3	-	-	51.7	0.0	0
Oct.	1	11.5	-	-	20.0	0.0	0
	2	5.0	0.0	0	77.5	38.9	50
	3	0.0	0.0	0	0.0	0.0	0
Nov.	1	0.0	0.0	0	1.5	0.0	0
	2	0.0	0.0	0	0.0	0.0	0

P = Pluviometrie
R = Ruissellement
Sol travaille manuellement
Culture de sorgho, Absence de mulch.

La reserve utilisable du sol est estimee a 70 mm, compte tenu d'une limitation de l'enracinement par la cuirasse et de l'evaluation de la capacite de retention (Tab. 4) mesuree par la methode ponderale (ROOSE-ARRIVETS, POULAIN, 1974). La vitesse d'infiltration (Methode de MUNTZ) diminue avec l'apparition de la fraction argileuse (10-20 cm).

Tableau 4. Vitesse d'infiltration en mm/h

Vitesse d'infiltration en mm/h	6H	24 H	48 H	3J	4J	5J
0-10 cm	10.8	13.7	18.7	24.1	24.1	32
10-20 cm	7.2	2.9 a 9.4	4.3 a 10.1	16.2 a 14.0	14.6 a 14.4	14.4

Permeabilite Muntz en mm/h			
Tranche de sol	0-30 cm	0-60 cm	0-1 m
Capacite de retention	30 mm	60 mm	120 mm

Elements du protocole experimental

L'essai "entretien de la fertilite" concerne trois traitements secondaires caracterisant trois rotations, associes (Fig. 2) a six traitements principaux representant les modes de fertilisation (Tab. 5).

Moyens et methodes

Un module de simulation des termes du bilan hydrique et la methode de regression lineaire multiple sont utilises pour analyser et expliquer la fluctuation de la monoculture de sorgho grain entre les annees 1962 et 1981.

Le modele de bilan hydrique

Le modele de bilan hydrique (FOREST, 1981) consiste a simuler le taux de satisfaction des besoins en eau de la culture au cours de son cycle vegetatif a partir de la prise en consideration de 4 groupes de parametres.

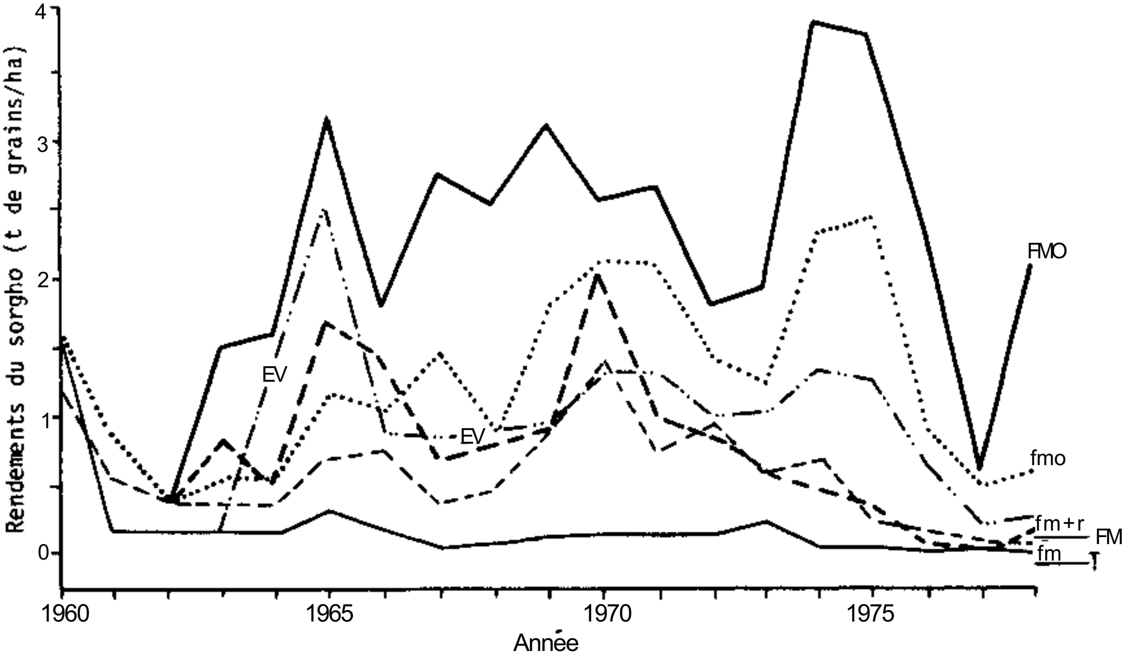

Figure 2. Essai entretien de la fertilite-Saria.

1. Les données météorologiques

Sous la forme d'un fichier de pluviométrie journalière observée à proximité de la parcelle accompagné d'un vecteur "demande évaporative" constitué des 36 valeurs décadaires de l'évaporation du bac classe A (EVA). En l'absence de ces données EVA, des valeurs calculées de l'ETP PENMAN (ETPc) sont utilisables.

2. Les données pédologiques

Caractéristiques de la parcelle et des techniques culturales comprenant :

- l'estimation d'un coefficient de ruissellement pris en compte par le modèle à partir d'une pluviométrie seuil correspondant au déclenchement du ruissellement si des données expérimentales le permettent.
- l'évaluation de la réserve utile RU* pour la culture obtenue en considérant la profondeur de sol favorable à l'enracinement de la plante et la quantité d'eau extractible par la plante (entre la capacité au champ et l'humidité au point de flétrissement).

3. Les données agrophysiologiques

Elles indiquent le potentiel de consommation en eau ETM de la plante au cours de sa période de vie. Un fichier comprenant la série des valeurs de K = ETM/EVA constitue la base plante du modèle (DANCETTE, 1981) celle-ci est complétée par la définition de cycle de végétation en cinq tranches de vie représentatives de l'évolution physiologique de la plante. (Fig.3).

4. La situation agroclimatologique de la culture

Il s'agit de préciser les conditions d'implantation de la culture en rapport avec le régime d'installation des pluies :

- définition d'une pluviométrie seuil "au plus tôt" autorisant le semis et la levée générale de la culture.
- évaluation d'un "délai" exprimant le décalage (technique ou accidentel entre l'événement "pluie de semis au plus tôt" et le semis effectif.

Dans le cas de l'essai analysé, les dates de semis ont été prises en considération sans tenir compte de la distribution des pluies (modèle STATION différent du modèle PAYSAN).

Méthode d'estimation de l'évapotranspiration réelle ETR

L'expression du bilan hydrique dans tous ses termes calculée pour une période (i) :

$$P(i) = RUISS(i) + DR(i) + ETR\ (i) + \Delta S \qquad (1)$$

appliquée à la situation agricole considérée, comprend les étapes de calcul suivantes :

.Le ruissellement RUISS n'est pas évalué. Le terme DR ou drainage indique un excès d'eau non utilisé par la plante au cours de la période (i).

Si le cumul de la pluviométrie P(i) et de la réserve RS(i − 1) est supérieure à la valeur de la réserve utilisable RU, l'expression suivante est calculée :

$$DR\ (i) = P(i) + RS(i-l) - RU \qquad (2)$$

Tableau 5. Description de l'essai.

L'essai realise par l'IRAT depuis 1962 comprend 6 traitements principaux appliques a trois situations agricoles distinctes :

Monoculture de sorgho
Altemance sorgho - cotonnier
Alternance sorgho - legumineuse
(arachide ou niebe)

TRAITEMENT[1]

T	Temoin sans engrais
fmr	fumure minerale faible + recyclage des residus de recolte tous les 2 ans
fm	fumure minerale faible seule
FM	fumure minerale forte seule
fmo	fumure minerale faible + 5 tonnes de fumier tous les 2 ans
FMO	fumure minerale forte + 40 tonnes de fumier tous les 2 ans

[1] La surface de cheque traitement est de 85 m^2; les lignes sont de 20 m avec l'ecartement entre les lignes de 0.8 m.

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*La reserve utile, c'est, pour un sol d'une profondeur donnee, la capacite de stockage en eau accessible a la plante.

RU mm = (Hc - Hf) x DA x Z

(Hc - Hf) = humidite utile du sol ou pourcentage maximum d'eau du sol accessible a la plante Cela correspond a la tranche d'humidite comprise entre la capacite de retention et le point de fletrissement permettant.

DA = densite apparente du sol qui permet de passer des humidites massiques aux humidites volumiques,

Z = profondeur du sol exploitable par les racines.

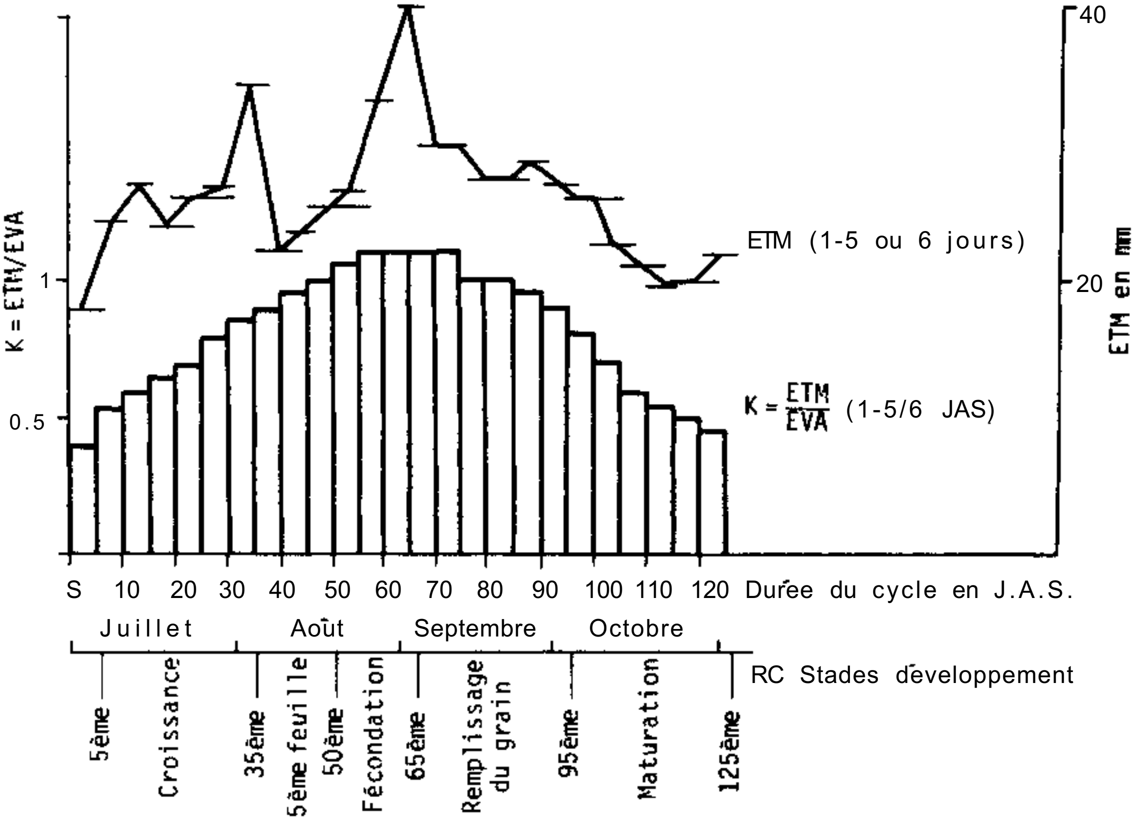

Figure 3. Les besoins en eau du sorgho (125 jours) en relation avec la demande evaporative EVA et les coefficients culturaux K=ETM/EVA. Saria, Haute-Volta.

Dans ce cas l'eau extractible EX (i) = RU
Dans la situation inverse, le drainage prend la valeur nulle et:

$$EX(i) = P(i) + RS(i-l) \qquad (3)$$

Le mode de calcul de ETR consiste en un algorithme adapte des travaux d'EAGLEMANN (1971) et necessite de connaitre les besoins en eau de la plante ETM et une expression de l'humidite du sol extractible par les racines HR (Tab. 6) (J. CHAROY, F. FOREST, J. C. LEGOUPIL, 1978).

Le calcul de HR est realise a partir d'une reiteration simple associant la valeur de HR a la proportion du systeme racinaire jugee apte a extraire l'eau du sol. L'hypothese de base consiste a admettre que la descente du systeme racinaire, en ('absence de contraintes externes, s'ajuste sur la descente du front d'humectation. (P. FRANQUIN, F. FOREST 1977).

L'humectation integre les termes P(i) et le stock d'eau residuel RS (i - 1) exprimes en mm d'eau extractible :

$$HR(i) = \frac{EX(i)}{\text{Valeur maxima } (P_{(k)} + RS\ (k-1))}$$

$$\text{avec } K \leqslant i$$

$$0 \leqslant HR \leqslant 1 \qquad (4)$$

Tableau 6. Mode de calcul de ETR journalier

$ETR = 0{,}732 - 0{,}05\ ETM$ $+ (4{,}97\ ETM - 0{,}661\ ETM^2)\ HR$ $- (8{,}57\ ETM - 1{,}56\ ETM^2)\ HR^2$ $+ (4{,}35\ ETM - 0{,}88\ ETM^2)\ HR^3$	Calcul journalier de ETR par sous-programme EAGLEMANN.

La limite superieure du denominateur equivaut a la valeur de la reserve utilisable RU. Une fois que celle-ci est atteinte le mode de calcul de HR s'ecrit:

$$HR(1) = \frac{EX(1)}{RU} = \frac{EX(1)}{70} \qquad (5)$$

Connaissant HR et ETM, l'expression ETR est calculee ainsi qu'un ensemble d'indice permettant l'interpretation agroclimatologique de l'essai (Tab. 7) en particulier.

ETR/ETM : Taux de satisfaction des besoins en eau
DR : Exces d'eau cumulant ruissellement et drainage
DR/RU : Indice d'exces hydrique:

Resultats et discussion

La fluctuation du rendement (Fig. 2)

L'analyse de la distribution des valeurs observees des rendements agricoles exprimes en quintaux de grain/ha met en evidence un ajustement correct a une droite de HENRY (Fig.4). L'ecart type, tres important, souligne le caractere instable de la production du sorgho grain, cultive d'une maniere intensive. Le risque climatique ainsi illustre, revet un caractere preoccupant du point de vue de la faisabilite agroeconomique des systemes de culture modernises.

Les resultats du bilan hydrique

La periode de croissance et de developpement

Tableau 7. Resultat de la simulation du bilan hydrique-monoculture de sorgho. Saria, Haute-Volta (1962-1982).

Termes Explicatifs		$\frac{ETR}{ETM}$	$\frac{DR}{RU}$	$\frac{ETR}{ETM}$	Production	Observation
Annee	Dates semis	1-50 JAS	1-30 JAS	5/9-15/10	Quintaux ('00kg)/ha	
1974	27/06	88%	0%	86%	38.5	
1975	27/06	81	48	80	37.2	
1965	27/06	85	6	87	32.5	
1969	23/06	79	59	85	30.6	
1967	23/06	84	0	57	27.5	
1981	03/07	85	29	43	26.4	
1971	03/07	82	88	60	26.3	
1980	03/07	89	63	59	26.0	
1970	23/06	80	87	75	25.3	
1968	03/06	67	0	97	25.0	
1979	27/06	64	0	97	23.0	
1976	18/06	85	0	81	23.0	
1978	27/06	92	18	91	23.0	
1973	23/06	87	206	45	19.5	
1972	13/06	71	0	81	18.1	
1966	08/07	63	0	70	18.0	
1964	23/05	71	0	66	15.5	
1963	23/06	90	4	76	14.8	+
1977	03/07	64	0	63	5.9	
1962	03/07	54	0	91	3.0	

*Exces pluviometrie a la recolte (15-31 octobre)
+Onze jours de pluie du 18 au 29 aout, periode correspondant a la pollinisation.

JAS = jours Apres Semis.

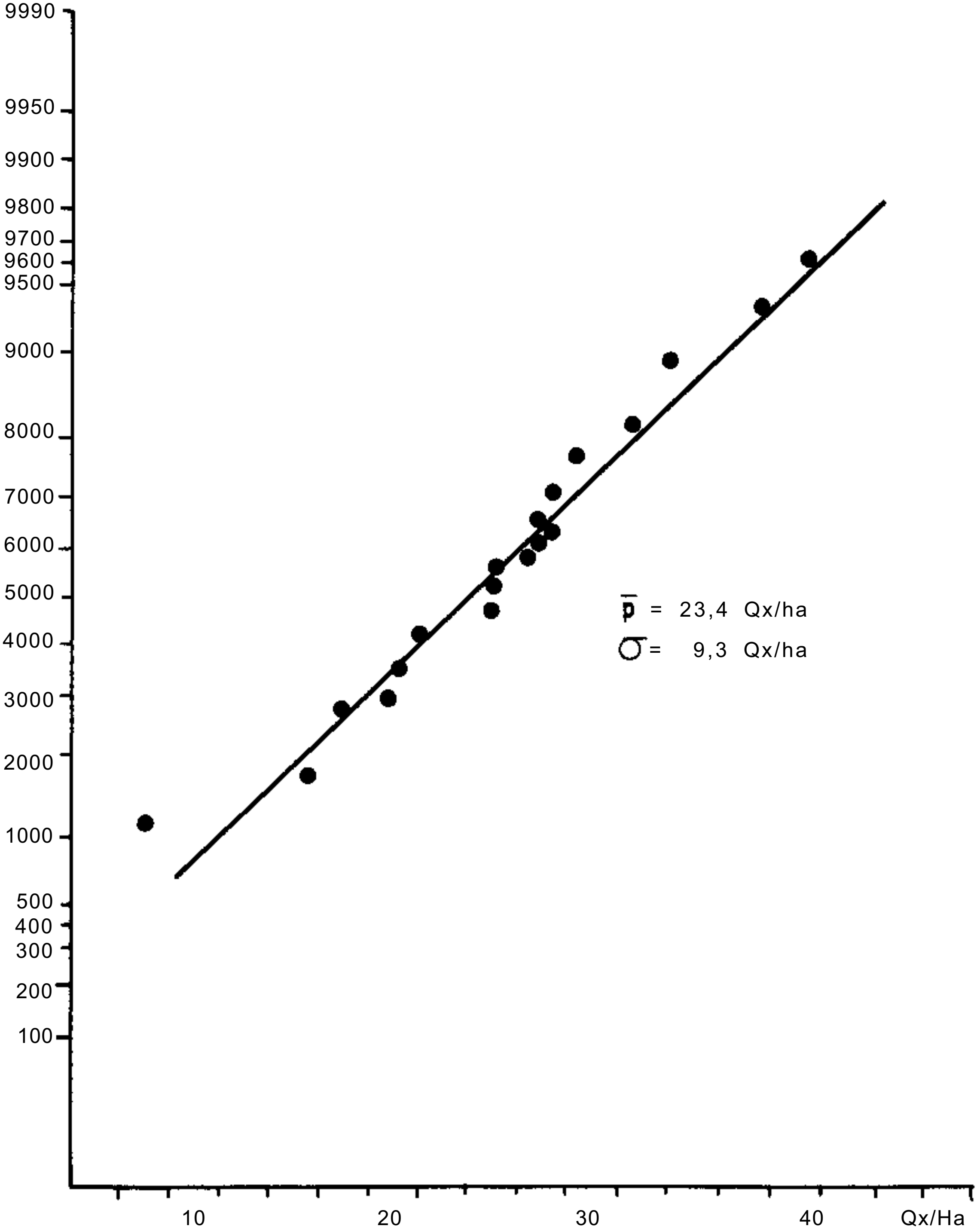

Figure 4. Ajustement de la production a une droite de Henry.

de la culture est décomposée en 4 tranches de vie correspondant à l'évolution physiologique de la plante.

1 – 30 JAS	Période de levée jusqu'à la couverture total du champ.
31 – 50 JAS	Stade 5 feuilles-sortie de la dernière feuille (maximum de couverture foliaire).
51 JAS – 4 SEPT	floraison, pollinisation, fécondation
5 SEPT - 5 OCT	Période de remplissage du grain, arrivant à date fixe compte tenu du caractère photosensible des variétés.

A l'exception de l'année 1963, les conditions d'alimentation hydrique ne sont pas limitantes lors de la phase de floraison-fécondation. Au regard de ce constat, les termes du bilan hydrique significativement explicatifs de la production ont été réduits à trois.

Influence de l'excès d'eau sur la production

En présence d'un excédent pluviométrique en début de cycle (1–30 JAS).

Le rendement (Tab. 7) est sensiblement affecté (1973, 1971, 1970) L'hypothèse d'un effet "lessivage" mériterait d'être approfondie, avec des conséquences sur l'alimentation de la plante en éléments fertilisants. On notera que la production obtenue sur FMO en 1973 (Fig. 2) pour un indice DR/RU = 206% est inférieure au rendement maximum réalisé en 1975 sur fmo (DR/RU (75) = 48%).

En conséquence, l'effet de l'excès hydrique en début de cycle sera de réduire l'efficacité de la fumure organominérale forte.

On notera qu'en 1976 et 1978, les rendements en grain ont été considérablement réduits par l'arrivée de pluies importantes au moment de la récolte.

Influence du déficit hydrique sur la production

- Le taux de satisfaction des besoins en eau au cours des cinquante premiers jours du cycle influence directement le rendement. Le seuil de 80% apparaît nécessaire pour espérer une production supérieure à 30 quintaux/ha.

  Inversement, le seuil 65% semble constituer une condition suffisante pour limiter les rendements à 23 quintaux/ha.

Une analyse détaillée des pluies journalières montre que la sensibilité au déficit hydrique apparaît plus importante entre les 30ème et 50 ème jours du cycle, période correspondant à la sortie de la dernière feuille (point de différenciation de la croissance GPD).

- L'alimentation hydrique entre le 5 septembre et le 5 octobre joue un rôle différent selon la qualité de la satisfaction des besoins en eau en début de cycle. Si celle-ci a été élevée (1967, 1980, 1981) la culture tolère un taux de satisfaction faible (40 à 60%). Si les conditions sont déficitaires (1966, 1964, 1977, 1962) le rendement est directement affecté par l'intensité du déficit hydrique au cours de la phase de formation du grain.

Identification d'une courbe de réponse à l'eau

Malgré le caractère plurivariable du déterminisme du rendement du sorgho, il est possible d'approcher la relation production—bilan hydrique en considérant le taux de satisfaction des besoins en eau au cours des cinquante premiers jours (Fig. 5).

La réponse à l'eau de type cubique mise en évidence correspond aux années où aucun accident climatique n'est survenu en cours de végétation (1974, 79, 62 etc. . .).

La sensibilité exprimée par le rapport

$$S = \frac{\Delta \text{ Production}}{\Delta \text{ ETR}}$$

est estimée à 4.0. Cette valeur rejoint les résultats (S = 4.5) obtenus par ailleurs (S. J. MAAS, G. F. ARKIN, 1980). L'effet du déficit hydrique au cours de la phase de remplissage du grain (67, 81, 64 etc. . .) apparaît nettement pour les années où l'espérance de production était élevée (1980–1981).

Les résultats pour les années 1963, 1976, 1978 ne sont pas à retenir dans l'analyse de la réponse à l'eau dans la mesure où des événements exceptionnels de nature physique (pourrissement du pollen ou des grains) sont intervenus pour modifier le rendement final.

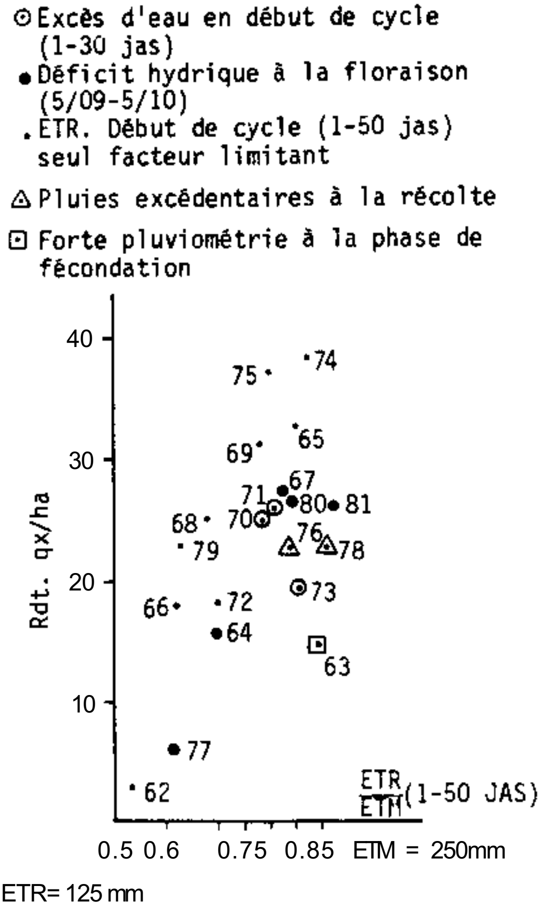

Figure 5. Alimentation hydrique (1-50 JAS) et rendement du sorgho, monoculture fertilisee. Saria, Haute-Volta.

Application Pratique

La simulation du rendement par la modelisation du bilan hydrique

Une explication "pedopluviometrique" du rendement est proposee (Tab. 8) en integrant dans une regression multilineaire les trois termes du bilan hydrique explicatifs associes a la production de sorgho grain obtenue pour 17 annees jugees homogenes du point de vue agroclimatologique.

La formule ci-dessous explicite les termes de la fonction de production ainsi definie :
avec :

$$PRO(kg) = -6999 + 95.3\ EE1 - 2.5\ DR1 + 29.7\ EE2 \quad (6)$$

PRO : Production.
EEI : rapport ETR/ETM en % au cours des cinquante permiers jours après le semis.
DR1 : Indice d'excès d'eau (DR/RU) au cours des trente premiers jours après semis.
EE2 : Rapport ETR/ETM en % du 5 septembre au 5 octobre.

La matrice de corrélations indique bien le caractère déterminant (EE1) de l'alimentation hydrique au cours des cinquante premiers jours.

L'excès d'eau (DR1 = DR/RU) au cours du premier mois a parallèlement un effet significatif, indépendant de la satisfaction des besoins en eau (R = 0.49).

L'alimentation hydrique à la phase de remplissage EE2, considérée séparément à un effet relativement faible. Il a été démontré par ailleurs que son effet était proportionnel à la valeur de EE1. Pour des raisons climatologiques, il apparaît une corrélation négative entre EE2 et EE1. Cette observation souligne encore une fois l'acuité du risque climatique dans la région considérée.

La prévision de production constitue un résultat pratique de la modélisation (Fig.6).

La valeur du coefficient d'explication R^2 pour la 3ème régression intégrant les 3 termes est élevée R^2 : 0,83. Si l'on considère la simplicité des données introduites, la validité du modèle peut être confirmée par le calcul de l'écart quadratique

$$EQ = \frac{\text{Moyenne } \Sigma (x-y)^2}{\text{Moyenne } \Sigma\ y} \quad (7)$$

x = rendement observé au champ
y = rendement simulé

Pour le cas de la monoculture de sorgho fortement fertilisée, la valeur calculée de EQ est de 8,5%. On notera qu'une valeur de 10,7% est obtenue pour la simulation du rendement du riz pluvial en région centre de Côte d'Ivoire (F. FOREST, J. M. KALMS, 1982).

Conclusion

Dans l'essai de longue durée de Saria, la culture continue de sorgho grain est soumise à des conditions d'alimentation hydrique très fluctuantes qui réduisent fréquemment les gains de production espérés de la maîtrise des techniques culturales et de l'apport régulier d'une fumure organominérale forte.

Tableau 8. Explication du rendement.

Estimateurs: PRO : Production en quintaux
EE1 : ETR/ETM au cours des cinquante premiers jours apres semis.
DR1 : Indice d'exces d'eau au cours des trente premiers jours apres semis.
EE2: ETR/ETM du 5 septembre au 5 octobre.

Estimateurs			Matrice de correlation				
Variable	Moyenne	Ecart-type		PRO	EE1	DR1	EE2
PRO	23429	9.25989	PRO	1.00000			
EE1	76.118	10.34057	EE1	0.74625	1.00000		
DR1	34.471	53.23656	DR1	0.11843	0.49411	1.00000	
EE2	73.059	16.38676	EE2	0.09911	-0.46904	-0.49874	1.00000

1 ere regression

Coefficients de regression

R^2 = 0.56689
PRO = -27.437040
+ 0.66876 EE1 Coeff. normalise = 0.74625

Variable	Corr. mult.	Corr. part.
DR1	0.24414	-0.43250
EE2	0.22000	0.76396

2 eme regression

Coefficients de regression

R^2 = 0.81550
PRO = -69.617882
+ 0.91011 EE1 Coeff. normalise = 1.01632
+ 0.32538 EE2 Coeff. normalise = 0.57581

Variable	Corr. mult.	Corr. part.
DR1	0.33553	-0.27580

3 eme regression

Coefficients de regression

R^2 = 0.82954
PRO = -69.997145
+ 0.95352 EE1 Coeff. normalise = 1.06480
-0.02528 DR1 Coeff. normalise = -0.14533
+ 0.29727 EE2 Coeff. normalise = 0.52606

PREVISION DE PRODUCTION ('00 kg/ha)

Individus	Valeur	Explication	Erreur	Individus	Valeur	Explication	Erreur
A74	38.5000	39.4779	-0.9779	A68	25.0000	22.2239	2.2761
A75	37.2000	29.8062	7.3938	A79	23.0000	19.8633	3.1357
A65	32.5000	36.7629	-4.2629	A73	19.5000	21.1289	-1.6289
A69	30.6000	29.1075	1.4925	A72	18.1000	21.7817	-3,6817
A67	27.5000	27.0430	0.4570	A66	18.0000	10.8835	7.1165
A80	26.4000	23.1016	3.2984	A64	15.5000	17.3226	-1.8226
A71	26.3000	23.8032	2.4968	A77	5.9000	9.7562	-3.8562
A81	26.0000	30.8126	-.4.8126	A62	3.0000	8.5445	-5.5445
A70	25.3000	26.3805	-1.0805				

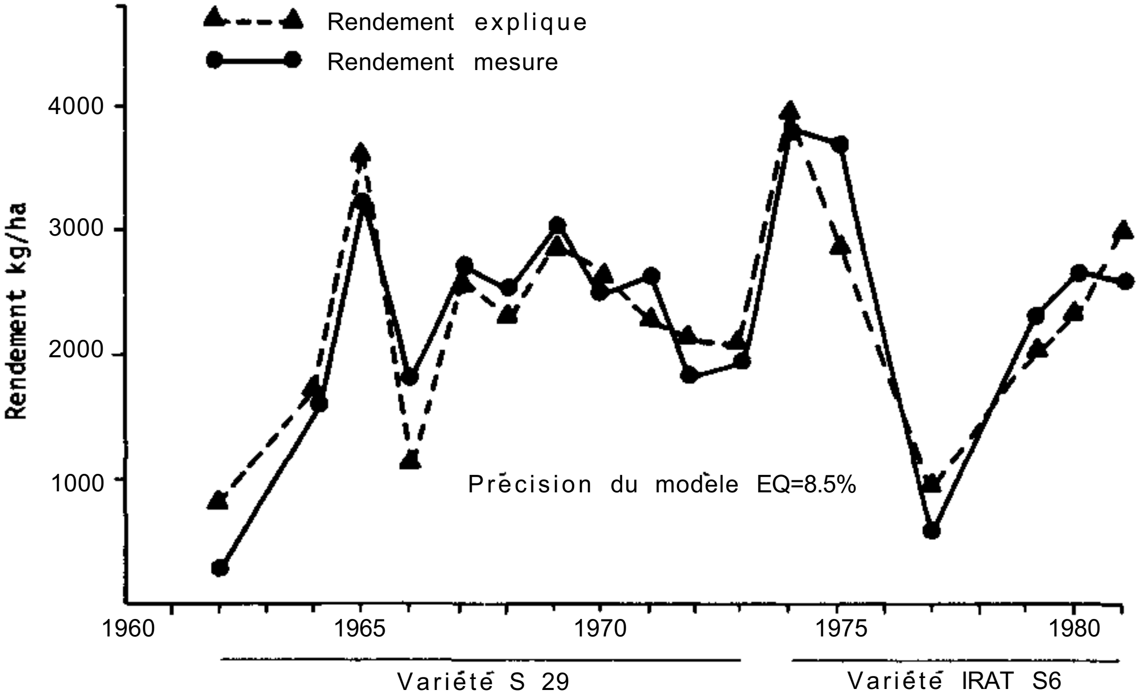

Figure 6. Explication du rendement en grains d'une monoculture de sorgho par modelisation du bilan hydrique. Saria, Haute-Volta, 1962-1981.

En debut de cycle

- L'exces d'eau diminue sensiblement l'esperance de production. Le resultat peut etre du a un lessivage des elements mineraux et a une probable reduction de l'ensoleillement.
- Le deficit hydrique, joue un role preponderant sur l'esperance de rendement. Ce resultat confirme le role de l'eau sur le developpement vegetatif des plantes.

En milieu de cycle

Dans les conditions pluviométriques de Saria, le risque de déficit hydrique est exceptionnel. C'est plutôt un excès d'eau au cours de la phase de pollinisation qui est à redouter.

Au remplissage du grain

Le déficit hydrique assez fréquent à Saria a un effet dépressif sur l'espérance de production. La baisse de rendement est d'autant plus sensible que la culture s'est développée préalablement dans de bonnes conditions d'alimentation hydrique.

Cette observation est a rapprocher des problemes d'echaudage constates sur les cereales.

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Influence of the Rainfall Pattern on Fluctuations in an Intensified Sorghum Crop Yield

F. Forest and B. Lidon*

Abstract

The influence of rainfall on grain yield fluctuation was analyzed through a water-balance model, based on yield observations over several years (1962-81) of a highly fertilized sorghum sole crop in Upper Volta (Saria Station).

Using data on evaporative demand, daily rainfall, available water capacity, and crop water requirements during the growing cycle, the level at which water requirements are met (actual evapotranspiration/maximum evapotranspiration orAET/MET) and a moisture excess index were calculated for successive periods, from crop emergence to harvest.

Fluctuations in grain sorghum experimental yields are mainly due to three factors of the water balance at three stages of the vegetative cycle.

1. *Excess water (runoff and/or drainage) during the first month is a yield-limiting factor. The cultural practices—plowing plus heavy organic and mineral fertilization—used in tnis trial probably resulted in considerable drainage, which in turn, caused leaching of minerals (reduced activity of the root system).*
2. *The level at which water requirements are met during the first 50 days after planting has a decisive influence on production estimates.*
3. *The level at which water requirements are met appears to play a determinant role during the grain-setting and -filling period, which generally occurs between 5 September and 5 October for the photosensitive sorghum varieties S29 and IRAT-56.*

It was observed that, 3 years out of 20, exceptionally high rainfall considerably affected yield, either by preventing pollination (long rainy spells in 1963) or by causing damage during maturation (heavy rain in late October in 1976-78).

Introduction

In the semi-arid tropics, rainfall is often a primary constraint to rainfed crop production.

In Central Upper Volta, sorghum is usually grown as a sole crop on soils with a poor water-holding capacity, where continuous water supply is not ensured to the crop during dry spells in the growing period.

Unfavorable changes in the soils which lead to reduced fertility, add to this pedoclimatic risk and the effect of these changes on yield was evaluated during a long-term fertility maintenance trial begun in 1960 at the Saria agricultural station (Pichot et al. 1981).

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Note: This paper was presented by Dr. P. Franquin in the authors absence. This is an edited translation of the original French paper immediately preceding.

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This paper attempts to understand yield fluctuations using data on available yields of a heavily fertilized grain sorghum sole crop and a water-balance model (Forest and Kalms 1982). The FMO (heavy mineral fertilization +40 tonnes manure every 2 years) treatment was selected in order to identify the water factor involved in producing grain sorghum yields.

Conditions of the Study

Location

Situated in central Upper Volta, the Saria agricultural station is representative of a region characterized by a Sudanese type climate. Average rainfall is 820 mm (Fig. 1), and the actual rainy season extends from 15 June to 15 October. Climatic risks are high due to rainfall variability (Table 1 a) combined with frequent occurrence of successive days without rain (Table 1 b).

The experiment was conducted on tropical ferruginous soils (Jenny 1966) with indurate crust, which confines the crop root system to a depth of 0.7 to 1 m.

The surface horizon (0-10 cm) made up of fine sands and coarse loams is characterized by high permeability (Table 2). The underlying horizon (20-40 cm) is more clayey.

A moderate slope of 0.7% (Table 3) increases runoff on this soil. But soil cultivation with ox-drawn implements stopped runoff occurrence in this experiment.

The available water-holding capacity was estimated at 70 mm since rooting is limited by the laterite crust; it is also based on the evaluation of the retention capacity (Table 4), measured by the

Table 1a. Frequency analysis of rainfall at the Saria station, Upper Volta.

1 January to 31 December		
		Rainfall (mm)
Maximum		1093.6
Pentad maximum	0.2	966.1
Median	0.5	812.5
Pentad minimum	0.8	711.2
Minimum		568.7
1 May to 31 October		
		Rainfall (mm)
Maximum		1063.6
Pentad maximum	0.2	914.2
Median	0.5	780.6
Pentad minimum	0.8	686.6
Minimum		549.4

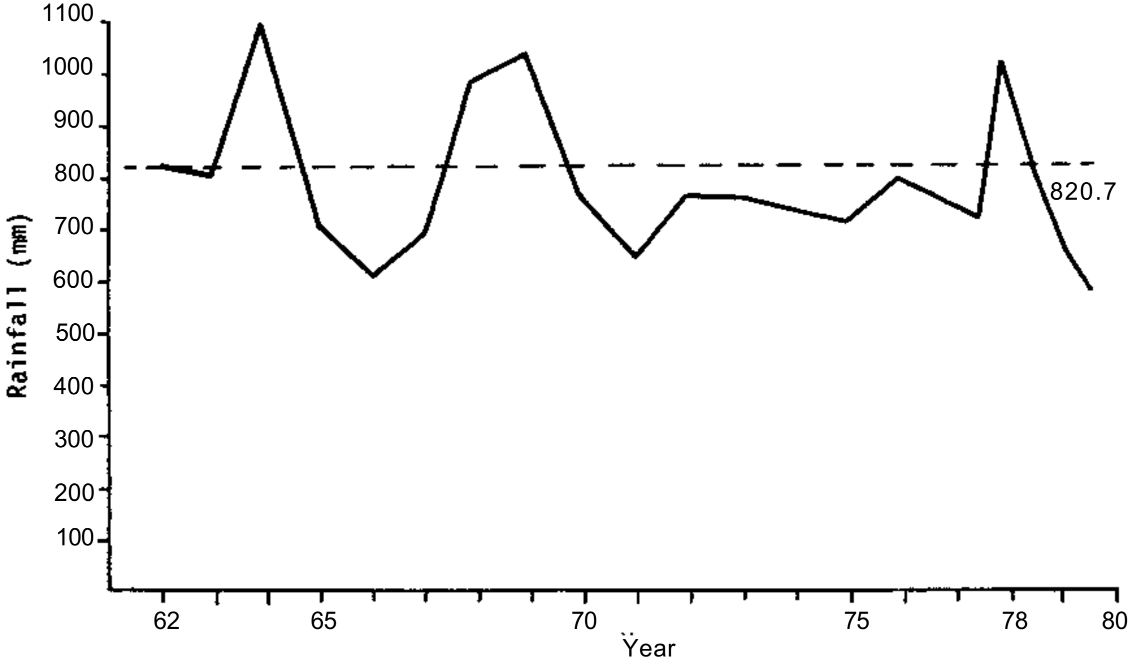

Figure 1. Interannual rainfall variability at the Saria station, Upper Volta.

Table 1b. Consecutive days without rain at the Saria station, Upper Voita.

Year	5 Days	10D	15D	20D	25D	30D	35D	40D	45D	50D
1944	29	1	0	0	0	0	0	0	0	0
1945	26	3	0	0	0	0	0	0	0	0
1946	27	3	0	0	0	0	0	0	0	0
1947	26	3	1	0	0	0	0	0	0	0
1948	32	2	0	0	0	0	0	0	0	0
1949	27	1	0	1	0	0	0	0	0	0
1950	30	1	0	0	0	0	0	0	0	0
1951	27	1	1	0	0	0	0	0	0	0
1952	28	2	0	0	0	0	0	0	0	0
1953	26	1	2	0	0	0	0	0	0	0
1954	22	4	0	0	0	0	0	0	0	0
1955	29	1	0	0	0	0	0	0	0	0
1956	30	1	0	0	0	0	0	0	0	0
1957	26	5	0	0	0	0	0	0	0	0
1958	27	0	0	0	0	0	0	0	0	0
1959	19	2	0	0	0	0	0	0	0	0
1960	27	3	0	0	0	0	0	0	0	0
1961	24	2	0	0	0	0	0	0	0	0
1962	30	2	0	0	0	0	0	0	0	0
1963	26	2	0	0	0	0	0	0	0	0
1964	29	0	0	1	0	0	0	0	0	0
1965	31	2	0	0	0	0	0	0	0	0
1966	29	0	1	0	0	0	0	0	0	0
1967	27	1	0	1	0	0	0	0	0	0
1968	34	0	0	0	0	0	0	0	0	0
1969	31	1	0	0	0	0	0	0	0	0
1970	31	1	1	0	0	0	0	0	0	0
1971	29	0	1	0	0	0	0	0	0	0
1972	28	2	0	0	0	0	0	0	0	0
1973	24	4	0	0	0	0	0	0	0	0
1974	29	0	0	0	0	0	0	0	0	0
1975	25	1	0	0	1	0	0	0	0	0
1976	27	1	1	0	0	0	0	0	0	0
1977	25	2	0	0	0	0	0	0	0	0
1978	33	0	0	0	0	0	0	0	0	0
1979	28	2	0	0	0	0	0	0	0	0
1980	17	4	1	0	0	0	0	0	0	0
1981	29	1	1	0	0	0	0	0	0	0
Period	27.5	1.6	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0

Period : 15 June-15 October
Number of years = 38

gravimetric method (Roose et al. 1974). The infiltration rate (Muntz's method) decreases with the appearance of the clay fraction (10-20 cm).

Experimental Design

The fertility maintenance trial included three secondary treatments representing three rotation systems combined with (Fig. 2) six main fertilizer treatments (Table 5).

Materials and Methods

A simulated model of the water balance terms and the multiple linear regression method were used to analyze and explain the fluctuations in grain sorghum sole-crop yields between 1962 and 1981.

The Water-balance Model

The water-balance model (Forest 1981) involves a simulation of the level at which water requirements are met during the growing period, based on four groups of parameters:

Table 2. Soil analysis of the fertility maintenance trial plot.

Horizon	Clay	Fine silt	Coarse loam	Fine sand	Coarse sand
0-20 cm	9	5	22	33	31%
20-40 cm	28	5	19	24	21%
Bulk density					
Horizon cm:	2-12	15-25	30-40	50-60	90-100
Bulk density	1.91	1.76	1.69	2.39	2.14

1. Meteorological data

This group is in the form of daily rainfall data observed near the plot, along with an "evaporative demand" vector made up of 36 10-day interval values of class-A pan evaporation (evaporative demand, or PE). In the absence of PE data, potential evapotranspiration (PET) calculated by Penman's method can be used.

2. Soil data

This group includes characteristics of the plot and cultivation techniques used:

- The runoff coefficient can be calculated by the model from the rainfall threshold value corresponding to the start of runoff.

Table 3. Estimation of the mean runoff coefficient. (Hand-cultivated soil; sorghum crop without mulch.)

		1977			1978		
		P	R	R/P(%)	p	R	R/P(%)
April	1	0.0	0.0		25.0	5.2	21
	2	0.0	0.0		3.0	0.0	0
	3	29.0	7.8	27	21.5	0.0	0
May	1	1.4	0.0	0	23.2	2.7	12
	2	10.2	1.6	16	18.0	3.5	19
	3	15.1	3.6	24	33.5	7.1	21
June	1	27.8	6.4	24	17.8	1.6	9
	2	31.0	4.9	16	24.7	0.0	0
	3	74.3	28.1	30	42.4	8.4	20
July	1	4.4	0.0	0	35.8	14.3	40
	2	26.9	1.1	4	72.7	31.7	44
	3	29.8	3.9	13	129.5	72.2	56
Aug	1	75.1	8.9	11	44.7	16.3	36
	2	133.1	41.5	31	84.0	15.4	18
	3	132.3	41.8	32	125.4	65.8	52
Sept	1	56.5	13.3	23	61.5	18.8	31
	2	12.0	-	-	70.5	36.2	51
	3	33.3	-	-	51.7	0.0	0
Oct	1	11.5	-	-	20.0	0.0	0
	2	5.0	0.0	0	77.5	38.9	50
	3	0.0	0.0	0	0.0	0.0	0
Nov	1	0.0	0.0	0	1.5	0.0	0
	2	0.0	0.0	0	0.0	0.0	0

P = Precipitation (mm); R = runoff (mm).

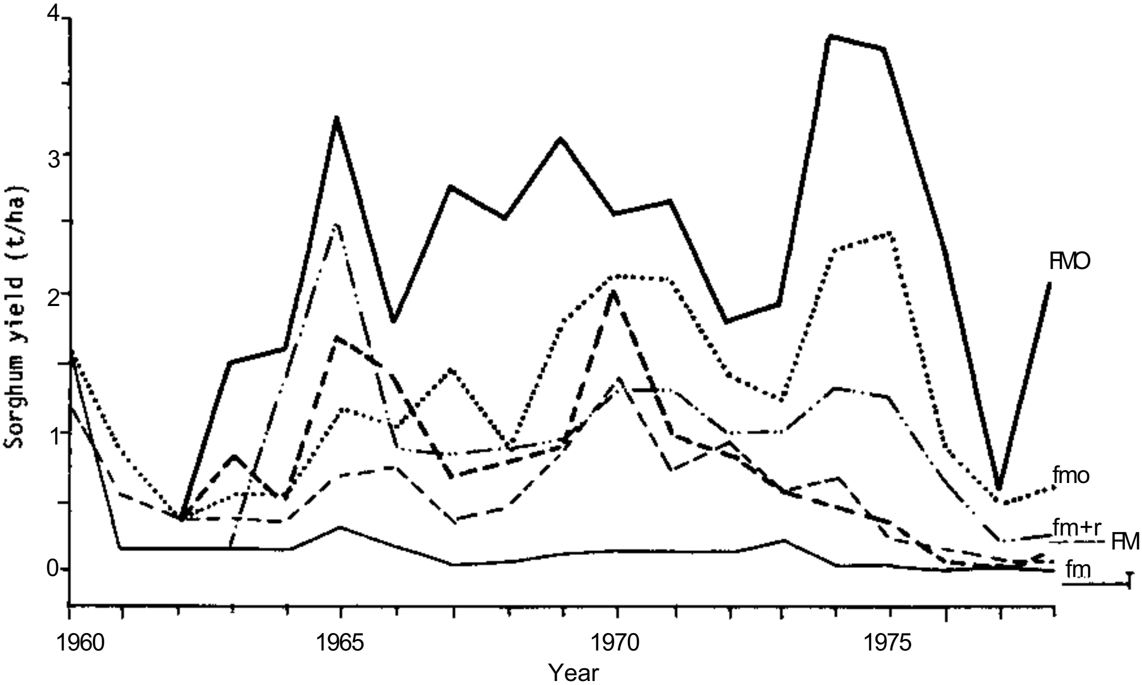

Figure 2. Sorghum grain yields (t/ha) for different fertilizer treatments in the fertility maintenance trial at Saria station, Upper Volta.

- The available water holding capacity (AWC)[1] estimate is based on soil depth favorable to root development and the quantity of water available to the plant between field capacity and wilting point.

3. Agrophysiological data

These indicate the potential plant water consumption or maximum evapotranspiration (MET) during its life cycle. A series of K = MET/PE values represents the plant variable of the model (Dancette 1981).

This is supplemented by the division of the vegetative cycle into five phases of the physiological evolution of the plant (Fig. 3).

Table 4a. Infiltration rate (mm/h).

	6h	24 h	48 h	3D	4D	5D
0-10 cm	10.8	13.7	18.7	24.1	24.1	32
10-20 cm	7.2	2.9 to 9.4	4.3 to 10.1	16.2 to 14.0	14.6 to 14.4	14.4

Table 4b. Soil permeability according to the Muntz method (mm/h) in the fertility maintenance trial.

Soil layer	0-30 cm	0-60 cm	0-1 m
Water-retention capacity	30 mm	60 mm	120 mm

4. Agroclimatic conditions

The conditions for crop establishment in relation to the onset of the rain should be defined through the

- determination of a threshold value for the "earliest" rainfall enabling crop sowing and emergence and

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[1] The available water-holding capacity (AWC) for a soil of given depth is its capacity to store water that is available to the plant.

AWC (in mm) = (Hc-Hf) x DA x Z where (Hc-Hf) = Effective soil moisture, which is the maximum percent of soil water available to the plant. This is the moisture held between field capacity and permanent witting point. DA = bulk density of the soil; Z = depth of the soil mm.

Table 5. Fertilizer trial carried out by IRAT since 1962, which includes six main treatments[1] for three different agricultural conditions.

Crop	Sorghum monoculture Sorghum-cotton rotation Sorghum-pulse (groundnut or cowpea) rotation
Fertilizer treatment	
T:	Nonfertilized check
fmr:	Light mineral fertilizer + recycling of crop residues every 2 years
fm:	Only light mineral fertilizer
FM:	Only heavy mineral fertilizer
fmo:	Light mineral fertilizer + 5 tonnes of manure every 2 years
FMO:	Heavy mineral fertilizer + 40 tonnes of manure every 2 years.

[1] Each treatment 85 m^2 in area; sorghum rows 20 m long, with 0.8 m between rows.

- evaluation of the interval (technical or accidental) between the "earliest rain for sowing" and actual sowing.

In this trial, sowing dates were considered, but not rainfall distribution (STATION model differs from the FARMER model).

Estimation of Actual Evapotranspiration (AET)

The water balance for a period (i) is

$$R(i) = \text{Runoff}\ (i)+DR(i)+AET(i)+\Delta S; \quad (1)$$

When applied to a given agricultural situation, runoff is not estimated. The drainage term (DR) indicates excess water not utilized by the plant during the period (i).

If the cumulative rainfall R(i) and the reserve RS(i-1) are greater than the available water-holding capacity (AWC) value, the following equation is obtained:

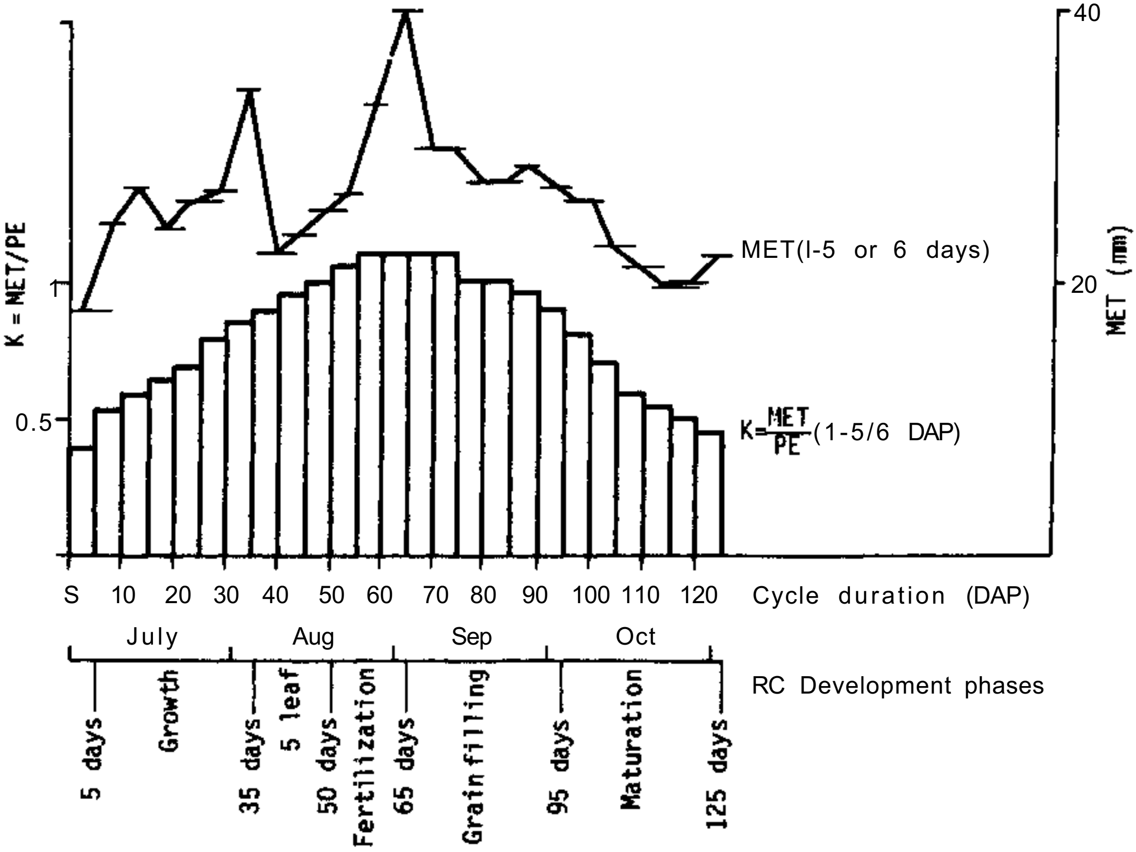

Figure 3. Water requirements of a 125-day sorghum variety in relation to evaporative demand (PE) and crop coefficients K = MET/PE at Saria, Upper Volta.

$$DR(i) = R(i) + RS(i-1) - AWC \qquad (2)$$

In this case, extractable soil water EX(i) = AWC. If this is not the case, drainage has no value and:

$$EX(i) = R(i) + RS(i-1) \qquad (3)$$

AET is calculated by using an algorithm based on Eaglemann's formula (1971); for this plant water demand (MET) and extractable soil water (HR) must be known (Table 6) (Charoy et al 1978).

HR is calculated from an iterative procedure whereby the value of HR corresponds to the proportion of the root system capable of extracting soil water. The fundamental hypothesis is that the depth of the root system in the absence of external constraints adjusts itself to the downward movement of the wetting front (Franquin and Forest 1977).

Wetting is expressed by the terms R(i) and the residual moisture reserve RS(i-1) expressed in mm of extractable water:

$$HR(i) = \frac{EX(i)}{\text{maximum value } (R_{(k)} + RS(K-1))} \qquad (4)$$

with $K \leqslant i$, $0 \leqslant HR \leqslant 1$

The maximum value of the denominator is equivalent to the AWC value. Once this is known, HR is calculated:

$$HR(1) = \frac{EX(1)}{AWC} = \frac{EX(1)}{70} \qquad (5)$$

Once HR and MET are known AET can be derived along with an index set which enables an agroclimatological interpretation of the trial (Table 7):

AET/MET: Level at which water requirements are met
DR: Excess water: runoff + drainage
DR/AWC: Excess water index

Results and Discussion

Yield Fluctuations

The analysis of the distribution of observed values of agricultural yields expressed in quintals (100 kg) of grain/ha shows a correct fit to the straight line of Henry (Fig. 4). The high standard deviation here emphasizes the unstable nature of an intensive grain sorghum crop. This climatic risk seriously compromises the agroeconomic feasibility of modern farming systems.

Table 6. Calculation of daily AET based on Eaglemann's formula.

$AET = 0{,}732 - 0{,}05\ MET$ $+ (4{,}97\ MET - 0{,}661\ MET^2)\ HR$ $-(8{,}57\ MET - 1{,}56\ MET^2)\ HR^2$ $+ (4{,}35\ MET - 0{,}88\ MET^2)\ HR^3$	Daily AET computation through Eaglemann's formula.

Water Balance Results

The crop growth and development period is divided into four phases corresponding to the physiological evolution of the plant.

1-30 days after planting (DAP)—emergence until total covering of the field

31 -50 DAP—emergence of the last leaf (maximum leaf cover)

51 DAP-4 Sept—flowering, pollination, and fertilization

5 Sept-5 Oct—grain-filling stage, occurring at a fixed date, since these are photosensitive varieties.

Except in 1963, water supply was not a limiting factor at the flowering-fertilization phase. Therefore, the water-balance terms explaining production were reduced to three.

Effect of Excess Water on Production

Yield (Table 7) was seriously affected (1973,1971, 1970), due to excess rainfall during the first 30 days of the crop. The hypothesis of a leaching effect should be further studied, especially its effect on fertilizer efficiency. Yields obtained with the FMO treatment in 1973 (Fig. 2) for DR/AWC =206% are lower than the maximum yield obtained in 1975 with the fmo treatment and DR/AWC = 48%. Consequently, excess water at the start of crop growth reduces the efficiency of heavy organic and mineral fertilization.

We can also see that in 1976 and 1978, grain yields decreased considerably due to heavy rainfall at harvest.

Effect of Moisture Deficit on Production

The level at which water requirements are met in the first 50 days of the crop has a direct influence

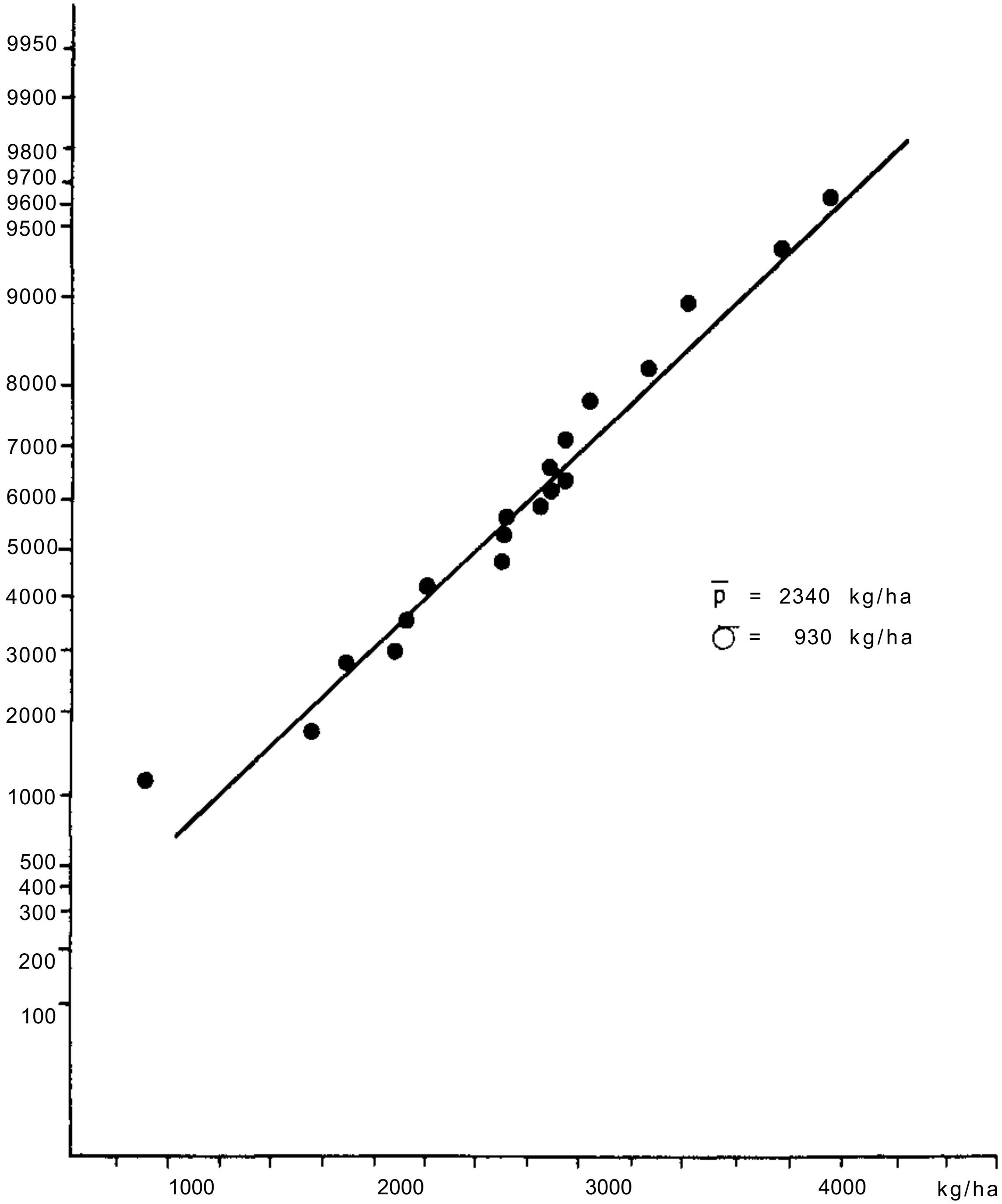

Figure 4. Fitting production to Henry's straight line.

on yield. Eighty percent appears to be a threshold value for an estimated yield of 3 tonnes/ha; 65% seems to limit yields to 2.3 tonnes/ha.

A detailed analysis of daily rainfall shows that crops are more susceptible to moisture deficits between 30 and 50 DAP, a period corresponding to

Table 7. Results of a simulated water balance of a sorghum monoculture in Saria, Upper Volta (1962-1981).

Explanatory terms		AET/MET	DR/AWC	AET/MET	Production	Observations
Year	Sowing dates	1-50 DAP	1-30 DAP	5/9-15/10	00 kg/ha	
1974	27/06	88%	0%	86%	*385*	
1975	27/06	81	48	80	37.2	
1965	27/06	85	6	87	32.5	
1969	23/06	79	59	85	30.6	
1967	23/06	84	0	57	27.5	
1981	03/07	85	29	43	26.4	
1971	03/07	82	88	60	26.3	
1980	03/07	89	63	59	26.0	
1970	23/06	80	87	75	25.3	
1968	03/06	67	0	97	25.0	
1979	27/06	64	0	97	23.0	
1976	18/06	85	0	81	23.0	
1978	27/06	92	18	91	23.0	
1973	23/06	87	206	45	19.5	
1972	13/06	71	0	81	18.1	
1966	08/07	63	0	70	18.0	
1964	23/05	71	0	66	15.5	
1963	23/06	90	4	76	14.8	+
1977	03/07	64	0	63	5.9	
1962	03/07	54	0	91	3.0	

* Excess rainfall during harvest (15-31 Oct)
+ 11 rainy days from 18 to 29 August, period corresponding to pollination.
DAP - Days after planting

the emergence of the last leaf (growth point differentiation, GPD).

Moisture supply between 5 September and 5 October plays a different role, depending upon the level at which water requirements are met at the beginning of the cycle. When this is high (1967, 1980, 1981), the crop tolerates a low satisfaction level (40-60%). In case of a deficit (1962, 1964, 1966, 1977) yields are affected directly according to the intensity of the moisture deficit during the grain-formation stage.

Identification of Water Response Curve

Although a large number of factors are involved in determining sorghum yield, it is possible to establish a production:water-balance ratio on the basis of the level at which water requirements are met in the first 50 days (Fig. 5). The cubic type water response occurs during years without climatic instability at the vegetative phase (1974, 1979, 1962, etc.). Susceptibility expressed by the ratio S = Δ Production/Δ AET is estimated at 4.0, which corresponds to the results (S=4.5) obtained elsewhere (Maas and Arkin 1980). The effect of a water deficit during the grain-filling stage (1967, 1981, 1964, etc.) is seen for the years when production estimates were high (1980-1981).

The results for the years 1963, 1976, and 1978 were not retained in the water-response analysis since the occurrence of exceptional physical events (pollen or grain rot) modified the final yield.

Practical Application

Yield Simulation by the Water-balance Model

A soil-rainfall explanation of yield is proposed (Table 8) by integrating, in a multilinear regression, the three agroclimatologically uniform water-balance terms related to grain sorghum production over 17 years.

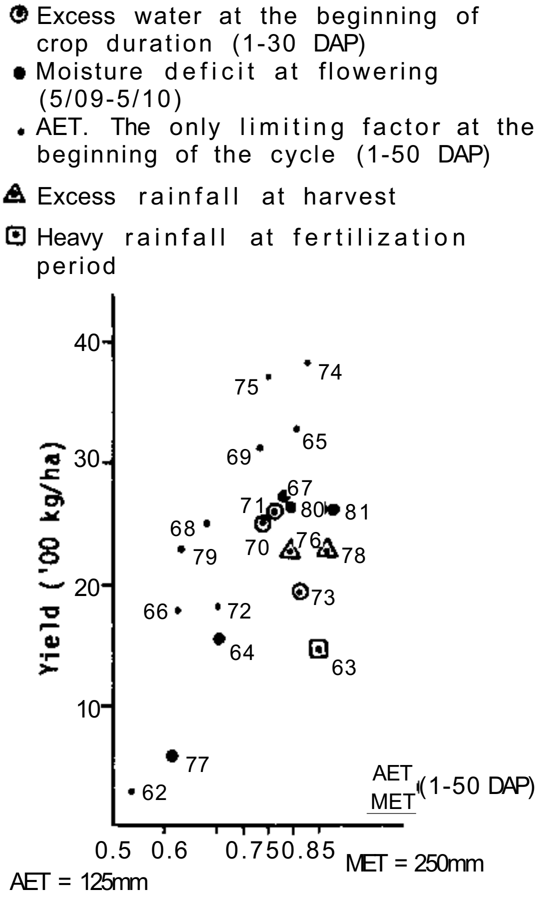

Figure 5. Water supply (1-50 DAP) and sorghum yield for a fertilized monoculture at Saria, Upper Volta.

The following formula explains the terms of the production function:

$$PRO(kg) = -6999 + 95.3\ EE1 - 2.5\ DR1 + 29.7\ EE2 \qquad (6)$$

where

PRO = grain production in kg

EE1 = AET/MET ratio in % for the first 50 days after planting (DAP)

DR1 = excess water index (DR/AWC) for the first 30 DAP

EE2 = AET/MET ratio in % from 5 September to 5 October.

The correlation matrix clearly indicates (EE1) that water supply is a determining factor during the first 50 days.

Excess water (DR1 = DR/AWC) during the first month also has a significant effect, regardless of the satisfaction of water requirements (R = 0.49).

Water supply during the grain-filling stage (EE2), considered separately, has a relatively weak effect, which is proportional to the EE1 value. There seems to be a negative correlation between EE1 and EE2 due to climatological reasons. This observation further emphasizes the high climatic risk in the region under study.

Production forecasting is a practical result of modeling (Fig. 6).

The value of coefficient of determination R^2 for the third regression of the three terms is high ($R^2 = 0.83$). Considering the simplicity of the input data, the model's validity can be confirmed by calculating the root square deviation, EQ, to obtain an accurate output from the model:

$$EQ = \frac{\text{Mean } \Sigma (x-y)^2}{\text{Mean } \Sigma\ y} \qquad (?)$$

where x = observed yield and y = simulated yield.

The EQ value for a well-fertilized sorghum sole crop is calculated at 8.5% here. A simulation of rainfed rice yields in Central Ivory Coast gave an EQ value of 10.7% (Forest and Kalms 1982).

Conclusion

In the long-term trial at Saria, grain sorghum was grown under widely fluctuating water-supply conditions, often reducing production increases expected from the application of cultivation techniques and regular and high organic and mineral fertilization.

1. At the Start of the Crop Cycle

- Water excess substantially decreases production estimates. This may be due to a leaching of minerals and a possible reduction in hours of bright sunshine.
- Water deficit plays a major role in yield estimation. This result confirms the importance of water for the vegetative development of plants.

Table 8. Proposed soil rainfall explanation of yield using a multilinear regression method.

Factors estimated:
PRO: Production ('00 Kg)
EE1: AET/ME in the first 50 DAP
DR1: Excess water in the first 30 DAP
EE2: AE/MET from 5 Sept to 5 Oct

Estimators

Variable	Mean	Standard deviation
PRO	23.429	9.25989
EE1	76.118	10.34057
DR1	34.471	53.23656
EE2	73.059	16.38676

Correlation matrix

	PRO	EE1	DR1	EE2
PRO	1.00000			
EE1	0.74625	1.00000		
DR1	0.11843	0.49411	1.00000	
EE2	0.09911	-0.46904	-0.49874	1.00000

1 st regression

Regression coefficients

$R^2 = 0.55689$

PRO = -27.437040

\+ 0.66876 EE1 — Standard coefficient = 0.74625

Variable	Multiple correlation	Partial correlation
DR1	0.24414	-0.43250
EE2	0.22000	0.76396

2nd regression

Regression coefficients

$R^2 = 0.81550$

PRO = -69.617882

\+ 0.91011 EE1 — Standard coefficient = 1.01632

\+ 0.32538 EE2 — Standard coefficient = 0.57581

Variable	Multiple correlation	Partial correlation
DR1	0.33556	- 0.27580

3rd regression

Regression coefficients

$R^2 = 0.82954$

PRO = -69.997145

\+ 0.95352 EE1 — Standard coefficient = 1.06480

-0.02528 DR1 — Standard coefficient =-0.14533

\+ 0.29727 EE2 — Standard coefficient = 0.52606

Production estimates ('00 kg/ha)

Individual	Value	Explanation	Error	Individual	Value	Explanation	Error
A74	38.5000	39.4779	-0.9779	A68	25.0000	22.2239	2.2761
A75	37.2000	29.8062	7.3938	A79	23.0000	19.8633	3.1357
A65	32.5000	36.7629	-4.2629	A73	19.5000	21.1289	-1.6289
A69	30.6000	29.1075	1.4925	A72	18.1000	21.7817	-3.6817
A67	27.5000	27.0430	0.4570	A66	18.0000	10.8835	7.1165
A80	26.4000	23.1016	3.2984	A64	15.5000	17.3226	-1.8226
A71	26.3000	23.8032	2.4968	A77	5.9000	9.7562	-3.8562
A81	26.0000	30.8126	-4.8126	A62	3.0000	8.5445	-5.5445
A70	25.3000	26.3805	-1.0805				

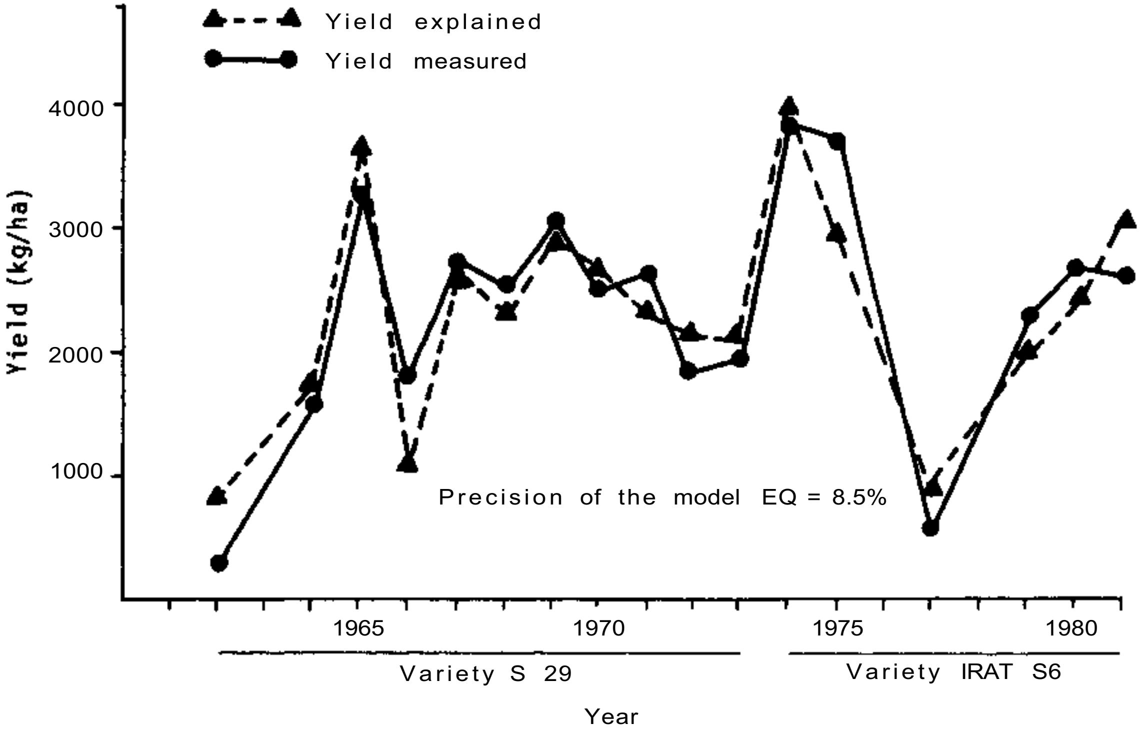

Figure 6. Sorghum monoculture yield explained through a water-balance model (Saria, Upper Volta, 1962-1981).

2. In the Middle of the Crop Cycle

In the rainfall conditions of Saria, the risk of a water deficit is rare. However, excess water at the pollination stage is a serious problem.

3. At the Grain-filling Stage

The frequent water deficit at Saria has an unfavorable effect on production estimates. This becomes more obvious when the crop develops under favorable water-supply conditions.

This observation should be related to the problems of shriveling of cereal crops in tropical countries.

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Session 4

Modeling of Climatic Response

Modeling the Effect of Environmental Factors on Sorghum Growth and Development

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Abstract

The yields of rainfed sorghum in the semi-arid regions in general are low and vary from year to year. An understanding of the interactions between the physical environment and the genotype is important to increase and stabilize production of sorghum. This information, through the systems-simulation approach, could be used to model sorghum growth and development. The grain sorghum growth simulation model—SORGF—was used as the basis to evaluate crop-weather interactions. A multilocation study was conducted in India over a period of 4 years to evaluate the growth and development of selected sorghum genotypes of varying maturity durations. Preliminary results suggested that several subroutines of the SORGF model needed modifications to simulate accurately the effect of environmental factors. Algorithms of the SORGF model dealing with light interception, phenology, leaf senescence, soil water, and total dry-matter accumulation and its partitioning to grain have been revised. The improvements resulting from the revisions made in each of the above subroutines are compared with the field data and the simulation results of the original SORGF model. The use of the SORGF model for irrigation scheduling and first-order screening of environments for sorghum production are illustrated.

Résumé

Facteurs environnementaux et la modélisation de la croissance et du développement du sorgho : En général, les rendements des cultures pluviales de sorgho dans les régions semi-arides sont faibles et varient d'une année à l'autre. Une compréhension des interactions entre le milieu physique et le génotype est importante pour augmenter et stabiliser la production de sorgho. Cette information sera utile à l'élaboration de modèles de croissance et de développement par l'approche de la simulation. Le modèle SORGF de simulation de la croissance du sorgho grain a servi de base pour l'évaluation des interactions entre le climat et la culture. Une étude multilocale fut menée en Inde pendant trois ans, afin d'évaluer la croissance et le développement de certains génotypes de sorgho à cycle variable. Les premiers résultats indiquent la nécessité de modifier plusieurs composantes du modèle SORGF, ce qui permettra de simuler avec précision l'effet des facteurs environnementaux. Les algorithmes du modèle SORGF portant sur l'interception de la lumière, la phénologie, la sénescence des feuilles, l'eau dans le sol, l'accumulation totale de matière sèche et sa répartition dans le grain ont été révisés. Le modèle perfectionné fut confronté avec les données réelles et les résultats de simulation du modèle SORGF de départ. L'emploi du modèle SORGF pour programmer les irrigations et l'évaluation préliminaire des milieux de culture du sorgho sont décrits.

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International Crops Research Institute for the Semi-Arid Tropics. 1984. Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics: Proceedings of the International Symposium, 15-20 Nov 1982, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

Sorghum (*Sorghum bicolor* [L] Moench) is an important cereal with potential grain yields similar to other cereals. Sorghum grain yields of 16500 and 14250 kg/ha have been reported by Pickett and Fredericks (1959) and Fischer and Wilson (1975). However, at the farm level in the semi-arid tropics, the yields normally range from 300 to 1000 kg/ha under rainfed conditions. An understanding of the interactions between the physical environment and the genotype is essential to identifying the important factors for increased and stabilized production of sorghum. For example, most sorghum genotypes take 85 to 140 days to mature; hence the matching of the genotype with the soil-moisture availability period would be crucial to achieving higher biomass and grain yield. This would depend, however, on the maturity duration and the variability in environmental factors during the vegetative and reproductive growth stages.

A systems-simulation approach could be used to integrate the knowledge of crop growth and development and interaction with the environment. The grain sorghum growth simulation model SORGF (Arkin et al. 1976) was used as a basic model to evaluate crop-weather interactions. Many of the initial users suggested that several subroutines of the model needed to be modified to provide accurate simulation of sorghum growth and development in relation to environmental factors (Huda et al. 1980). Accordingly, these subroutines were revised, using detailed field measurements of interception of photosynthetically active radiation (PAR), leaf number and leaf area, soil water content, dry-matter production and distribution in different components, and phenology for different genotypes. Improvements made by these revisions in different subroutines and the overall model evaluation by using independent data sets are presented in this paper. The revisions made in the model were discussed in detail by Huda et al. (1983).

Experiments

A study was conducted at eight locations in India over a period of 4 years to evaluate the growth and development of selected sorghum genotypes of various maturity durations during the rainy and postrainy seasons with and without supplementary water given at different growth stages. Standard data sets on crop, soil, weather, and management factors were collected (Table 1). Crop phenology, light interception, water use, leaf initiation and expansion, and dry-matter accumulation and partitioning were studied in detail to evaluate the role of environmental factors in these processes. The effects of temperature and daylength on the panicle initiation, flowering, and maturity of these genotypes were studied. The rate of canopy development was monitored to examine its role in crop water use and light interception.

Table 1. Input data required for SORGF—a sorghum simulation model.

Plant data
- Leaf number—total number of leaves produced
- Leaf area—maximum area of each individual leaf

Planting data
- Sowing date
- Plant population
- Row width
- Row direction
- Depth of sowing

Climatic data (daily from planting to maturity)
- Maximum temperature
- Minimum temperature
- Solar radiation
- Rainfall

Soil data
- Available water-holding capacity
- Initial available water content

Location data
- Latitude

Source: Arkin et al. (1976).

Subroutines Revised

Phenology

Accurate simulation of phenological development is important because it influences the daily dry-matter partitioning into various plant parts. The phenological simulation was based on three stages of sorghum development as defined by Eastin (1971):

Growth stage 1 (GS1)—Seedling emergence to panicle initiation.
Growth stage 2 (GS2)—Panicle initiation to anthesis.
Growth stage 3 (GS3)—Anthesis to physiological maturity.

In SORGF, the time from seedling emergence to panicle initiation is simulated as the sum of heat units (base temperature = 7°C and the upper limit of mean temperature = 30°C) and is a function of the maximum number of leaves. The time from emergence to anthesis is calculated as the simulated date the flag leaf was expanded plus 0.86 times the simulated number of days from panicle initiation to flag leaf appearance. The time from emergence to physiological maturity is calculated as 1.4 times the simulated number of days from emergence to anthesis. The effect of daylength and temperature was not systematically studied for developing the original SORGF model. The GS1 period is overestimated by SORGF, particularly at lower latitudes (e.g. ICRISAT Center, 17°N), probably as a result of the narrow data bases used in the development of the subroutines (e.g., only data from the USA, where daylengths are relatively longer).

Crop phenological data for almost all the growth stages were collected in 50 data sets, of which 10 were randomly selected for independent tests. The remaining 40 data sets were used to study phenological development in order to develop new algorithms.

The duration of GS1 was highly variable (Table 2), ranging from 17 to 31 days, with a mean of 23 days. The minimum and maximum length of GS1 was obtained for the same genotype (CSH-6) grown during the rainy season at different locations. The minimum duration was observed at ICRISAT Center and Parbhani (17°N); the maximum, at Ludhiana (31 °N). To account for this variability, the data were further analyzed to establish the effect of daylength and temperature on phenological development.

The approach of Stapper and Arkin (1980) was used to calculate growing degree days (GDD) for sorghum with various threshold temperatures:

$$GDD = \Sigma \text{ (Mean temperature-base temperature)}$$

A cutoff temperature of 38°C, with a base of 7°C, was used. To take into account the higher variability in growth stages, the effect of daylength was also analyzed. Daylength at emergence was plotted against the GDD values for GS1 for hybrids CSH-1 and CSH-6 (Fig. 1). A similar relationship was proposed by Major (1980) for short-day plants and by Stapper and Arkin (1980) for corn.

For the present study, the threshold value of daylength was 13.6 h at emergence for two hybrids, CSH-1 and CSH-6.

Duncan's multiple range test values were computed for three growth stages. Differences in GS1 can be accounted for by daylength effect as shown in Figure 1. A similar effect was found for GS2, but no effect of daylength was observed for GS3.

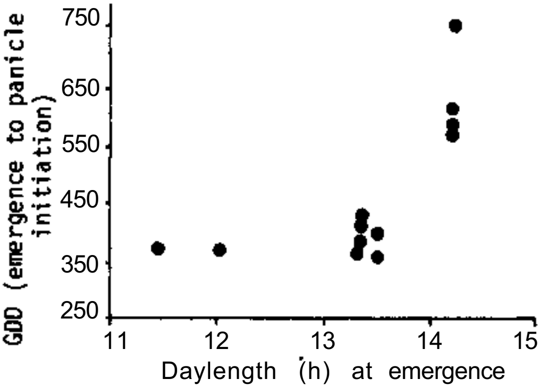

Figure 1. Relationship between growing degree days (GDD) from emergence to panicle Initiation and daylength at emergence for sorghum hybrids CSH-1 and CSH-6.

Table 2. Duration (days) of different sorghum growth stages (data pooled over locations, seasons, and genotypes).

Growth stage	N[1]	Duration (days) Mean	SD	Minimum value	Maximum value	CV(%)
GS1	29	23	4	17	31	19
GS2	29	37	6	30	50	10
GS3	30	35	6	22	53	18
GS1+GS2	39	60	7	50	80	11
GS1+GS2+GS3	40	96	10	80	115	15

1. N = No. of observations.

The algorithm for describing daylength at emergence (DAYEM) and GDD effects on GS1 derived from Figure 1 was:

$$GDD = 370 + 400^{*} (DAYEM - 13.6)$$

$$\text{if } DAYEM \geqslant 13.6 \text{ h}$$
$$GDD = 370 \text{ if } DAYEM < 13.6 \text{ h}$$

The algorithm for describing DAYEM and GDD effects on GS2, derived in the same way as that for GS1, was:

$$GDD = 660 + 120^{*} (DAYEM-13.6)$$

$$\text{if } DAYEM \geqslant 13.6\text{h}$$
$$GDD = 660 \text{ if } DAYEM < 13.6 \text{ h}$$

Differences in GS3 can be accounted for as a temperature effect, as shown by Schaffer (1980). The duration decreases with an increase in mean temperature (T) to 27°C and increases above 27°C. This increase in duration of GS3 with increase in temperature above 27°C needs further verification under controlled conditions. A base temperature of 7°C was derived for computing GDD in GS3. Thus for GS3 the following algorithms were used to account for temperature effects in GDD computation:

$$GDD = T\text{-}7, \text{ when } T \leqslant 27°C$$

$$GDD = (54\text{-}T)\text{-}7 \text{ when } T > 27°C$$

These revised algorithms were tested against 10 independent field study data sets. The root mean square error (RMSE) for SORGF and the revised algorithms are given in Table 3. The RMSE for all three growth stages was considerably reduced by using the revised algorithms, compared with the original SORGF model; thus the simulated phonological events were close to the actual values.

Table 3. Root mean square error (days) for different growth stages of sorghum for 10 independent field-study data sets, using SORGF model and revised algorithms.

Growth stage	SORGF	REVISION
GS1	7	4
GS1 + GS2	7	6
GS1 + GS2 + GS3	18	3

Light Interception

The light interception portion of the model simulates the relative quantum flux intercepted by a single plant. Intercepted photosynthetically active radiation (PAR) is calculated on an hourly basis following a Beer's law relationship using solar radiation and light transmission values. Hourly solar radiation is computed from the input solar radiation, and by accounting for the number of hours of sunlight for any day, which is calculated as a sine function of the local solar time and daylength. Validations with data collected at ICRISAT Center showed that model computation of solar declination and daylength are accurate, resulting in sufficiently accurate estimation of hourly solar radiation. The quantum flux density in Einsteins/m^2 per day is estimated in SORGF from the energy flux density (RS) in cal/cm^2 per day as

$$PAR = RS(0.121)$$

However, our results using measured data on PAR and RS for extended periods of time indicated that the constant relating PAR to solar radiation (RS) should be altered as follows:

$$PAR = RS\ (0.09)$$

Light transmission in SORGF is calculated from the relationship of extinction coefficient and maximum light transmission, using information on row spacings and leaf area index (LAI).

An examination of the computed and measured light transmission for different row spacings showed that the model was overestimating light transmission, especially at low levels of canopy light transmission, and that for row spacings of more than 137 cm, the SORGF model (Arkin et al. 1976) does not work, because computed light transmission exceeds 100%.

Comparison of predicted and measured light transmission for 45-cm rows, using the data sets collected at ICRISAT Center, are shown in Figure 2. Data points shown in Figure 2 deviate from the 1:1 line beyond the 15% limits at low levels of light transmission, and use of the revised equations substantially improves the predictability of light transmission.

Dry-matter Accumulation

In SORGF daily potential photosynthesis (DAYPOFO) is calculated in the PHOTO subroutine from intercepted PAR. In the SYNTH subroutine, the potential net photosynthesis (TOFOTO) is calculated as a function of DAYPOFO and the coeffi-

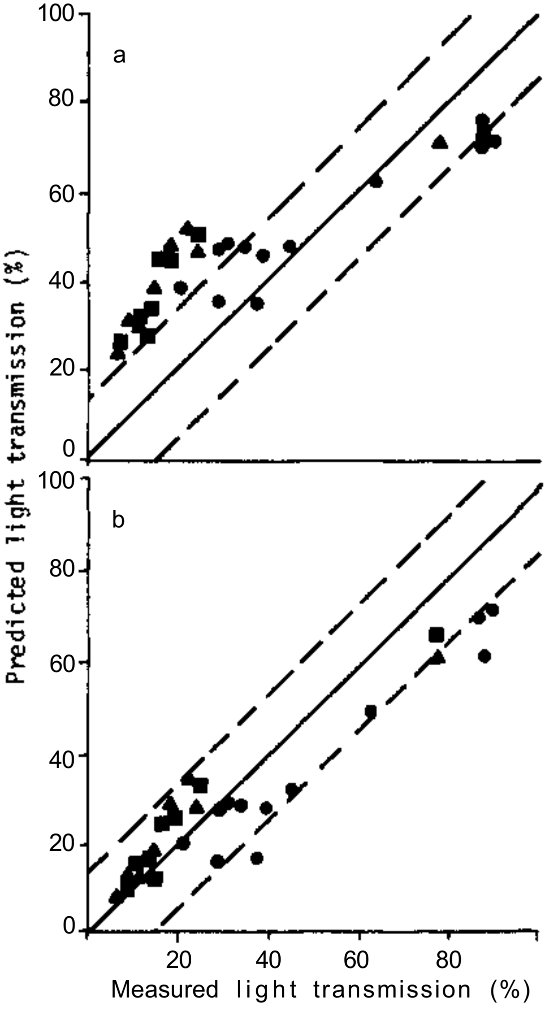

Figure 2. Relationship between measured and predicted light transmission in 45-cm sorghum rows according to (a) SORGF and (b) Revised algorithms (symbols represent data from different growing seasons).

cients of temperature stress (TEMPCO) and water stress (WATSCO) as described by Arkin et al. (1976). Net daily photosynthesis (TOFOTO) is then redefined by accounting for respiration. Daily increase in plant dry weight (DRIWT) is then determined in part from TOFOTO and soil surface area allocated for each plant.

Biscoe and Gallagher (1977) and Williams et al. (1965) showed that dry-matter production early in the season is related to the amount of radiation intercepted by the crop. Gallagher and Biscoe (1978) then showed that for wheat and barley grown at Sutton Bonington and Rothamsted, about 3 g of dry matter was produced for each MJ of PAR absorbed until ear emergence; for the whole crop, about 2.2 g of dry matter per MJ absorbed.

Dry-matter/intercepted PAR relationships were also examined at ICRISAT during the 1978 and 1979 growing seasons for sorghum (ICRISAT 1979, 1980). For several crops of sorghum, dry matter produced per MJ of absorbed PAR varied from 1.20 to 2.82 g, the lowest value corresponding to a nonirrigated crop during the postrainy season. The highest value was recorded for a sorghum crop that was irrigated at 10-day intervals in the postrainy season. From these observations, it seems reasonable to define a factor ALPHA (g of dry matter produced/MJ of PAR absorbed) and assign to it a value of 3.0 (Sivakumar 1981). This value defines an upper limit for cases with no water or temperature stress. The TEMPCO and WATSCO functions as defined in the model are then used to calculate daily dry-weight increase.

Dry-matter Partitioning

Partitioning of dry matter to plant parts varies according to the stage of development. Accurate simulation of grain yield depends upon the ability to correctly partition dry matter to grain and other plant parts.

Leaf, culm, head, and head+grain weights (g/plant) simulated with SORGF were compared with measured data collected at weekly intervals (27 field studies) throughout the growing season at ICRISAT Center. The root mean square error (RMSE) was calculated for measured and simulated plant part weights for each field study. The highest RMSE was observed for the head+grain component, with a range of 7 to 34 g/plant. The lowest RMSE was observed for culm weight, with a range of 2 to 12 g/plant. The range in RMSE for leaf weight was 6 to 21 g/plant. These RMSE values are indicative of the accuracy with which SORGF partitions dry matter to the plant organs.

Measured mean total dry matter (TDM) (g/plant) and percentage partitioned to the plant parts at panicle initiation (PI), anthesis (AN), and physiological maturity (PM) are given in Table 4. The TDM partitioned to the leaf decreases from 64 to 11% from PI to PM; that partitioned to the culm increases from 36 to 60% from PI to AN, then decreases to 36% again at PM. The TDM partitioned to grain at PM is 41%.

Table 4. Total dry-matter (TDM) and percent partitioned to leaf, culm, head + grain, and grain at three growth stages (data pooled over all genotypes, seasons, and moisture treatments; n=27).

	Panicle initiation		Anthesis		Physiological maturity	
	Mean	SD	Mean	SD	Mean	SD
Dry matter (%) partitioned to						
Leaf	0.64	0.04	0.24	0.04	0.11	0.02
Culm	0.36	0.04	0.60	0.06	0.36	0.07
Head+grain	0.00	0.00	0.16	0.04	0.53	0.08
Grain	0.00	0.00	0.02	0.01	0.41	0.08
TDM (g/plant)	1.60	1.20	35.20	15.00	67.40	23.30

Soil Water

In SORGF daily available water for the entire soil profile (single-layered) is calculated after Ritchie (1972), using information on initial available soil water, available water-holding capacity, rainfall/irrigation, and evaporative demand. Potential evaporation below a plant canopy (Eos) is calculated after simulating the potential evaporation from bare soil (Eo) and using LAI values. Eo is calculated in the model using the Priestley-Taylor (1972) equation, which requires net radiation as input data. Net radiation is calculated from albedo, maximum solar radiation reaching the soil surface (Ro), and sky emissivity. Ro in the SORGF model was calculated using a site-specific sine function. This function was revised to calculate Ro for any latitude and resulted in improved estimates of Eo.

Daily values of the water-stress coefficient (WATSCO) are simulated in the SOLWAT subroutine, using the current available soil water (SW) and the maximum amount of water (UL) in the profile. Values of UL are Inputs of the model. Current available soil water (SW) is calculated in the model after Ritchie (1972). Values of potential evaporation from bare soil (Eo) and below a plant canopy (Eos) used in simulating SW are calculated in the subroutine EVAP. This approach could result in erroneous simulation of a true water-stress coefficient because the available soil water in the entire soil profile is not available to the plant in the early stages of crop growth.

A more representative coefficient could be obtained by considering an effective rooting depth function and calculating available soil water for the portion of the profile where roots are present. In order to incorporate this aspect in the computation of the water-stress coefficient, the extraction of drainage components developed by Williams and Hann (1978) was used. This approach consists of a routing technique to predict flow through the root zone.

Amounts of plant-available water and their upper and lower limits for different layers of a 187-cm deep Vertisol were given by Russell (1980). Seasonal changes in modeled and measured available soil water for irrigated and nonirrigated sorghum on a deep Vertisol are shown in Figures 3 and 4, respectively. Available soil water predicted by the SORGF model is consistently higher than measured soil water. Available soil water summed over all the layers and using the new algorithm for calculation of Ro is referred to as "REVISION" here. REVISION estimates of soil water for irrigated sorghum are better than SORGF estimates, but still higher than the measured soil water amounts. For the nonirrigated sorghum, the REVISION estimates are excellent.

Use of a layered model provided consistently better estimates of WATSCO than SORGF did when compared with field measurements (Table 5). For the nonirrigated sorghum, with progressive depletion of available soil water, the measured WATSCO decreased from 0.93 at 15 days after emergence (DAE) to 0.73 by 79 DAE, and WATSCO computed by the layered model also decreased to 0.72 by 79 DAE, while WATSCO predicted by SORGF stayed at 1.0 throughout the growing season. The use of the layered model appears to provide improved estimates of water-stress coefficients (WATSCO) to account for the effect of water stress on sorghum growth.

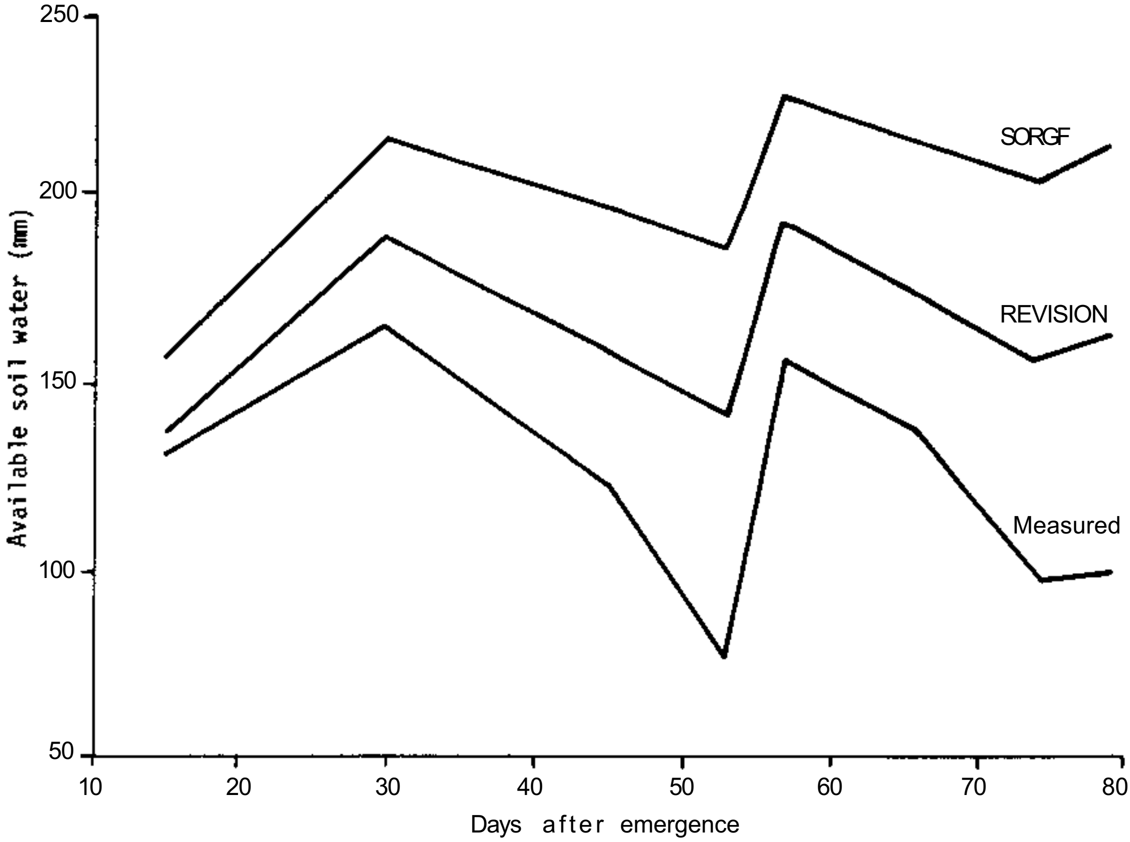

Figure 3. Seasonal changes in the available soil water for irrigated sorghum in a deep Vertisol, as shown by simulated (SORGF and REVISION) and measured values.

Leaf Development

Leaf area is overestimated by SORGF, particularly in the grain-filling period. Total number of leaves and maximum area of each leaf are input data requirements for SORGF. In SORGF, each leaf achieves its maximum area irrespective of moisture and temperature stress conditions. Leaf senescence is accounted for as follows: the first leaf senesces after the 11th leaf expands fully, and as each successive leaf expands fully, the next leaf senesces. No leaf senescence occurs after the last leaf is fully expanded. It was previously observed (Huda 1982) that when leaf 7 is fully expanded (leaf 8, 9, 10.....), consecutive leaves from the bottom (leaf 2, 3,4......) senesce. The maximum leaf area per plant was achieved at anthesis (Table 6) with a mean of 1710 cm^2 and a standard deviation of 622 cm^2. Leaf area at physiological maturity was 50% of that at anthesis. These results were included in the revised SORGF model.

Simulation Comparison

The revised algorithms discussed earlier were incorporated in SORGF. Simulation results of several components of the model and the yield simulations were compared with observed data. Examples of testing some of the revised algorithms with the data obtained from 1981 /82 experiments (which were not utilized for model revision) are given below.

Emergence

The results of the emergence simulation were compared with the data obtained from 1981 rainy-season experiments conducted at ICRISAT Center. Dry seeding of sorghum (a practice recommended by ICRISAT for Vertisols) was done on a deep Vertisol (10 June) and on a medium-deep Vertisol (12 June), ahead of the monsoon. The available water-holding capacity of the deep Vertisol is 200 mm; that of the medium-deep, 165 mm. At the time of sowing the available water in the

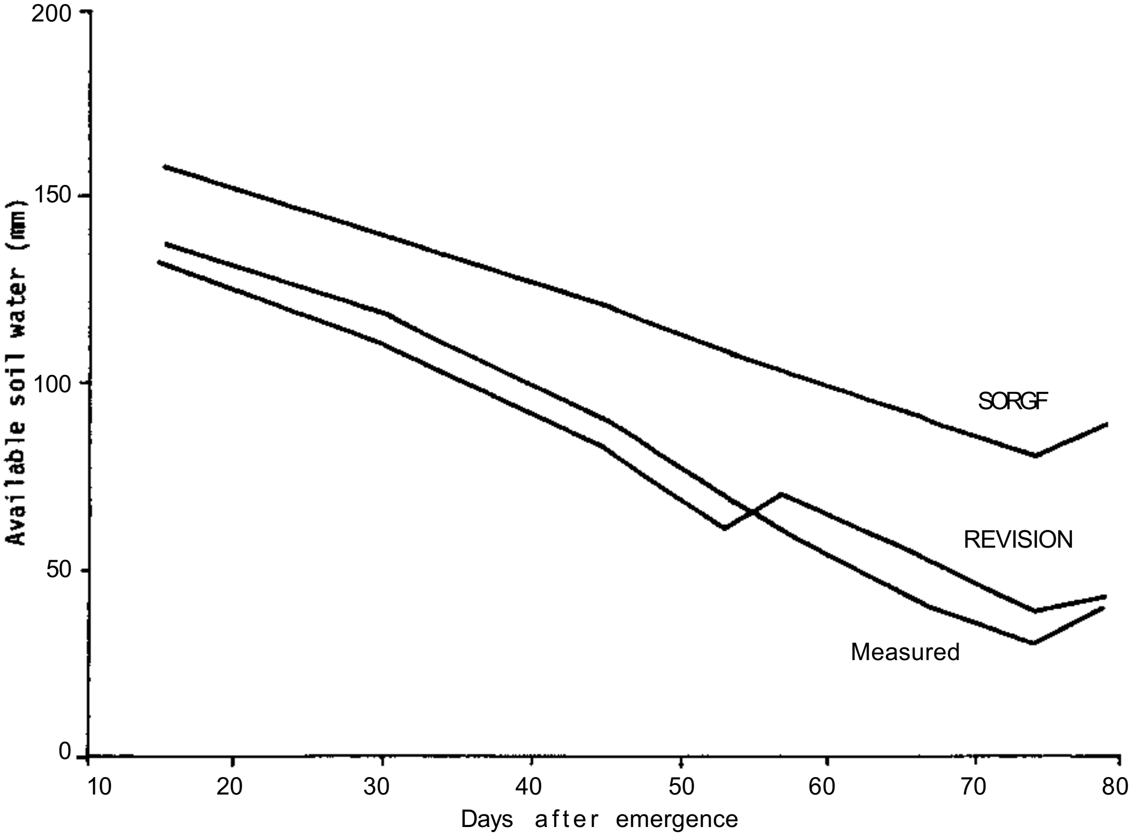

Figure 4. Seasonal changes in the available soil water for nonirrigated sorghum in a deep Vertisol, as shown by simulated (SORGF and REVISION) and measured values.

Table 5. Seasonal changes in water-stress coefficient (WATSCO) for a nonirrigated sorghum on a deep Vertisol, as simulated by two models and measured in the field.

	Simulated WATSCO		
Days after emergence	SORGF	Layered model	Measured WATSCO
15	1.0	0.58	0.93
30	1.0	0.99	0.98
45	1.0	0.98	0.97
53	1.0	0.95	0.90
57	1.0	0.92	0.94
66	1.0	0.76	0.85
74	0.9	0.56	0.67
79	1.0	0.72	0.73

Table 6. Leaf area (cm^2/plant) at three growth stages of sorghum (data pooled over all genotypes, seasons, and moisture treatments).

Stage	Mean	SD	Minimum	Maximum
Panicle initiation	369	268	145	1022
Anthesis	1710	622	761	3227
Physiological maturity	876	449	196	1848

entire profile for the two fields was 65 and 29 mm respectively (above 10% of the entire profile for both fields). In SORGF, emergence is simulated when 70 heat units above 7°C base temperature accumulate after sowing, provided the available soil water for the entire profile is above 10%. Thus SORGF simulated emergence within 4 days after sowing, while actual emergence in the field occurred much later.

There was no available water in the top 30-cm layer in either field, and emergence in both these fields actually occurred only on 22 June after 35 mm rainfall was received on 18 June. The revised SORGF model with a layered soil water subroutine (top 0-30 cm and beyond 30 cm) simulated emergence date for both these fields as 21 June.

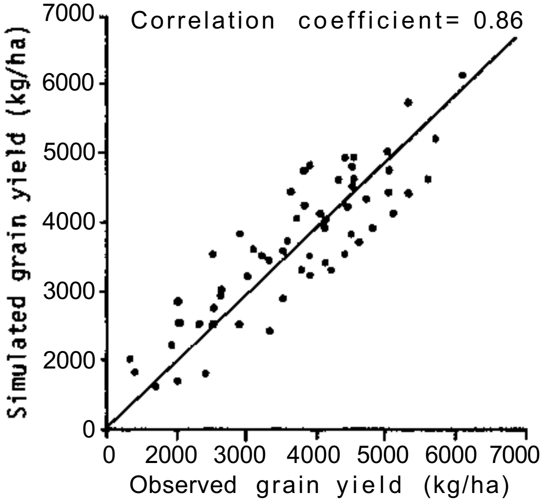

Figure 5. Relationship between observed and simulated grain yield (kg/ha) of sorghum according to revised sorghum model for pooled data (n = 59).

Phenology

The simulation of the course of phenological events, such as panicle initiation, anthesis, and physiological maturity, was compared with 19 observations obtained from 1981 experiments. The revised algorithms simulated the duration of GS1 (seedling emergence to panicle initiation) to within ±2 days of actual values in the field, whereas the SORGF simulated value was ±5 days. Similarly, revisions reduced the root mean square error (RMSE) in simulating the duration of the period from emergence to maturity from ±15 days to ±4 days.

Grain Yield

Improvements made in the model were tested with data sets obtained during 1981 at ICRISAT Center. Revisions in the model improved the coefficient of determination (R^2) by 35% (SORGF = 0.48, REVISION = 0.83) for grain yields. The root mean square error (RMSE) was reduced by the revision from 1423 kg/ha to 592 kg/ha.

We used pooled data (n=59) over different seasons and genotypes from ICRISAT Center and other cooperating centers to simulate the grain yield. The R^2 improved from 0.27 for SORGF to 0.74 for the revised model. The RMSE was reduced from 1479 kg/ha for SORGF to 591 kg/ha for the revised model. The relationship between observed and simulated grain yield for the pooled data is given in Figure 5.

Conclusions

The studies reveal that the effect of environmental factors on sorghum growth and development can be better understood from a standard set of crop, soil, and weather data. Such information would be useful in devising management practices to optimize yields in different environments.

First-approximation answers to questions on sorghum yield potential can be generated by this model, using climate and soil information. Answers to questions about the sorghum yield potential and the optimum crop-duration period to match the

Table 7. Simulated response of grain yield to supplemental irrigation at different growth stages of sorghum at Tombouctou, Mali (Simulation base: 43 years).

Supplemental irrigation at			Grain yield (kg/ha)		
Sowing	Panicle initiation	Anthesis	Mean	Maximum	Minimum
-	-	-	191	1798	0
X[1]	-	-	1725	2879	1586
X	X	-	2028	3174	1888
X	X	X	4249	4899	4094
X	-	X	4010	4657	3844

1. X = Irrigation of 100 mm.

water availability were sought by the Magarini Land Settlement Scheme in Kenya. May et al. (1981) used this model to delineate the cumulative probability distribution of simulated grain yields in Kenya for optimum sowing dates chosen from the rainfall probability analysis.

The model was used to construct cumulative probability distribution of sorghum grain yields for two locations (Bamako and Tombouctou) in Mali. Historical weather data (rainfall and temperature) for 49 years for Bamako and 43 for Tombouctou were used. Analysis showed that under adequate management conditions sorghum can be grown rainfed in Bamako, but in Tombouctou sorghum cultivation without irrigation could involve a high element of risk.

The mean annual rainfall for Tombouctou is only 195 mm; thus the model was also utilized to simulate the response of sorghum grain yield to supplemental irrigation (Table 7). Results showed that the model is sensitive enough to determine when and how much water should be applied to achieve optimum yield. For example, if only 200 mm irrigation water is available, it would be economical to use 100 mm at sowing for crop establishment and another 100 mm at anthesis for grain filling.

Some interagency projects would be required to evaluate the suitability of climatic environment for sorghum. Studies of the effect of environmental factors on growth and development of sorghum under controlled conditions would help supplement the information obtained from field studies.

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Evaluating Sorghum Production Strategies Using a Crop Model

G.F. Arkin and W.A. Dugas, Jr.*

Abstract

Selecting the appropriate crop-production strategies is critical for the success of a production system. Strategies are normally selected based upon observations over long periods of time. Using crop-growth models that simulate plant growth and development and account for fundamental physiological processes to develop strategies is a new technique. Examples are presented that illustrate the utility of crop-growth models in selecting cultural practices, forecasting yields, scheduling irrigation, making drought assessments, mapping land productivity, developing agricultural weather advisories, and planning breeding programs. The effect of model accuracy on the utility is considered, along with requirements for computer hardware, execution speed, and input data.

Résumé

Evaluation des stratégies de production par la modélisation : Le choix d'une stratégie appropriée est essentiel au succès du système de production des cultures. Ce choix est normalement fondé sur de longues séries d'observations. Une nouvelle technique pour définir ces stratégies utilise des modèles qui simulent la croissance et le développement des plantes, en tenant compte des processus physiologiques. Des exemples sont donnés pour illustrer les différentes applications de ces modèles : choix des pratiques culturales, prévision des rendements, détermination de l'époque d'irrigation, évaluation de la sécheresse, délimitation des aires de culture, établissement des avertissements météorologiques et amélioration des programmes de sélection. L'effet de la précision du modèle sur son utilité est expliqué. Des renseignements sur le matériel informatique, la vitesse d'exécution et les données d'entrée sont également fournis.

Often the stability of an existing crop-production system or the success of a newly initiated one is dependent, in part, upon selecting the proper long-term (strategic) production practices (e.g., sowing date, genotype, irrigation schedule). Strategies normally are chosen based on qualitative information or trial-and-error experiences. Choosing crop-production strategies using a crop model has the potential for providing useful quantitative information for decision making and eliminating much of the repetitive trial and error of selecting production strategies.

Stable and successful strategies have evolved from conventional agronomy and traditional agriculture. These strategies, adapted to local environments, generally resulted from observations over long periods of time. In some instances, strategies developed in this manner are unattractive because of the time and expense required or the difficulty of adapting them to other regions. In this paper, stra-

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tegic and, to a lesser extent, tactical (short-term or within-season) production practices developed using crop models, regardless of crop, are discussed when the practice is relevant to sorghum production. In so doing, concepts and methods are exposed that have not yet been considered for developing sorghum production strategies.

Agroclimatic classifications (see Burgos 1968 for review) were initially developed to overcome the limited utility of locally derived strategies. Strategies deemed successful in a particular environment were conjectured to be equally successful in environments of similar classification. Classification techniques similar to those developed by Koppen (1931) and Thornthwaite (1948), although useful for codifying climatic information, do not account for crop response and are too general for farm-level applications. Similarly, the classification scheme of Papadakis (1965), which included crop-specific considerations, and the numerical method of Russell and Moore (1970,1976) suffer from the same general limitations. Angus et al. (1974) noted that strategic suggestions for formulating production strategies based on sophisticated quantitative climatic analyses are of a qualitative nature and have little practical utility.

Baier (1979) identified the following three categories of crop-weather models for evaluating influences on crop growth and development: (a) empirical statistical models, (b) crop-weather analysis models, and (c) crop-growth simulation models. Frere and Popov (1979) subsequently summarized the description of each category and elucidated the significant components of each. Even so, definitive distinctions still remain elusive because of the overlapping methodology between categories.

Although empirical statistical models are widely used in agroclimatic analyses to develop production strategies, their most suited applications are for predicting crop yield using a single variable, e.g., rainfall. In environments where a particular environmental variable is the primary yield-limiting factor, the predictive value of these models has been demonstrated (Fisher 1924; Lomas 1972). Their deficiency lies in their site-specificity and inability to adequately describe complex and dynamic causal relationships between crop growth and yield and environmental factors.

The more robust crop-weather analysis models account for the effects of several environmental factors on crop yield. In general, these models relate one or more derived parameters, such as heat units, soil moisture deficits, and evapotranspiration, to yield. They have been shown to be helpful in assessing strategies (Nix and Fitzpatrick 1969; Baier 1973; Baier et al. 1976; Berndt and White 1976; Slabbers et al. 1979; Stewart and Hash 1982; Liang et al. 1983), but require considerable calibration with yield data that are often unavailable. Although more relevant for developing production strategies than climatic classifications and empirical statistical models, these models are constrained in application to a limited set of production scenarios. These constraints are a result of unaccounted-for crucial crop growth and development processes affected by environment, management practices, and genetic attributes. Despite the limitations of the empirical statistical and crop-weather analysis models, they are the most commonly used, primarily because of formulation simplicity and limited data requirements.

Crop-growth models (CGMs) that convert changes in atmospheric, management, and soil variables into changes in plant growth and account for the fundamental physiological processes governing crop growth have the potential for overcoming many of the limitations attributed to the other model categories. Although generally considered research tools only (Frere and Popov 1979; Legg 1981), their utility in management decision making has recently been demonstrated. The following examples illustrate CGM utility in several categories of decision making.

Crop-growth Model Strategies

Cultural Practices

Using a wheat model, Smith and Ritchie (1978) and Ritchie (1979) assessed risks, in terms of probable yields, associated with sowing date, soil type, and crop maturity at Altus, Oklahoma, USA. They used 59 years of weather records and simulated yields for two sowing dates, two soil types with different values of extractable water, and two maturity genotypes and developed yield cumulative probabilities to illustrate the influence of each variable.

DeCoursey (1980) combined hydrology, infiltration, moisture redistribution, and rill-interrill erosion models with the CGM GOSSYM to assess alternative land-management schemes. After calibrating the model with data from a 15.5 ha Mississippi watershed in 1974, DeCoursey simulated runoff, sediment, and cotton yield on the same watershed in 1975 for three plant densities, five fertilizer patterns, three row spacings, three land slopes, and three tillage practices.

A hydrology model was also combined with a CGM by Stinson et al. (1981) to evaluate the feasibility of sorghum ratoon cropping and impact on yield, runoff, and erosion in central Texas. Sorghum ratoon cropping had not been practiced in this region. Using 40 years of historical weather records, they established ratoon cropping risks in terms of probable yields and runoff and erosion amounts; they also provided guidelines for identifying cropping seasons in which ratoon cropping risks would be minimized.

Yield Forecasts

Conditional probability functions were developed by Arkin et al. (1978) using a sorghum model, SORGF (Arkin et al. 1976), to develop a scheme for forecasting crop yields. They generated cumulative probability functions using 20 years of weather data from Temple, Texas, conditioned on two state variables: leaf area and extractable soil water. Cumulative distribution functions computed from the probability functions were used to forecast yields at selected dates over the season. Forecast accuracy improved as the season progressed. The methodology of forecasting yields was extended (Arkin et al. 1980) by including a feedback option in SORGF for updating forecasts with observed data. Their forecast estimates for ten fields, made using the feedback option, converged on observed yields as the season progressed.

Irrigation

Barfield et al. (1979) used a corn model, SIMAZE (Barfield et al. 1977), in a risk analysis study to determine the economic benefit of supplemental irrigation using impounded surface water in Kentucky. They combined SIMAZE with (a) a water-yield model to determine daily water inflow to an irrigation reservoir, (b) a reservoir water-balance model to estimate daily reservoir volume, and (c) a reservoir sizing model and an economic model to compare investment options. Using an optimization technique and 25 years of climatic data, they demonstrated that from an economic standpoint the required optimum reservoir size was approximately half that recommended for that area. Kundu et al. (1982), using data from Colorado and California, determined that CORNGRO, another corn CGM, can be effectively used to schedule irrigation for different varieties, soils, and climatic conditions.

GOSSYM was used by Baker et al. (1979) to evaluate irrigation, tillage, pest management, and breeding practices in Mississippi. GOSSYM was validated with data from Arizona, Mississippi, and Israel by Reddy (1981). Because only a relatively few site-specific changes were needed to achieve realistic simulations at all locations, Reddy concluded that the model was indeed a feasible tool for general application.

Concern for declining groundwater supplies and increasing energy costs prompted Zavaleta et al. (1980) to develop irrigation strategies, using a CGM, that maximize net returns per hectare for sorghum grown in the Texas Southern Plains region. Swaney et al. (1983) developed a simulation method for evaluating within-season irrigation decisions using a soybean CGM, SOYGRO (Wilkerson et al. 1983). Their method, developed and validated in Florida for application in humid regions, enables farmers using an interactive computer program to make cost-effective real-time center-pivot irrigation decisions.

Drought

Two methods using sorghum and wheat CGMs were presented by Dugas et al. (1983a) for early assessment of drought impacts. Regression equations were developed at various times in the season between modeled soil water within the season and modeled sorghum and wheat yield. An additional forecasting technique was developed for sorghum which involved running-out the model to the end of the season from various times within the season, using different weather scenarios to obtain a distribution of simulated yields. James and Eddy (1980) and Vanderlip and Schmidt (1981), using a sorghum CGM, evaluated the effect of precipitation timing, frequency, and amount to determine the benefits of schemes to alleviate drought by augmenting precipitation.

Land Productivity Mapping

Another unique and interesting application of a model resembling a CGM was to derive first approximations of the production potentials of land in Africa, southwest Asia, and South and Central America (FAO 1978a, 1978b, 1981). Extensive meteorological, soil, and crop data bases were translated into production potential. This series of reports on the Agro-Ecological Zones Project provides useful information for planning future agricultural development in these areas.

Agriculture Weather Advisories

A project wherein real-time interpreted weather information is disseminated is operational in three major production regions of Texas (Arkin and Dugas 1981). Several CGMs are used to interpret daily weather data and provide farmers, agricultural advisors, and agribusiness with weekly reports on crop status and yield assessment to aid in decision making.

Breeding

Sorghum and wheat CGMs were used to predict yields resulting from modifications of the plant or plant response to its environment in order to identify crop improvement strategies in regions that experience drought (Jordan et al. 1983). Maturity, deep rooting, and osmoregulation modifications were studied for potential benefits that might result from breeding alterations of these plant characteristics for crops grown in Temple and Lubbock, Texas, and Manhattan, Kansas, USA. In studies of a similar nature, Landivar et al. (1983a, 1983b) showed how a CGM could be used in a breeding program to predict the performance of cottons of different leaf types (e.g. okra leaf), photosynthetic rates, specific leaf weights, and leaf longevities in various environmental conditions. These authors identified several promising plant characteristics for consideration in a breeding program.

CGM Constraints and Considerations

Seemingly, CGMs have a niche in crop-production strategic planning, but their adoption should be cautiously undertaken. Model accuracy (validation) is undoubtedly a major consideration of model utility. Hardware (computer), execution speed, and input data requirements are other considerations determining model utility.

Accuracy

Complex biological and physical processes are simulated with CGMs. CGM accuracy is described in terms of accuracy of simulated process parameters which, in turn, is determined by comparing simulated with measured process parameters to establish confidence in the model. However, there is usually a paucity of independent measured data for comparison. Each CGM is unique; hence, measurement data required to determine accuracy are different for each. Even where only estimated yield accuracy is of concern, adequate meteorological, soils, cultural, and cultivar data are seldom readily available for enough crop years and locations to enable a meaningful determination of accuracy. Obtaining useful data for comparative analyses is both costly and time consuming. Comparative analyses of the type described are initially performed by most model developers (Vanderlip and Arkin 1977; Kanemasu 1981). In many instances, further analyses by the user are warranted to establish confidence. Several papers on this general topic have been written (e.g. Baker and Curry 1976; Penning de Vries 1977; Bell 1981).

Sensitivity analyses can also help determine model accuracy. Two recent publications (Larsen 1981, 1983) describing methods for evaluating model sensitivity to the accuracy of input data and processes are indicative of the difficulty of such evaluation. The statistical procedures used by Larsen are enlightening and will have an impact on future analytical techniques applied to CGM evaluations.

Simulated yield errors were also shown by Dugas et al. (1983b) to be influenced by the extent to which the estimates are spatially extrapolated. Although they found that the magnitude of estimated yield errors was independent of the two CGMs analyzed, they cautioned that for other CGMs the converse may be true. Their results have significance for determining weather station densities required in using CGMs and for assessing CGM accuracy.

Execution Speed and Hardware

Complexity (detail and number of processes modeled) of the CGM generally dictates computing capability requirements and influences the time required to complete a simulation. CGMs inherently have a time step for which input data are averaged or accumulated. Jackson et al. (1983) evaluated the effect of lengthening the time step of a CGM on simulated yield errors and execution speed. Although simulated yield errors increased with longer time steps, the potential for reducing simulation time and maintaining acceptable simulated yield errors was evident. These findings are, of course, dependent upon the CGM and computer used.

Simulation time may or may not be of consequence. Clearly, there are trade-offs between the computer selected and the simulation time. CGMs are generally thought of as requiring a mainframe computer for execution. This conception is gradually being dispelled with the advent of powerful micro- and mini-computers and other technological advances in computer hardware.

Recently, Arkin and Jackson (1983) converted SORGF (Maas and Arkin 1978), a grain sorghum CGM, into the BASIC computer language and configured it for execution on a microcomputer. The converted model, SORG-AP, has a longer simulation time than SORGF and differences in precision between the two CGMs are insignificant. SORG-AP is a user-interactive model enabling feedback data input for updating and retracking model simulations using within-crop season field measurements.

Input Data

Amount and detail of input data (e.g., meteorological, soils, cultivar, and cultural) required for either model execution or validation may preclude use of a CGM. The utility of the CGM may depend upon availability of, or resources needed to collect, input data. Because of the paucity of validation data discussed earlier, complex CGMs requiring exhaustive input data are not often adopted as management tools for strategic (or tactical) decision making.

Remarks

Illustrative examples of CGM applications to management decision making for several crops have been presented to exhibit the range and diversity of production strategies (similar to those encountered in sorghum production) that might be addressed with a CGM. As progress is made in quantitative developmental physiology and other relevant disciplines, CGMs will improve in accuracy and sensitivity and become more widely adopted. Although herein not emphasized, future opportunities to employ CGMs in developing pest and fertilizer management programs and assessing the economic benefits of alternative production practices are real and, to some extent, already being realized.

Those considering using a CGM should initially develop an understanding of its workings, capabilities, and shortcomings. This can be accomplished by using the CGM with various combinations of input data and comparing simulated output data with observed or known values. With experience and a developed ability to adjust the CGM to simulate growth and development for particular locations and applications, the user may be in a position to use it as a management tool capable of providing information helpful in decision making.

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Problems and Prospects in Modeling Pearl Millet Growth and Development: A Suggested Framework for a Millet Model

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Abstract

Physical environment plays an important role in determining crop duration, water availability, the occurrence of pests and diseases, and thereby the ultimate yield. Knowledge of the influence of environmental factors on pearl millet growth and development will thus be helpful in devising the means to increase and stabilize pearl millet production. Simulation modeling is an effective approach to integrating various processes involved in crop growth and development Currently no simulation model for pearl millet is a vailable in the literature, but because of the similarity in some of the growth and development processes between pearl millet and sorghum, the suitability of adapting certain subroutines of the existing sorghum model (SORGF) is examined. The difficulty in modeling the tillering habit of pearl millet is recognized. However, the effects of temperature and daylength on the duration of growth stages and tillering habit of the selected pearl millet genotypes are discussed. The total dry matter computed from the amount of light intercepted by the canopy, and partitioning of dry matter to different plant parts are dealt with. Based on the available information, a framework for developing a pearl millet model is suggested.

Résumé

Problèmes et perspectives de la modélisation de la croissance et du développement du mil; proposition d'un cadre pour la modélisation du mil : Le milieu physique exerce une forte influence sur le cycle de croissance, la disponibilité en eau, ainsi que l'incidence des ravageurs et des maladies, donc le rendement d'une culture. Une compréhension de l'influence des éléments environnementaux sur la croissance et le développement du petit mil permettra d'établir des méthodes visant à augmenter et à stabiliser la production de petit mil. Des modèles simulés permettent d'intégrer les différents processus impliqués dans la croissance et le développement des cultures. Actuellement il n'existe pas de tels modèles pour le petit mil. Cependant, compte tenu des ressemblances entre les différents processus physiologiques du sorgho et du petit mil, il conviendrait d'examiner l'adaptabilité au petit mil de composantes du modèle utilisé pour le sorgho (SORGF). Le processus de tallage chez le petit mil pose un problème particulier. Les auteurs discutent l'effet de la température et de la durée du jour sur la durée des différentes phases de croissance et le tallage chez certains génotypes de mil. Suit une analyse portant sur la matière sèche totale calculée en fonction de la lumière interceptée par le couvert végétal, ainsi que sa répartition entre les différentes parties de la plante. A la lumière des informations disponibles, les auteurs proposent un cadre pour la mise au point d'un modèle.

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International Crops Research Institute for the Semi-Arid Tropics. 1984. Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics: Proceedings of the International Symposium, 15-20 Nov 1982, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

Pearl millet (*Pennisetum americanum* [L] Leeke) is a major cereal grown by subsistence farmers in the dry semi-arid tropics. It is most extensively grown as a rainfed crop in sandy and often shallow soils in areas with 200 to 800 mm annual rainfall. More than 95% of the world's millet crop is grown in Africa and South Asia, principally in the Sahelian-Sudanian zones of West Africa and in the semi-arid regions east and southeast of the Thar desert in India. The areas of adaptation of the species are clearly defined by the mean annual rainfall isohyets of 200 to 600 mm in both continents (Bidinger et al. 1982). These zones are generally characterized by short rainy seasons (2-4 months), high mean temperatures, high potential evapotranspiration rates, and shallow, sandy soils (Cocheme'and Franquin 1967, Kowal and Kassam 1978). Inter- and intra-seasonal variability in available soil moisture is the major hazard to pearl millet production.

Millet grain yields exceeding 5 tonnes/ha can be obtained in favorable environments (Rachie and Majmudar 1980). Physical environment plays an important role in determining crop establishment, crop duration, water availability, occurrence of pests and diseases, and thereby the ultimate growth and yield. Excellent information on the relationship between environment and sorghum growth and development is available in the literature (Downes 1972; McCree 1974; Arkin et al. 1976; Vanderlip and Arkin 1977; Sivakumar et al. 1978; Huda and Virmani 1980; and Huda et al. 1980b). However, we have very little quantitative information on the response of pearl millet to environment; the available information mostly deals with the effect of temperature.

Effect of Temperature

Fussell et al. (1980) studied the effect of temperature during various growth stages on grain development and yield of *Pennisetum americanum* in glasshouses. They found that high temperature (33/28°C day/night) during all three growth stages (vegetative, stem elongation, and grain development) lowered grain yields by reducing basal tillering, number of grains per inflorescence, and single-grain weight. Low temperatures (21 /16°C) when imposed at different growth stages had different effects on grain yield. Low temperatures during the vegetative stage increased grain yield due to increased basal tillering, and during the grain development stage due to a longer grain-filling period. However, low temperatures during the stem-elongation stage reduced spikelet fertility and inflorescence length, and thereby reduced the potential main-shoot grain yield.

Monteith et al. (1983) found that germination rate increased linearly in millet with temperature from a base of 10 to 12°C to a sharply defined optimum at 33 to 34°C and declined to zero at about 45 to 47°C. Other developmental processes such as leaf and spikelet initiation and the period from panicle initiation to anthesis responded similarly to temperature (Ong and Monteith, these Proceedings).

Little is known about the effects of high temperature (>32°C) on leaf area development in millet. Evidence from maize (Watts 1972) and sorghum (Peacock 1982) suggests that the rate of leaf extension declines rapidly between 35 and 40°C. Ong and Monteith (these Proceedings) suggested an optimum temperature of 32 to 34°C for leaf extension in millet.

Ong (1983) reported that soil temperature (19, 25, and 31 °C) appeared to affect many aspects of vegetative development such as seedling emergence, the initiation and appearance of leaves and early tillering. The rates of these processes increased linearly with temperature. He suggested that the rate of these processes can be described by a specific thermal time (summation of degree days above an extrapolated base temperature). However, the duration of the vegetative phase (GS1) appeared to be independent of meristem temperature within a range of 19 to 30°C at 12 h daylength (Ong 1983).

Simulation Modeling

Simulation modeling is an effective approach to interpreting the interrelationships between weather and physiological processes leading to final yield. Currently no simulation model for pearl millet is available in the literature. However, because of the similarity in some of the growth and development processes of pearl millet and sorghum, the possibility of adapting certain subroutines of an existing sorghum model, SORGF (Arkin et al. 1976) will be examined (Fig. 1). In brief, the SORGF model simulates timing of development of the plant, dry-matter production by a single plant, and partitioning of that dry matter into different plant parts based upon the stage of development of the plant as it is influenced by the environmental conditions.

Yields of sorghum and millet grown over a wide

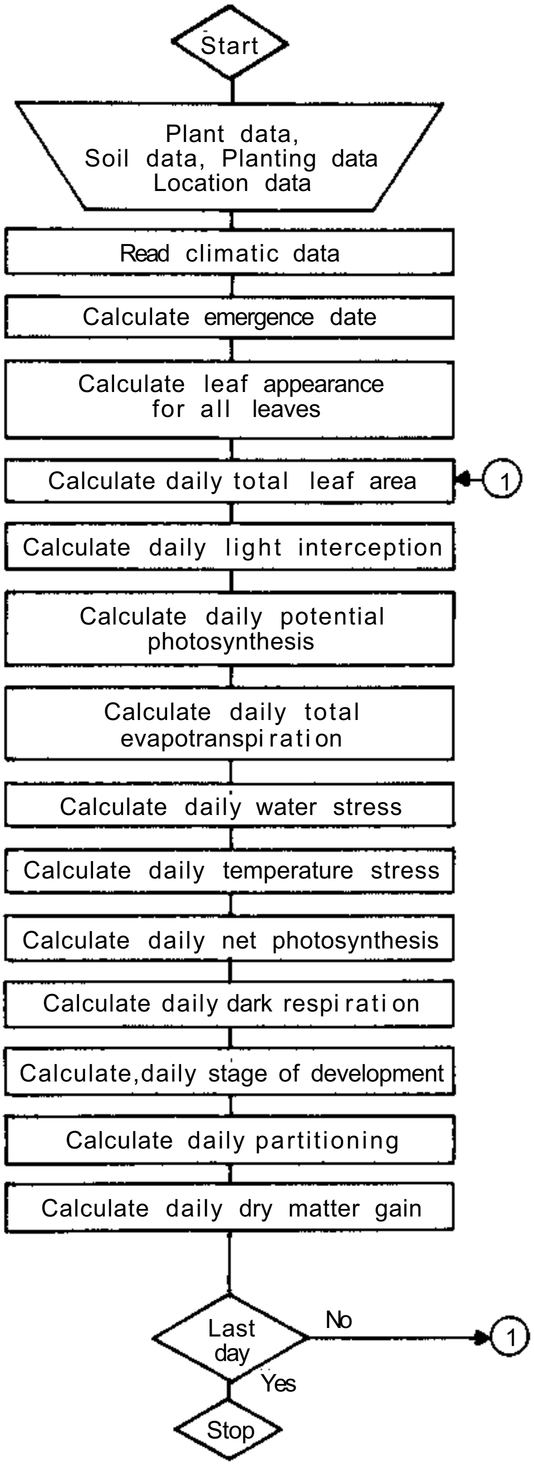

Figure 1. A generalized flow diagram of the growth model SORGF. (Source: Arkin et al. 1976.)

range of environments in the USA showed that the response of these two crops to the same environmental conditions is different (Fig. 2). Thus suitable modifications in SORGF are required for modeling pearl millet growth and development to mimic such differential responses to a given environment.

Problems and Prospects in Pearl Millet Modeling

It is recognized that much more physical and physiological information is required for building a sound simulation model for pearl millet. Therefore, interdisciplinary experiments similar to the sorghum modeling experiments coordinated by ICRISAT (Huda et al. these Proceedings) were initiated in the 1981 rainy season. Standard data sets on soil, crop, weather, microclimate, and management factors as suggested by Huda et al. (1980a) are collected to help develop a pearl millet simulation model. In this paper, the problems and potential of building relevant subroutines of a millet model that would describe features such as phenology, tillering, leaf area, evapotranspiration, dry-matter accumulation and its partitioning, etc., are described.

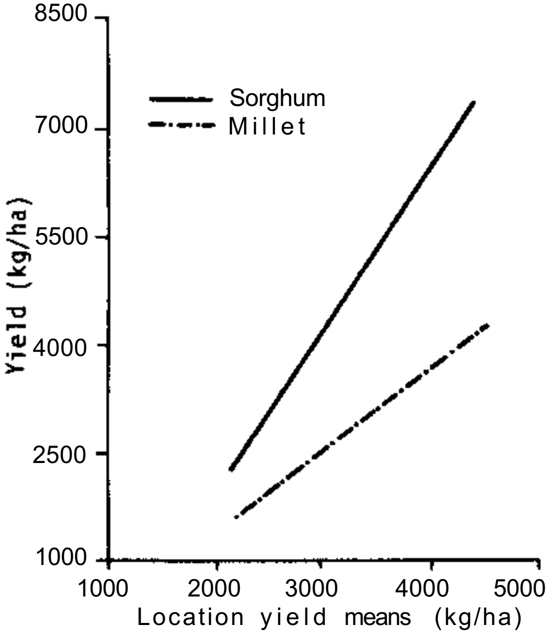

Figure 2. Average yields of sorghum and millet grown over a wide range of environments in the USA.

Phenology

Accurate simulation of phonological development is also important to determine partitioning of dry matter to different plant parts. The duration of three growth stages—emergence to panicle initiation (GS1), panicle initiation to anthesis (GS2), and anthesis to physiological maturity (GS3)—were studied. Duration of three growth stages for genotypes BJ-104, Ex-Bornu, and ICH-412 grown at ICRISAT Center during the 1982 rainy season is given in Table 1 to show the genotypic variability for phonological development. The maximum and minimum number of days, mean number of days, and the coefficient of variation for three growth stages for millet (BJ-104) pooled from different experiments conducted in different seasons at ICRISAT Center are given in Table 2. Greater variability in GS1 than in GS2 or GS3 suggests that variation in environmental factors (temperature, daylength) should be examined to explain the variability in GS1.

Table 1. Duration (days) of growtn stages of three genotypes of pearl millet grown in the 1982 rainy season at Patancheru, India.

	Genotype		
Growth stage	BJ-104	ICH-412	Ex-Bornu
GS1	15	18	18
GS2	25	36	34
GS3	27	28	27
GS1 + GS2	40	54	52
GS1 + GS2 + GS3	67	82	79

By using the concept of growing degree days (GDD) (Stapper and Arkin 1980), we studied the variability in the growth stages of pearl millet genotype BJ-104 (Table 3). However, no progress was made in reducing the variability in growth stages by accounting for the effect of temperature alone. Previous work showed the effect of daylength on the duration of GS1 in sorghum (Huda 1982) and maize (Stapper and Arkin 1980). Pooled data from our field studies in different seasons and from an experiment on the influence of daylength on millet phenology (personal communication, Peter Carberry, Research Scholar, ICRISAT) were used to plot the relationships (Fig. 3). Since pearl millet has a quantitative short-day response, the duration of GS1 increased with increased daylength. When daylength correction was introduced, variability in GS1 was reduced to 10%. Further work in this direction is under way.

Tillering

In the SORGF model sorghum was described as a single-culm plant. However, pearl millet generally produces tillers, the total number and appearance dates of which vary. Moreover, the number of effective (grain-producing) tillers varies depending upon genotype and environment. Tiller initials or buds

Table 2. Variation in phenology of pearl millet genotype BJ-104 grown over different seasons at Patancheru, India.

Growth stage	Maximum	Minimum	Mean	SD	CV (%)
	Days				
GS1	34	13	18	5	28
GS2	36	21	25	3	13
GS3	35	25	30	3	10

Table 3. Growing degree days (GDD) required for different growth stages of pearl millet genotype BJ-104 grown over different seasons (base temperature = 7°C) at Patancheru, India.

	Growing degree days (GDD)				
Growth stage	Maximum	Minimum	Mean	SD	CV(%)
GS1	687	257	351	103	29
GS2	664	375	472	66	14
GS3	657	486	567	51	9

develop in the axils of the lower leaves and are initially enclosed by the leaf sheath. Tillers develop on alternate sides of the main shoot, following the alternate arrangement of leaves. The development and growth of the tillers follow a pattern identical with that of the main shoot, with a difference in time scale. Tiller development may be nearly synchronous with the development of the main shoot or may be considerably delayed, or even suppressed by the main shoot.

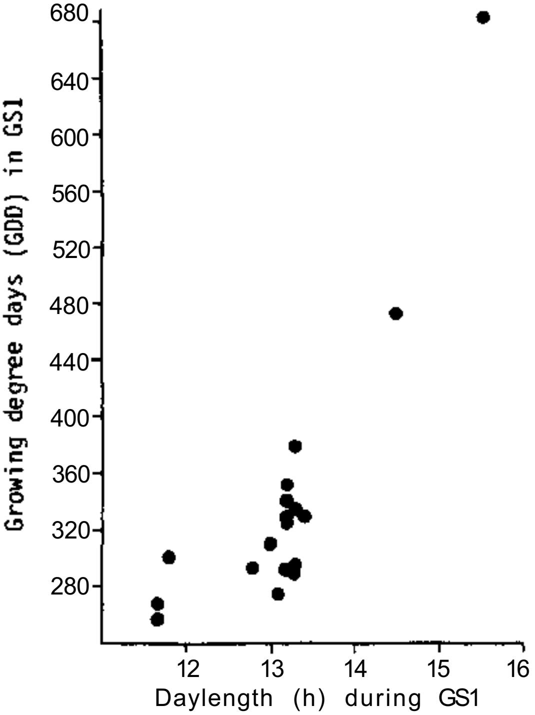

Figure 3. Relationship between growing degree days for GS1 and daylength during GS1 for pearl millet genotype BJ-104 at Patancheru, India.

Some varieties produce nodal tillers from the upper nodes of the main stem after grain set in the main panicle. These have a short developmental cycle, producing only a few leaves and usually a small panicle. Nodal tillers are common when grain set on the main panicle is poor or the main panicle is damaged in some way (Bidinger et al. 1982).

Base temperature for rate of tillering is lower than for the production and expansion of leaves (Pearson 1975; Ivory and Whiteman 1978). Ong and Monteith (these Proceedings) reported that longer days increased the duration of GS1 and produced more tillers. Tiller production at 21 °C was seven or eight times more than at 31 °C (Fussell et al. 1980).

Genotypic variability in the production of tillers was observed in an initial experiment conducted at ICRISAT Center during the 1981 rainy season (Table 4), using three genotypes—BJ-104, WC-C75, and ICMS-7703. The number of effective tillers per main shoot was much lower than the total number of tillers produced. The number of effective tillers was highest in BJ-104.

In the same experiment, we also observed that the number of effective tillers also depends on the time of planting. In the first planting, emergence occurred on 22 June; in the second, on 7 July. Table 5 compares the effects of early and late planting, showing the relative contributions of main plant and tillers to grain yield in each genotype. Early planting produced more effective tillers than late planting. The contribution of tillers to total grain yield also varied among genotypes. In late planting, contribution of tillers to total grain yield for genotypes BJ-104, WC-C75 and ICMS-7703 were 52, 20, and 16% respectively.

The interaction of time of planting (temperature, daylength, etc.), genotype, environment (moisture availability), and management conditions (planting

Table 4. Number of tillers and the time of their appearance in pearl millet genotypes grown in the 1981 rainy season at Patancheru, India.

	No. of tillers					No. of effective tillers/main plant
Genotype	1	2	3	4	5	
	—Days after emergence —					
BJ-104	23	23	25	30	45	1.2
WC-C75	23	23	30			0.4
ICMS-7703	23	25	30	45		0.5

Table 5. Effect of early and late planting on contribution of tillers to grain yield of pearl millet grown in the 1981 rainy season at Patancheru, India.

	Grain yield (kg/ha)				Effective tillers/ main plant	
	Early		Late			
Genotype	Main culm	Tiller	Main culm	Tiller	Early	Late
BJ-104	1563	2308	1600	1759	2.3	1.2
WC-C75	1889	984	2306	572	1.0	0.4
ICMS-7703	1609	1281	2462	469	0.3	0.5

density) makes it difficult to quantify tillering. Much work is needed to understand the tillering habit so as to incorporate this information into a subroutine of the pearl millet model.

Leaf Area

The rate of development of the total leaf area per plant in pearl millet is a product of the rate of leaf expansion and the size and longevity of the individual leaves for both the main shoot and the tillers. Rate of leaf area development is slow early in the season, because of the small size of the embryonic leaves, but increases rapidly approximately 15 to 20 days after emergence, as the size of the individual leaves increases and as tillers begin to expand their leaves (Maiti and Bidinger 1981).

In millet the maximum number of leaves to be produced is determined during the GS1 growth stage (Ong and Everard 1979). The contribution of the tillers to the total leaf area in pearl millet varies with genotype and with other conditions such as fertility, water availability, etc. Gregory and Squire (1979) reported that leaves from tillers can account for 60 to 70% of the total leaf area in a healthy millet crop. Maximum leaf area is attained at approximately 50% flowering of the crop, by which time the majority of the tillers have expanded all their leaves.

As the plant reaches physiological maturity, the decrease in leaf area index (LAI) is faster in pearl millet than in sorghum (Fig. 4). Because of this difference in leaf senescence between sorghum and pearl millet, and the complex nature of the tillering habit, simulation of daily progression of leaf area throughout the season in pearl millet needs an approach different from that adopted in SORGF.

Daily LAI may be estimated in millet by modeling its components (tillers/plant, leaves/tiller, and leaf area/leaf). The other approach could be to calculate the leaf area based on the weight of available leaf dry matter (Penning de Vries 1980).

Evapotranspiration

Evapotranspiration (ET) is an important component for computing soil water. Daily available soil water can be simulated by Ritchie's (1972) procedure as used in SORGF. Potential evapotranspiration (PET) can be calculated after computing potential evaporation from bare soil (Eo) and using LAI values. Eo is calculated using the Priestley-Taylor (1972) equation that requires net radiation as input data. Net radiation is computed from albedo, maximum solar radiation reaching the soil surface, and sky emis-

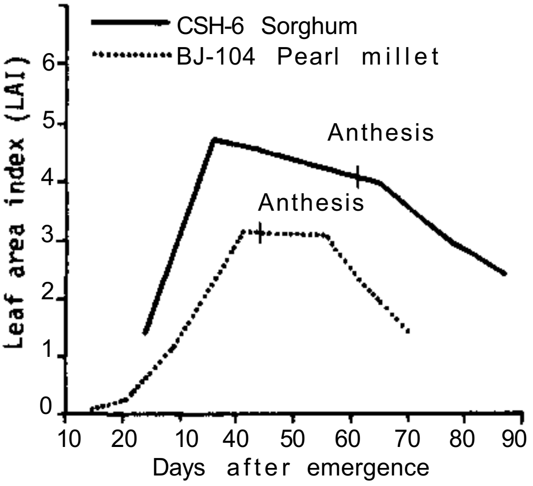

Figure 4. Comparison of leaf area index for sorghum (CSH-6) and pearl millet (BJ-104) grown during the rainy season at Patancheru, India.

sivity. The actual ET data for pearl millet obtained from Kansas (personal communication, E.T. Kanemasu, Kansas State University, Manhattan, Kansas, USA) were compared with simulated ET data (Fig. 5). The agreement between simulated and actual data is quite good, and the difference between them is consistent. However, further testing of this subroutine with additional data sets for millet is required.

Dry-matter Accumulation

Dry-matter production is related to intercepted radiation (Biscoe and Gallagher 1977; Sivakumar 1981; Ong and Monteith, these Proceedings). A simpler relationship for calculating daily dry-matter production in sorghum from intercepted radiation is discussed by Huda et al. (1982). Ong and Monteith (these Proceedings)—who studied the relationship between photosynthetically active radiation (PAR) and dry-matter production of pearl millet in the glasshouse at mean temperatures between 19 and 31°C—showed that 3.1 g of dry matter was produced for each MJ of PAR intercepted until anthesis. They expected larger values for field crops growing in the tropics.

The relationship between intercepted PAR and dry matter during the growing season was studied for three pearl millet genotypes (BJ-104, WC-C75, and ICMS-7703) grown at ICRISAT Center during the 1981 rainy season. It was observed that the rate of production of dry matter per MJ of PAR intercepted was considerably high until the completion of anthesis; thereafter, the conversion of intercepted radiation into dry matter was less efficient due to aging of the leaves. Hence it appears that simulation of dry matter from intercepted radiation should carefully consider the need to use different dry-matter conversion factors before and after anthesis.

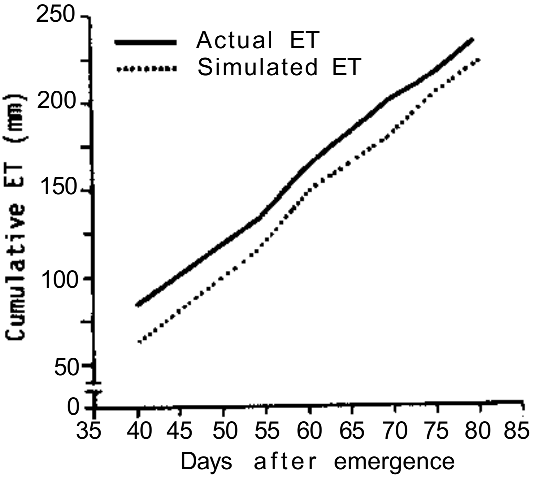

Figure 5. Comparison of actual and simulated evapotranspiration (ET) at Manhattan, Kansas, USA.

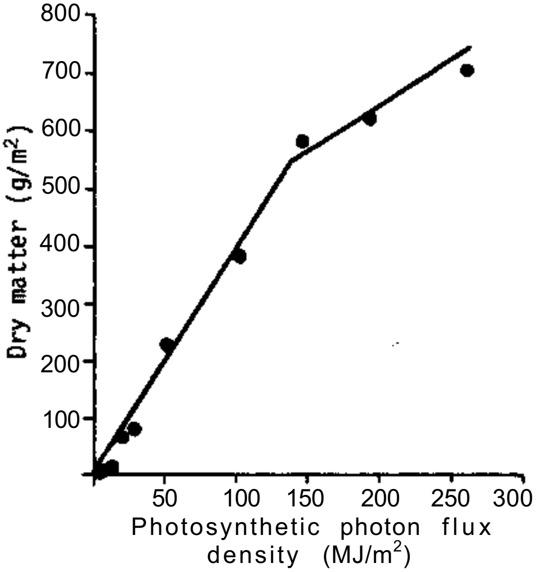

Figure 6. Relationship between dry-matter and intercepted photosynthetic photon flux density (PPFD) for pearl millet genotype WC-C75 grown during the 1981 rainy season at Patancheru. India.

For example, equations fitted to the relationship between intercepted PAR and dry matter for WC-C75 (Fig. 6) show that 3.96 g of dry matter was produced per MJ of radiation intercepted up to anthesis (GS2); after anthesis, dry matter produced dropped to 1.6 g per MJ of radiation intercepted. Williams et al. (1965) also showed for maize that dry-matter conversion from intercepted radiation could be treated in a two-stage process before and after anthesis. Gallagher and Biscoe (1978) found that aging or lack of adequate nutrition could reduce the efficiency of conversion of absorbed radiation in wheat; they obtained values of 3.1 and 2.8 g dry matter/MJ with and without applied nitrogen.

Dry-matter Partitioning

Accurate simulation of both dry-matter accumulation and plant development is essential to model partitioning of dry matter to various plant parts. Total dry matter and its partitioning to leaf, culm, head, and grain were periodically estimated throughout the growing season both for main culm and tillers in three genotypes (BJ-104, WC-C75, and ICMS-7703) grown at ICRISAT Center during the 1981 rainy season. Combined total dry matter of main culm and tillers and its partitioning to different plant parts in genotype BJ-104 are shown in Figure 7. Table 6 shows the proportion of total dry matter partitioned to various plant parts at three growth stages in genotype BJ-104 grown in different seasons at ICRISAT Center.

Model Framework

Based on the outline of the sorghum model SORGF and the USDA-SEA winter wheat ecological model, we suggest a framework for a pearl millet model (Fig. 8), with input data similar to the SORGF model. The proposed model operates on a daily basis, calculates phenological development, LAI, tiller appearance, daily ET, soil water, dry-matter accumulation, and its partitioning to different plant parts. The model simulates final grain yield and total dry matter after physiological maturity is simulated.

Table 6. **Partitioning of total dry matter (%) at three growth stages of pearl millet genotype BJ-104 grown over different seasons at Patancheru, India.**

Plant part	Growth stage		
	Panicle initiation	Anthesis	Maturity
Leaf	66	30	10
Culm	34	54	30
Head		16	16
Grain			44

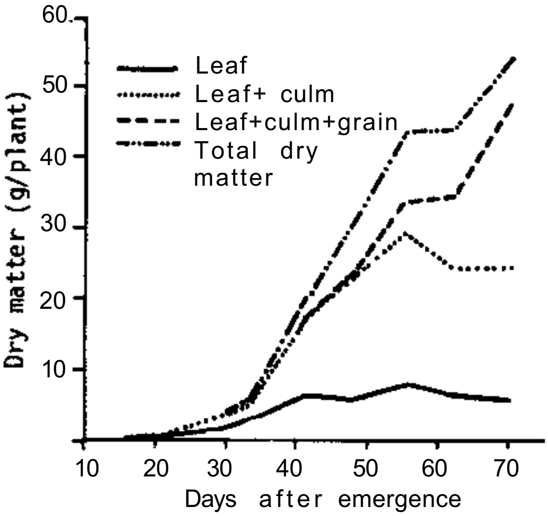

Figure 7. Total dry matter of pearl millet genotype BJ-104 and its partitioning to different plant parts during the 1981 rainy season at Patancheru, India.

Simulation Comparison

We used the preliminary suggested model (Fig. 8) to simulate grain yield of three pearl millet genotypes and compared the simulation results with the field data (Table 7). The agreement between observed and simulated values is satisfactory, but readers are cautioned that this data set was not independent of some of the information that was used for building the preliminary model. It includes many intermediate steps of the suggested model and takes the actual LAI and then simulates grain yield and total dry matter.

Table 7. **Comparison of observed and simulated grain yield and total dry matter in three pearl millet cultivars.**

Genotype	Grain yield (kg/ha)		Total dry matter (kg/ha)	
	Observed	Simulated	Observed	Simulated
BJ-104	3363	3200	7884	8000
WC-C75	2878	3313	8282	8582
ICMS-7703	2932	3428	8572	7919

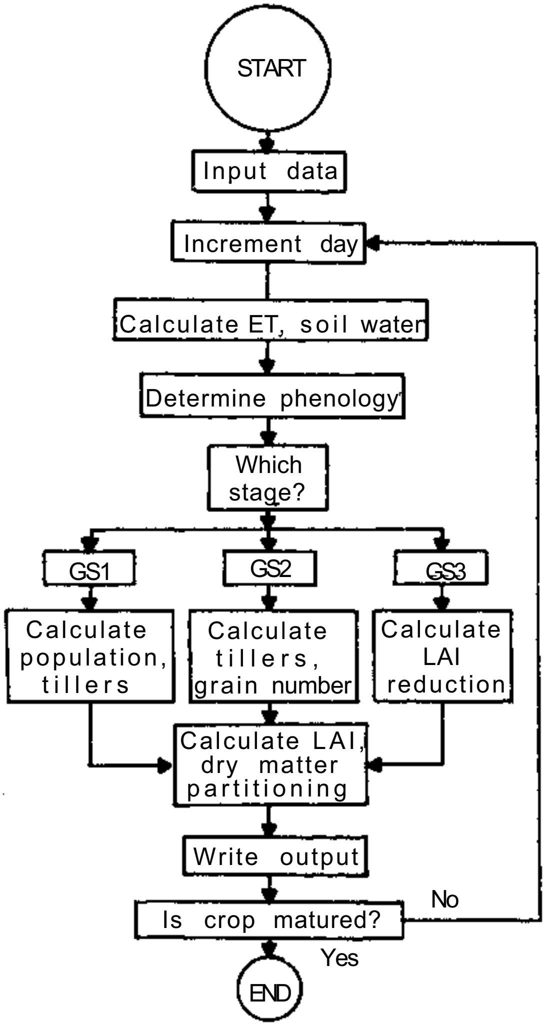

Figure 8. A suggested flowchart for a pearl millet simulation model.

Conclusions

1. A modeling approach similar to that of SORGF could be developed for pearl millet. A minimum data set required for developing and testing the model should be identified.
2. There are major differences in the growth of sorghum and pearl millet that should be carefully considered. The two most critical aspects—leaf area development and dry-matter partitioning—are both related to the tillering response of millet. Associated with that is the problem of trying to simulate the increase in leaf area on a daily basis. The approach in which LAI is computed directly from dry matter produced, instead of considering area of individual leaves, merits consideration.
3. Information on pearl millet growth and development is very scanty compared with that available on sorghum. Our progress in developing the model will therefore depend upon cooperative efforts to collect information. Effective integration of knowledge on pearl millet as it becomes available would go a long way to developing a working simulation model for this crop.

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Crop Monitoring and Forecasting

G.F. Popov*

Abstract

Many crop-forecasting models have been developed, based on statistical procedures. Unfortunately the indicators used are the condition of the crop as a result of dry spells, floods, etc.

The Food and Agriculture Organization (FAO) has designed an agrometeorological model for crop monitoring and forecasting based on a cumulative 10-day crop water balance, which shows at a given stage of the growing cycle of the crop an index (%) expressing the degree of satisfaction of the crop water requirements. This index is strongly correlated with the yield and gives a very good idea, at least qualitatively, of the yield to be expected.

If the area has a long record of statistical yield information, the index obtained over a number of years has also a quantitative value. The method has been successfully utilized in the semi-arid countries of tropical Africa. Last year it was also experimentally utilized to monitor the summer crops of rice, maize, and sorghum in south Asia.

Résumé

Surveillance des cultures et prévisions des récoltes : Il existe maintenant de nombreux modèles de prévision des récoltes fondés sur des méthodes statistiques. Malheureusement, les indicateurs utilisés considèrent l'état de la culture à la suite d'une sécheresse, des inondations, etc.

L'Organisation des Nations Unies pour l'alimentation et l'agriculture (FAO) a conçu un modèle agrométéorologique à ces fins de suivi et de prévision fondé sur un bilan hydrique cumulé sur un pas de 7 ou 10 jours. Ce bilan donne à un moment donné du cycle de croissance de la plante un indice (%) exprimant le degré de satisfaction de ses besoins en eau. Il y a une forte corrélation entre cet indice et le rendement donnant ainsi une très bonne idée, du moins qualitative, du rendement à escompter.

Si, pour la région considérée, on dispose de longues séries statistiques sur le rendement, l'indice obtenu sur un certain nombre d'années a aussi une valeur quantitative. La méthode a été appliquée avec succès dans les pays semi-arides de l'Afrique tropicale. En 1981, cette méthode a été utilisée à titre expérimental pour suivre les cultures de riz, de maïs et de sorgho dans le sud de l'Asie.

The Method

Objectives

The method presented in this paper has been designed by the Agrometeorology Unit of the Plant Production and Protection Division of FAO (Frere and Popov 1979). Its originality lies in the simultaneous use of actual rainfall data and climatological information for the calculation of the water requirements of crops. These two kinds of data are combined for the establishment of the crop water balance.

While being more precise than a single assessment of actual rainfall and its comparison with "nor-

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Note: This paper was presented by M. Frere in the absence of the author.

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mal" rainfall, the method remains simple enough to be easily operated without sophisticated equipment. It relies on a minimum amount of actual data and makes use of some climatological information, which may be assembled before the "operational" phase. Finally, the method is designed in such a way that it provides a first qualitative monitoring of crop conditions by successive steps and allows the preparation of quantitative yield assessments, provided enough information on agricultural yields is available for the region under consideration. The precision of these assessments will improve towards the harvest time.

Basic Principles of the Method

The method is based on a cumulative water balance established over the whole growing season for the given crop and for successive periods of 10 days (decades). The last decades of some months will have 8,9, or 11 days; evapotranspiration figures will be calculated accordingly. Some countries prefer to work with weekly periods, generally for reasons of organization of the work. This is possible, and FAO has prepared weekly forms in this respect. However, this approach presents some difficulties for the identification of the place of the week in the month or for the comparison of cropping seasons from one year to the next. For reasons of convenience, however, all the subsequent explanations will refer to decades.

The water balance is the difference between precipitation received by the crop and the water lost from the crop and the soil. The water retained by the soil should also be taken into account in the calculation.

It must also be mentioned that the method is intended mainly for utilization in developing countries, where in rainfed agriculture the main constraint is generally inadequate availability of water to the crop. Therefore the method does not directly involve use of temperature, which conditions the growth of the crop. However, temperature will in tact intervene indirectly in three ways in the method of crop water-balance assessment. Air temperature will first affect the length of the growing cycle, which is generally directly dependent on the temperature. Air temperature also influences directly the calculation of potential evapotranspiration and in this respect affects the whole water balance. Finally, extreme temperatures may be important in some climatic zones, particularly where frost is likely.

Calculation of the Water Balance

The different steps in the calculation of the cumulative water balance are detailed here and illustrated in Figure 1.

Normal Precipitation (PN)

Normal precipitation by decade is calculated from long-term series of climatological data for the station concerned. If only monthly totals exist, they can easily be broken down into decades by graphical processes or with the help of a minicomputer.

The normal precipitation appears only as information to indicate the "normal" date of the start of the rainy season and its "normal" length. It also shows to what extent the actual rainfall departs from the "normal" when compared with the actual amount of rainfall shown on the next line.

Actual Precipitation (PA)

The actual precipitation represents the total precipitation that falls in each decade, i.e., from 1 to 10, from 11 to 20, and from 21 until the end of the month. No account has been taken in this method of the notion of "effective" rainfall. However, it must be mentioned that rainfall is rounded to the nearest millimeter, eliminating small showers without agricultural significance. At the other extreme, large quantities of rainfall occurring during a decade penetrate into the soil and assure the recharging of the soil water storage up to the level selected for the given station. Any quantity of water penetrating into the soil beyond this threshold will percolate into the deep layers of the soil and be eliminated from the water balance. Since an excess of water will be harmful to the crops, either through mechanical action or through greater disease infestation, it is proposed to reduce the index for the decade by 3 units for every 100 mm appearing as excess water for a single decade. This assessment is in line with the relation between the index and the final yield made in some countries of tropical Africa. The precipitation measured is assumed to fall on a horizontal surface, ignoring possible lateral runoff. However, this reduction of the index should be applied taking into account other characteristics of the crop and its environment.

Number of Days of Rainfall

The observation of the number of rainy days in the decade allows a better understanding of the distri-

Station		January			February			March			April			May			June			July			August			September			October			November			December		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
MATAM 1978	PN													1	1	2	10	17	23	36	44	49	68	70	64	50	41	31	20	14	9	PN	554				
	P_a													0	0	0	0	23	11	33	46	17	41	10	6	23	21	29	0	14							
	d_a													0	0	0	0	2	1	2	5	2	5	1	1	3	2	2	0	2							
	PET																65	62	59	53	51	52	46	43	47	43	45	49	49	48	54						
	Kcr																			0.3	0.4	0.5	0.8	1.0	1.0	1.0	0.6	0.5									
	WR																			16	20	26	37	43	47	43	27	25				Σ	WR	284			
	P_a-WR																			17	26	-9	4	-33	-41	-19	-6	4									
	R_s																			17	43	34	38	5	0	0	0										
	S/D																			0	0	0	0	0	-36	-19	-6										
	I																			100	100	100	100	100	87	80	78	78									
ZIGUINCHOR 1978	PN													1	3	6	23	40	62	118	121	124	176	180	176	130	120	111	85	35	25	PN	1547				
	P_a													0	0	2	46	35	115	104	100	202	218	56	149	81	87	74	34	72							
	d_a													0	0	1	3	4	6	6	5	7	9	5	7	5	7	6	3	5							
	PET													64	61	62	52	48	44	41	38	21	35	34	38	37	39	40	41	41	45						
	Kcr																0.3	0.3	0.4	0.4	0.5	0.7	0.8	1.0	1.0	1.0	0.9	0.6	0.5								
	WR																16	14	18	17	19	19	28	34	38	37	35	24	20			Σ	WR	529			
	P_a-WR																30	21	97	87	81	173	190	22	111	44	52	50	14								
	R_s																30	51	60	60	60	60	60	60	60	60	60	60	60								
	S/D																0	0	97	87	81	173	190	22	111	44	52	50	14								
	I																100	100	100	100	100	97	94	94	94	94	94	94	94								
NIAMEY 1978	PN													11	16	19	20	26	32	50	61	70	69	70	67	45	40	16	12	7	2	PN	636				
	P_a													1	0	64	71	18	10	28	35	44	54	51	90	37	40	26	21	2	0						
	d_a													1	0	4	4	1	2	2	2	4	6	2	4	2	6	2	3	1	0						
	PET													75	76	82	69	64	61	59	56	59	49	46	52	46	51	54	58	58	64						
	Kcr															0.3	0.3	0.4	0.4	0.5	0.7	0.8	1.0	1.0	1.0	0.9	0.6	0.5									
	WR															25	21	26	24	30	39	37	49	46	62	44	31	27				Σ	WR	461			
	P_a-WR															39	50	-8	-14	-2	-4	-3	5	5	38	-7	9	-1									
	R_s															29	60	52	38	36	32	29	34	39	60	53	60	59									
	S/D															0	29	0	0	0	0	0	0	0	17	0	2	0									
	I															100	100	100	100	100	100	100	100	100	100	100	100	100									
ABECHE 1978	PN													6	8	10	6	8	12	40	48	53	77	80	75	30	20	17	8	6	3	P_N	505				
	P_a													0	2	21	18	21	15	72	74	107	15	11	83	7	45	0	6	0							
	d_a													0	2	2	1	2	2	6	3	8	4	2	8	2	5	0	1	0							
	PET													67	67	72	64	61	58	55	57	52	43	41	45	44	55	50	56	58	54						
	Kcr																			0.3	0.4	0.5	0.8	1.0	1.0	1.0	0.6	0.5									
	WR																			17	20	26	34	41	45	44	28	25				Σ	WR	280			
	P_a-WR																			55	54	81	-19	-30	38	-37	17	-25									
	R_s																			50	60	60	41	11	49	12	29	4									
	S/D																			0	49	81	0	0	0	0	0	0									
																				100	100	100	100	100	100	100	100	100									
DORI 1978	PN													7	9	10	14	20	25	49	50	52	63	65	61	40	32	24	10	4	1	PN	542				
	P_a													4	11	14	23	18	58	61	48	134	9	29	28	15	32	6	0	3							
	d_a													1	1	2	1	2	3	2	3	5	1	2	5	3	4	1	0	1							
	PET													76	78	80	68	63	59	59	57	59	48	47	50	47	50	52	55	59	59						
	Kcr																		0.3	0.4	0.5	0.8	1.0	1.0	1.0	0.6	0.5										
	WR																		20	24	29	47	48	47	50	28	25					Σ	WR	318			
	P_a-WR																		38	27	19	87	-39	-18	-22	-13	7										
	R_s																		38	60	60	60	21	3	0	0	7										
	S/D																		0	5	19	67	0	0	-19	-13	0										
	I																		100	100	100	100	100	100	94	90	90										

Figure 1. Cumulative water balances for selected stations in the Sahelian region of Africa.

bution of rain during the period. For example, total rainfall of, say, 150 mm which falls in only 1 or 2 days will imply heavy, ineffective rains, probably with some damage to crops, while the same quantity falling over 8 days would be more profitable to crops. In the same way, a total rainfall of 30 mm falling in a single day may mean some drought stress over the decade, particularly if in two successive decades two such rains occur, at the beginning of the first decade and at the end of the second one. For this reason, if a single rainy day occurs during the decade, its precise date should be indicated.

Potential Evapotranspiration (PET)

The potential evapotranspiration taken as reference in this work is the maximum quantity of water that may be evaporated by a uniform cover of dense short grass when the water supply to the soil is not limited, as defined by Penman (1948). Some slight modifications introduced in the calculation of the aerodynamic term in very hot and dry climates will in general not be applicable in this exercise, since it covers rainfed crops grown in more humid environmental conditions.

Climatological records of temperature, vapor pressure or relative air humidity, sunshine duration, and wind speed facilitate calculation of potential evapotranspiration on a monthly basis. Values for each decade of the year will then be deduced graphically or otherwise. This is possible because the variability of potential evapotranspiration is much less than that of rainfall and also because the daily fluctuations within the decade are evened out over the 10-day period. When no parameters are available for the Penman calculation, the Thornthwaite (1948) formula may be used, with precautions; good measurements made with an A pan evaporation tank are preferable. The A pan evaporation values should then be multiplied by a factor of 0.70 to 0.80 to obtain the values of PET, at least for the humid months corresponding to the effective growing season of rainfed crops.

It will not be possible to calculate potential evapotranspiration for all the stations where rainfall information is available. However, since evapotranspiration is much less variable in space than precipitation, especially if cumulated over 10-day periods, the values calculated for a station will be applicable in neighboring stations, provided conditions of altitude, temperature, relative humidity, sunshine, and wind are similar, as is generally the case in plains or plateau conditions. However, the situation is quite different in mountainous areas, where the difference in altitude and aspect will generally influence all the factors and will also modify the rainfall distribution.

Crop Coefficients (KC)

Reference PET is calculated for a dense cover of short vegetation in full growing stage. However, cultivated crops, particularly annual crops, pass through several stages of development from emergence until maturity.

The first, or vegetative, stage is from emergence to the appearance of reproductive parts (spikes for small-grain cereals and tassels for maize). During this period (Fig. 1) the maximum real evapotranspiration of the crop is a fraction of the reference potential evapotranspiration. This fraction, which increases from 0.3 at emergence to 0.9 to 1.0 at the heading stage, is the crop coefficient.

In the second stage the crop forms a uniform, dense cover; this stage lasts from 20 days before to roughly 20 days after flowering. During this period the crop coefficient is characterized by values of 1.0 or even slightly higher, up to 1.1 or 1.2.

The third main development stage of the crop starts with the formation of the grain. During this period the grain will develop and mature, while the vegetative components will be progressively reduced, and the crop coefficient will decrease from 0.9 to about 0.4 to 0.5 at maturity.

Table 1 and Figure 2 represent the evolution of the crop coefficients. Although these coefficients are far from covering the whole developing world, the general principle expressed is applicable to cereal and other seasonal crops.

For the application of the method to different crops, the crop coefficient should be suitably modified according to the above principles. For the organization centralizing the information for crop monitoring at provincial, national, and international

Table 1. Crop coefficients (KC) over three growth stages of a cereal crop.

	KC varies		
Growth stage	From		To
GS1	0.3-0.4		0.9
GS2	1.0	1.1-1.2	1.0
GS3	0.9		0.4-0.5

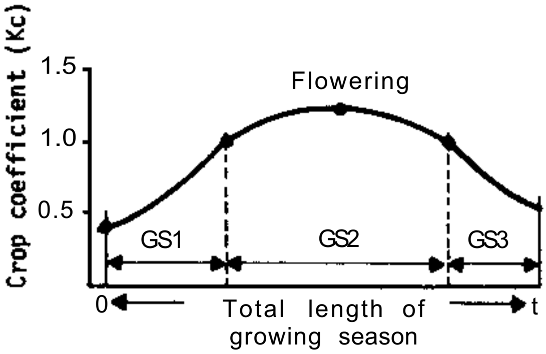

Figure 2. Variation of the crop coefficient over the growing cycle of the plant.

levels, it may be difficult to attribute the proper crop coefficient for given decades in the year; therefore, it is imperative that the inventory of background data for crop monitoring include precise information on the variety of crops grown in the various areas, the normal length of their growing cycle, and their dates of sowing. In semi-arid areas, where the short duration of the rainy season conditions the length of the growing cycle of crops, the situation is somewhat simpler than in more humid areas, where sowing of the crops may be spread over a longer period. In this kind of exercise phenological data are as important as meteorological data.

Water Requirements of the Crop (WR)

The definition of the water requirements of the crop is arrived at by multiplying the potential evapotranspiration for the decade by the crop coefficient for the same decade. Since potential evapotranspiration is calculated from climatological values and since the crop coefficient is "preset" according to the normal length of the growing period, it is possible to calculate at the beginning of the season the total water requirements of the crop for the season by adding the successive water requirements decade by decade.

Difference between Actual Precipitation and Crop Water Requirements (PA-WR)

The formula P_A-WR expresses the quantity of water available to the crops, without, however, taking into account the water stored in the soil. From this it can be seen that the effect of a given precipitation may vary according to the crop development stage.

Water Reserves in the Soil (RS)

The term RS expresses the water stored in the soil that can be readily used by the crop; in other words, it is the water reserve between the field capacity and the permanent wilting point. The amount of water usefully stored in the soil will depend on the depth of the soil exploited by the roots of the crop and on the physicochemical characteristics of the soil.

The depth of the soil exploited by the roots has to be given special consideration. It will depend on the development stage of the plant, the presence of hardpans or a permanent shallow water table, or a saline horizon, etc. On the crop side, it will also largely depend on the environment in which the crop is grown. Roots of millet grown in semi-arid areas may reach 69 to 80 cm. Taking into account the physical quality of the soil, this means an available water storage for the fully developed crop of 30 to 150 mm of water.

The physical characteristics of the soil will also influence the water-retention capacity for the same depth of soil. A layer of 50 cm of sandy soil will probably retain less than 30 mm of available water, while the same depth of loam might retain 60 to 80 mm of water.

Considering the crop development phases described earlier, it would be logical also to modify the depth of the rooting system and thus the potential water reserve available according to the development stage of the crop. In the present method it has been accepted, however, that since the crop coefficient (KC) during its first growing stages is relatively small, the water availability should generally be sufficient, and accordingly a fixed soil-water availability has been utilized. Working on a smaller scale than the one normally used in this kind of activity, one could consider a variable water-retention capacity according to the various development stages of the plant. This approach should, however, be based on experimental results on the rooting depth of plants, which are seldom available.

Surpluses and Deficits of Water (S/D)

This indicates the surpluses and the deficits regarding the water-storage capacity of the soil. Surplus refers to any quantity of water above the selected water-retention capacity level. Deficit refers to the shortfalls in the water requirements below the zero level of the water-storage capacity. These deficits are calculated taking into consideration the potential rate of crop evapotranspiration.

Index (I)

The index indicates in percentage the extent to which the water requirements of an annual crop have been satisfied cumulatively at any stage of its growing cycle.

The index is calculated as follows. It is assumed that at the beginning of the growing cycle sowing takes place when the water availability in the soil is ample. In countries characterized by a growing season shorter than 180 days (Sahelian region), effective sowing generally takes place when at least 30 mm of rain has fallen during a single decade. The index is thus assumed to be 100 and will remain at 100 for the successive decades until either a surplus of more than 100 mm or a deficit appears. If a surplus of more than 100 mm occurs during a decade, and the rainfall during the same decade has fallen in less than 3 days, the index is reduced by 3 units to 97 during this decade and remains at that level until a further stress period occurs. If after iwo decades the water reserves fall to 0 and a deficit of 20 mm appears, then the quotient between the water deficit 20 and the total water requirements 400 mm (as calculated previously) is calculated and gives a value of 0.05. This corresponds to 5% of the water requirement that is not satisfied, and the previous index figure goes from 97 to 92. The calculation is pursued to the end of the growing season, taking into account the fact that the index number starts in the first decade at 100 and thereafter can only remain at 100 or go down. The index at the end of the growing season will reflect the cumulative stress endured by the crop through excess and deficits of water and will usually be closely linked with the final yield of the crop, unless some other harmful factors (for example, pests and diseases, strong winds) have predominant effects. As illustrated in Figures 3 and 4, the index is directly related to yield and can at least give a very satisfactory and early qualitative indication of the yield.

It will also be possible to derive quantitative estimations of yields but these estimates will have to be based on the potential yield of crops, which will depend on the local environmental conditions and

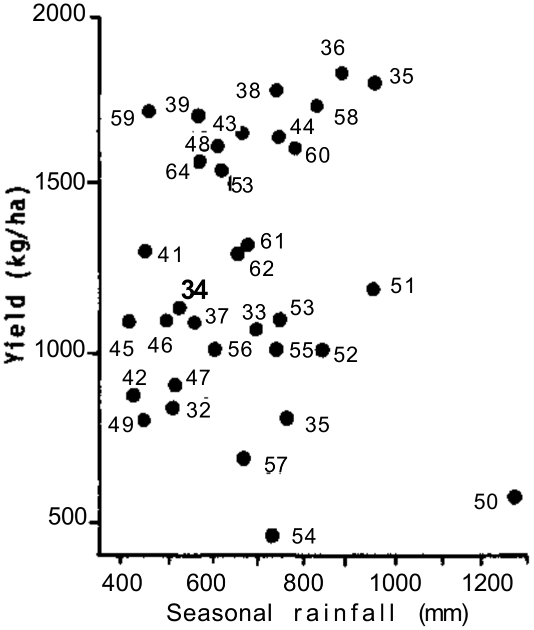

Figure 3. Comparison of groundnut yields and seasonal rainfall for 32 years (1932-1964), Bambey, Senegal.

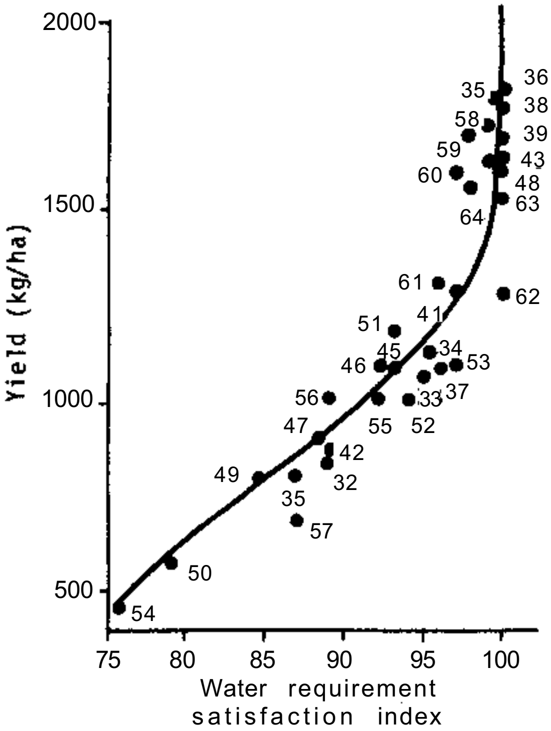

Figure 4. Comparison yield data and index 1 for 32 years (1932-1964), Bambey, Senegal.

will vary from place to place. In this way the establishment of precise correlations linking index, as defined above, and actual yields will only be possible when precise agricultural yield statistics are available for given regions. This shows the importance of keeping good statistical records of yields for the main crops and the various regions of a country. While the method allows good qualitative assessments, the quantitative forecast will always depend on good historical statistics of yields and production.

Other Factors Affecting Yields

While the present method demonstrates the utility of calculating cumulative water balances for short periods of 7 or 10 days to show the yield losses due to water stress during the growing cycle, it is also evident that other factors may contribute to the reduction of yields. These elements may be physical—such as strong winds, for example, or floods causing waterlogging—or biological, such as locusts or other insect pests, birds, or diseases.

For this reason, the establishment of a final forecast of the yield will probably depend in many cases on the water status in the plant but should also take into account all the other causes. This is why complete information on all aspects of crop development is important for the establishment of a good crop-monitoring and forecasting system in the country. This emphasizes also the importance of regular reports prepared by the agricultural authorities.

Length of the Cropping Season

In the direct application of the method in the field, the length of the cropping season and its location in the year is well known from local use. However, it may happen that the method will be used in a central planning office, where field liaison is less direct, or at regional or international levels. It is interesting in this case to have available some generalized information on crop calendars. Such information, unfortunately still incomplete, has been collected by the FAO and published in the Plant Production and Protection Series (no. 12). This publication gives information on the dates of sowing, flowering, and maturity for ten of the main agricultural crops by country. It also gives information by country on area, yield, and production of these crops.

Conclusions

Cumulative water balance resulting in an agrometeorological index gives a good indication of the satisfaction of the crop water requirements in the many areas of the world where water represents the main constraint for crops. Direct relationship to yield has been demonstrated.

The reason for presenting these results was to familiarize the reader with the method itself and to show the importance of the correct adjustment of the various parameters and coefficients utilized. Water-retention capacity in this sense is a very important value that will greatly influence the way the crop weathers unfavorable spells.

An adequate appreciation of the water stress, and hence of the probable yield of the crop, can be obtained with the method at an early date through the value of the index.

It is also important for the management of a crop-forecasting system to keep up-to-date phenological and statistical information, such as the date of sowing or, better, the conditions required by the farmers to make sowings, the length of the growing season for the various crop species and varieties, and their areas of cultivation. Attention must also be given to the representativeness of the meteorological station utilized in the application of the method.

Organization of a Crop-monitoring and Forecasting System Based on Agrometeorological Information

Basic Principles

The FAO's experience in the field of crop forecasting has been oriented mainly towards developing countries. The results of the experience gained primarily in Africa will now be presented.

The system, as it has been proposed by the FAO, can be started using the present infrastructures and does not require any sophisticated equipment. The first step in such a system is to form at the national level a committee comprising the various governmental services involved in agricultural production and covering the fields related to the factors influencing agricultural production. This formal committee should have an equivalent at the technical level, which would constitute an operational working group responsible for the conception and the day-to-day operation of the system in specific regions or at national levels, according to the possibilities offered.

The number of institutions concerned may vary from one country to another, according to the organizational scheme at the national level of agricultural research and production. For example, in Togo a working group has been created with the participation of representatives from the following institutions:

Ministry of Rural Development
- Service of Agricultural Statistics
- Service of Plant Protection

Ministry of Transport
- Meteorological Service

Ministry of Rural Land Management
- Service of Soil Surveys
- Service of Land Improvement

In other countries, such as Tanzania and Haiti, the basis of the system may be a development project financed by external sources with experts and equipment provided by the FAO or other donors. The purpose of the project is to establish progressively the kind of committee or working group referred to above and to introduce the system into the country.

Contribution of Technical Fields to the Operation of the System

Because the names of services or institutions may vary from one country to another, we prefer to enumerate the contributions to the system by technical fields.

Agrometeorology

Agrometeorology is generally one of the divisions of the National Meteorological Service. Our method is hybrid, inasmuch as the water balance is calculated from actual data (rainfall) and climatological historical data (evapotranspiration). The first task of the agrometeorological service will thus be to collect the climatological data necessary for the calculation of potential evapotranspiration by the Penman method for each month of the year, these values being divided thereafter into decadic or weekly values.

The second task of the agrometeorological service will be to assemble, in the shortest possible time after the end of the decade (2-4 days), information on cumulative rainfall and the number of rainy days during the previous decade, together with information on extreme rains capable of causing damage to crops through lodging, waterlogging of the soil, or flooding of entire areas. The agrometeorological service, in cooperation with the agricultural services, will also collect data on the average dates of sowing and the length of vegetative cycles of the main crops under investigation in the various regions.

The main task of the national meteorological service will be the utilization of the national meteorological network (synoptic and also climatological, as far as possible) to transmit the necessary data. The selection of the stations that will contribute to the system will include primarily the synoptic stations, which are already equipped for the immediate transmission of meteorological observations. It would then be useful to complete this basic network with "satellite" stations. These satellite stations should be

- representative of important agricultural regions;
- reliable as far as observations are concerned;
- able to communicate data to the synoptic station within 2 days by telephone or any other means of communication (bicycle, car, etc.).

The purpose of completing a basic system by satellite stations is to reduce the errors made by interpolating results between stations. In 1978, for example, a drought occurred in a region of Upper Volta and was not detected. Indeed, the stations of Ouagadougou, Dori, and Ouahigouya, situated outside the area, reported normal crop conditions.

On a national scale it is of course essential that, besides the network of stations providing cumulative data 2 or 4 days after the end of the decade, a close watch continue to be exercised on the climatological network and that complementary data obtained from that network be compared when received with those of the "rapid exchange network."

Agronomy

Agronomists will have to define at the outset which crops will be under investigation, considering as a general guide that the method has been designed primarily for annual cereal crops. Other annual crops might also be used, however, since the method, based on ecophysiological characteristics of the plant, is of general application.

Agronomists should also establish the precise crop calendars for the various administrative regions and for the varieties of crops investigated. They will also have to carry out a precise study of the timing of the phenological phases of the crop, so as to build the succession of crop coefficients for the whole cycle of the crop. In this regard, the results of experiments carried out by agricultural research institutions may be of great interest for the system, and representatives of these institutions should form part of the operational working group.

Plant Protection

An appraisal of any phenomena (pests and diseases) that will affect the productivity of the crop, over and above the fluctuations of the water balance, will be of interest for the monitoring and final forecasting.

Agricultural Statistics

The role of agricultural statisticians will be to collect reliable information on the areas cultivated with the crops under investigation, their yields, and their production. This information must be gathered by administrative unit so as to establish the relative agricultural importance of the various regions. For example, should the forecasting exercise demonstrate a compromised crop in two different areas of a country, it is important to know that one area produces 40% of the total production of the country and the other only 2%. Statistical data are also very important to ensure the quantitative aspect of the forecast by obtaining historical yield data of crops and comparing them with the results of the crop water-balance calculations.

Soil Science

The contribution of soil scientists is very important in assessing the physicochemical characteristics of the soils in the areas under investigation. It will be of particular interest to assess the rooting depth of crops, especially if there are serious soil constraints such as sterile horizons, hardpans, etc. Their contribution will also be important for the determination of the water-storage capacity of the soil in each region under investigation, particularly in the horizons where the roots acquire major development. This determination is most important for crops characterized by a shallow rooting system, such as rainfed rice.

Tasks of the Working Group

Having considered the various disciplines involved in the crop-forecasting system, let us now summarize the various tasks of the working group. This group will have to gather the available information throughout the crop growing season and prepare every 10 days the cumulative water balances for all the crops and the stations initially selected, taking care to obtain in time any missing or delayed information. Interdisciplinary discussions should also take place within the working group in order to improve the system during its operation as new elements are collected, particularly about the phenological stages during the current season and other phenomena capable of modifying unexpectedly the final asessment.

The working group should also consider the desirability of publishing interim reports evaluating the crop status for various crops and regions at one or several points of the cropping season. Another important task of the working group will be the selection of plots where crop situations may be considered as average and that will be harvested by specialists of the working group or by the farmers themselves, under close supervision. The results from these plots will be necessary for the physical assessment in kg/ha and for the "calibration" of the index in terms of crop yields. This operation is of utmost importance, and appropriate methods commensurate with the final results expected have to be developed by the agricultural field statisticians.

The above considerations on the organization of a system of crop forecasting based on agrometeorological information are not meant to constitute rigid rules but rather to provide some guidance derived from the experience acquired by the FAO and the World Meteorological Organization in countries where such activities have been jointly developed over the past several years. The FAO and the WMO, which are developing more and more joint activities in this respect, may usefully contribute to the establishment of the system through short consultants' missions at the beginning of the system and during the successive cropping seasons.

Conclusion

This paper has attempted to describe some of the experience gained by the FAO in the use of a method of crop assessment and forecasting based on agrometeorological information. The method has been designed for semi-arid countries; however, experience in the humid tropics has also demonstrated the occurrence of harmful dry spells that may cause reductions of varying degrees in the yield of agricultural products. It is by no means a sophisticated method and it uses several working hypotheses, which makes its operation quite simple. In addition, a lot of calculations may be performed before the cropping season begins.

The agrometeorological crop monitoring method developed by the FAO has been so far used for the last 6 years in the countries of the African Sahel; the method has also been tested in Ethiopia, Sudan, Togo, Ghana, and Zaire. National projects supported by the FAO are presently carried out in Tanzania, Zambia, and Nepal and experimental crop monitoring is done for India, Bangladesh, and Thailand. Recently the SADCC (Southern Africa Developing Countries Coordination) has requested the FAO to identify the needs in this respect for the SADCC countries and to formulate a regional technical assistance project.

The method presented here does not claim to replace other forms of crop assessment based mainly on statistical sampling. Rather, it constitutes a useful complement to statistical sampling, allowing an early assessment of the crop situation based on the causes of water stresses in crops leading to production losses. It is hoped that the introduction of such a method in national crop forecasting systems will improve their general food situation assessments.

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Agroclimatological Research in the Service of the Sorghum and Millet Farmer: Need for a Network

S.M. Virmani*

Abstract

The semi-arid tropics are characterized by a short rainy season with low and variable rainfall. In the agroecological zone growing sorghum and millet crops, agricultural production is highly variable from year to year. Agroclimatological research and applications could provide a great service of both strategic and operational importance, leading to productive viable systems. There is an urgent need to establish a network to evaluate meteorological data, in agronomically relevant terms, for the use of agricultural research and development agencies. Rainfall probability estimates, length and variability of growing season, and prediction of drought through water-balance studies are a few examples of the kinds of analyses that could be furnished on a uniform comparative basis.

Résumé

Recherche agroclimatique au service des agriculteurs du sorgho et du mil—Nécessité d'établir un réseau : Les zones tropicales semi-arides sont caractérisées par une courte saison des pluies avec des précipitations faibles et aléatoires. Dans la région agroécologique de cultures du sorgho et du mil, il y a une forte variabilité interannuelle de la production agricole. La recherche agroclimatique et son application seraient très utiles tant aux niveaux stratégique qu'opérationnel, entraînant des systèmes productifs et viables. L'auteur souligne le besoin pressant d'un reśeau afin d'évaluer les données météorologiques aux fins agronomiques dans l'intérêt des agences de recherche et de développement. Les estimations de probabilité, la durée et la variabilité de la saison de végétation et la prévision de sécheresse à l'aide des études du bilan hydrique sont quelques exemples d'analyses possibles sur une base comparative standardisée.

Over the last 3 days we have discussed the scientific advances that have been made on agrometeorological assessments for improving and stabilizing yields of sorghum and millet. Research on quantifying and characterizing the canopy environment has been presented. These studies could help alleviate the recurrent drought stress to which crops grown in the semi-arid tropical environment are exposed. Agroclimatologists could provide a great service of both strategic and operational importance, leading to productive viable farming systems for the ecological area growing sorghum (*Sorghum bicolor* [L] Moench) and millet (*Pennisetum americanum* [L] Leeke) in the semi-arid tropics of India, Africa, and the South American countries.

Sorghum and Millet Production in the SAT

The semi-arid tropics, following Troll's classification, are areas where monthly rainfall exceeds

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potential evapotranspiration for 2 to 7 months annually and the mean monthly temperature is above 18°C for most of the year. Within this climatic zone, the areas with 2 to 4.5 wet months are called the dry semi-arid tropics, and almost all the millet (> 90%) and most of the sorghum (>75%) are grown in this area. Millet production is concentrated in the areas with 2 to 3 wet months or less—a drought-prone belt of Sahelian Africa and the low-rainfall areas of the Indian subcontinent. The farmers' average yields are 500 to 600 kg/ha over the 26 million ha grown (Table 1). In southern Africa the production has been declining at 0.5% per year and in West Africa a growth rate of 1.0% has been observed. India and eastern Africa had growth rates of 1.3 and 2.9% per year, respectively, which are well below the projected demand growth.

The yield of sorghum grown in the SAT areas of Africa and the Indian subcontinent (Table 2) is only 800 kg/ha compared with 3400 kg/ha in non-SAT high-technology systems. Although historical sorghum production growth in the semi-arid tropics exceeds the projected demand growth in developing countries (ICRISAT 1982), there are major regional imbalances. In West Africa over the last 20 years, sorghum production has been growing at a rate of only 0.7% per year; in southern and eastern Africa, over the same period, at less than 2.7% per year; and in India, at just over 1.6% per year.

Table 1. Geographic regions of pearl millet production (1978 data base) including area and yield.

Region	Area (million ha)	Average yield (kg/ha)
Sahelian Africa Cameroon, Chad, Mali, Mauritania, Niger, Nigeria, Senegambia, Sudan, Upper Volta	13.55	520
Southern and eastern Africa Botswana, Egypt, Tanzania, Zambia, Zimbabwe	0.69	500
Northern India and Pakistan Gujarat, Haryana, Madhya Pradesh, Punjab, Rajasthan, Uttar Pradesh, and Pakistan	8.39	430
Central and southern India Andhra Pradesh, Karnataka Maharashtra, Tamil Nadu	3.31	420

Sources: FAO (1978); India (1978); International Association of Agricultural Economists (1976); PARC (1976).

Table 2. Geographic regions of sorghum production including area and yield.

Region	Area (million ha)	Average yield (kg/ha)
Indian subcontinent	16.6	784
West Africa, low to intermediate rainfall areas (Nigeria, Senegambia, Sudan, Mali, Upper Volta)	13.4	654
West Africa, high rainfall areas	22.9	655
Eastern Africa and Yemen (Ethiopia, Kenya, Tanzania, Yemen)	6.2	956
Southern Africa (Zimbabwe, Mozambique, Malawi, Botswana)	0.8	758
Central America and Mexico	1.9	1655
Tropical South America	0.65	2171
Far East	8.6	1043
Southeast Asia	0.5	1183
Mediterranean - USSR		
Temperate America	7.9	2508
Oceania (primarily Australia)	0.4	1812

Source: FAO (1978).

It seems clear that the developing countries within the SAT region will experience either increasing shortages *of* sorghum and pearl millet at present prices or, more likely, much higher prices and large numbers of low-income people with unmet food needs (Ryan and von Oppen, these Proceedings). One estimate from the USDA is that the deficit in food in the sub-Saharan Africa could be between 9 and 13 million tonnes by 1990.

The Urgent Need for an Information Network

Several international and national organizations—such as the WMO, ORSTOM, ASCENA, and the meteorological establishments of the countries growing sorghum and millet in the SAT—have assembled a large data base on the climatic environment. But these data are available only piecemeal, from a variety of sources, and there is an urgent need to put them together, placed so as to be easily accessible to all. ICRISAT has tried to collect rainfall and related meteorological data at its center. We request assistance from other organizations to broaden this data base.

Analysis of the rainfall data on a uniform comparative basis for evaluating the climatic attributes of diverse locations is essential. ICRISAT has undertaken publication of rainfall prooability estimates for several West African countries. We would encourage publications from other semi-arid tropical areas by providing our computer resources, by making available computer programs, and by training scientists and technicians.

Relevance of Agroclimatic Studies

The SAT is noted for its variable rainfall and high evaporation; hence monthly mean rainfall is insufficient for the fine agroclimatic divisions within the ecological region; probability estimates of rainfall on a weekly basis would be a much more sensitive parameter. Robertson (1976), Virmani et al. (1978), and Sivakumar et al. (1979) have shown that the use of Markov chain procedures for estimating initial and conditional probabilities of rainfall could be used effectively for defining the dependability of precipitation during the rainy season. The risks associated with the survival of crops on receipt of sowing rains and the dependability of rainfall at critical stages of crop development could be assessed through such analyses.

Rainfall Probability Analyses

Table 3 shows the probability of receiving at least 10 mm of cumulative weekly rainfall during the rainy and postrainy seasons for Bellary, India (latitude 15°N, annual precipitation 533 mm) and Niamey, Niger (latitude 13°N, annual precipitation 584 mm) for initial (W) and conditional probabilities (W/W) and (W/D). It is evident that the rainy season at Bellary is much shorter than at Niamey, although both locations receive approximately similar amounts of total annual rainfall. The seasonal rainfall at the two locations is unimodal and that seasonality is strongly exhibited at both. Further, the initial probability of weekly rainfall does not exceed the 70% level in any week at Bellary during the rainy season. The wet/wet conditional probability estimates exceed this threshold value in only 2 weeks. A review of wet/dry probabilities further shows that the dependability of rainfall throughout the rainy season at this location is fairly low. All these factors show that dryland crop production at the Bellary location would be risky.

At Niamey, on the other hand, the initial and conditional probabilities of rainfall are fairly high (>70%) from standard meteorological week 28 through week 36, i.e., 9 July-9 September. Thus at this location (Table 3) there is an excellent stability of rainfall for the 60-day period commencing from 9 July in at least 8 or 9 years in a 10-year period. The agroecological potential of the Bellary and Niamey locations would therefore be entirely different. The crops and their management practices would also differ considerably. Such agroclimatic studies could be of considerable use in rainfall resource assessment and its management in the SAT.

Efficient Water Use in the Semi-Arid Tropics

In the semi-arid tropics the amount of precipitation is highly variable from year to year. Water-balance studies are therefore important for characterizing the variations in availability of water for crop production.

Ideally, any study of the water balance of an area should be based on long records of water supply (precipitation, water inflow, soil moisture storage) and water loss (evaporation, transpiration, water runoff, subsurface outflow). Water-balance studies can contribute significantly to the study of such needed parameters as soil moisture, water deficit, water surplus, and water runoff. A knowledge of these values is important for evaluating risks to dependable crop production in dryland areas and for developing strategies to overcome them; however, few empirical data are available.

Virmani (1976) carried out an in-depth analysis of the water balance of a range of soils commonly found in the Hyderabad region (mean annual rainfall: 760 mm) using the approach developed by Nix (cited by Keig and McAlpine 1974). The results (Fig. 1) showed that the water-holding capacity of the soil has a considerable influence on the availability of soil moisture during the growing season. For example, deep Vertisols with approximately 300 mm available water-holding capacity (AWC) would have a growing season extending to 26 weeks, medium-deep soils (150 mm AWC) to about 21 weeks, and shallow soils (50 mm AWC) an average growing season of 18 weeks, commencing from mid-June. Such information based on

Table 3. Initial and conditional probabilities of receiving 10 mm weekly rainfall at two locations during the rainy and postrainy season.[1]

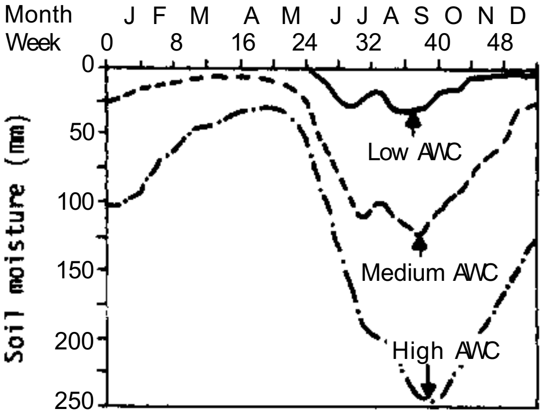
Bellary (India)[2]				Niameyville (Niger)[2]			
Standard week	W	W/W	W/D	Standard week	W	W/W	W/D
	Rainy Season				Rainy Season		
35	0.37	0.38	0.30	22	0.37	0.50	0.24
36	0.33	0.35	0.53	23	0.54	0.55	0.32
37	0.47	0.76	0.62	24	0.57	0.67	0.63
38	0.69	0.73	0.59	25	0.65	0.63	0.59
39	0.69	0.67	0.64	26	0.62	0.64	0.58
40	0.66	0.61	0.38	27	0.62	0.90	0.88
41	0.53	0.41	0.48	28	0.89	0.88	1.00
42	0.44	0.39	0.36	29	0.89	0.88	0.86
43	0.37	0.54	0.27	30	0.87	0.91	1.00
44	0.37	0.50	0.30	31	0.92	0.93	1.00
	Postrainy season						
45	0.37	0.38	0.11	32	0.94	0.95	1.00
46	0.21	0.20	0.15	33	0.95	0.90	1.00
47	0.16		0.10	34	0.90	0.88	1.00
48	0.09	0.17	0.05	35	0.89	0.79	0.86
				36	0.79	0.66	0.77
				37	0.68	0.51	0.50
				38	0.51	0.19	0.48
				39	0.33	0.33	0.21
					Postrainy season		
				40	0.25	0.13	0.11
				41	0.11	0.14	0.4

1. Data base: Bellary 58 years; Niameyville 63 years
2. W is initial probability; W/W is conditional probability of a rainy week following a rainy week, each receiving at least 10 mm of rainfall; W/D is conditional probability of rainy week receiving at least 10 mm of rainfall following a week receiving <10 mm of rainfall.

water-balance research is useful to agricultural scientists in devising cropping strategies for optimizing crop production in different types of soils, for evaluating risks, and for optimizing inputs. As an example, one could say that water-recycling systems would be an attractive proposition in soils with low and medium available water storage capacities in the Hyderabad area. Our watershed studies have confirmed this hypothesis.

Water Balance and Crop Production

One other aspect of our water-balance work relates to watershed-based land and water management studies on deep Vertisols. We have observed (Kanwar et al. 1982) that water-balance components show marked differences under different land-use systems. Under the traditional rainy-season fallow system of land use, the use of water for productive purposes is limited to about 40% (Table 4). Through an innovative technology in which crops are raised both in the rainy and postrainy seasons, the ET component of the water-balance could be raised to over 70%. With this technology the evaporation and runoff losses of water have been significantly decreased. Since the production of dry matter by field crops is directly proportional to the amount of water transpired (DeWit's hypothesis), yields under the two systems



Soil	Average water storage capacity
Low AWC	50 mm
Med AWC	150 mm
High AWC	300 mm

AWC - Available water holding capacity

Figure 1. Weekly soil moisture storage in three soils of the Hyderabad (India) region (Hyderabad rainfall records 1901-1970).

were dramatically different. Under rainy-season fallow, chickpea yields averaged 634 kg/ha; sorghum yields, 483 kg/ha. Under the improved two-crop system, maize yields averaged 2791 kg/ha; and pigeonpea 1060 kg/ha. I should add that the results of this technology were achieved through a team approach. While the agroclimatologists showed that adequate amounts of water were available for crop production, the agronomists and engineers designed practices to exploit this available potential.

Conclusion

Agrometeorological research is a highly interdisciplinary field. Climatologists must work in close collaboration with soil scientists and agronomists. A continuous awareness of the interdisciplinary research needs and exchange of empirical experimental results are necessary. A network to act as a clearing house for this information in the SAT should be established.

To be of agronomic relevance, climatic water-balance studies must be integrated with the soil moisture holding characteristics. Such studies could help construct different crop production scenarios. Across the SAT there is a great diversity of soils and a similar diversity of measurement of soil moisture-holding characteristics.The agrometeorological network should establish a working relationship with the soil physics research so that comparative and uniform data for assessing the length of the crop-growing season are obtained. Such a knowledge would be of great value to the agrotechnologists, who could use it to construct practical models to predict crop response to environmental variables.

Finally, I believe a quantification of the climatic environmental research would assist greatly in our search for productive and stable agricultural systems for the semi-arid tropical areas.

Table 4. Water-balance components observed under two systems of land use on deep Vertisols at ICRISAT Center, near Hyderabad, India.

	Water-balance component				Period of study
System of land use	Runoff	Deep percolation	Evaporation	Evapo-transpiration	
	% of seasonal rainfall				
Rainy-season fallow Postrainy-season cropped (Oct-Jan)	25	9	25	41	1973-78
Rainy and postrainy seasons cropped (Jun-Jan)	12	10	6	72	1977-79

Source: Kanwar et al. (1982).

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