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Progress Report-5

RP

Report of Work

1980-81

Agroclimatology

Farming Systems Research Program

ICRISAT

International Crops Research Institute for the Semi-Arid Tropics
ICRISAT Patancheru P.O.
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1981

NOTE TO THE READER

This is pre-publication informal report of work for June 1980-May 1981. This report is designed to stimulate thinking and comments from professional colleagues and is not to be considered as a formal publication bearing the endorsement of the Institute.

This is one of seven subprogram reports from the Farming Systems Research Program. The seven subprogram reports include the following:

Agroclimatology
Environmental Physics
Soil Fertility & Chemistry
Farm Power & Equipment
Land & Water Management - Hydrology
Cropping Systems
Agronomy & Weed Science

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INTRODUCTION

Agroclimatology research during 1980-81 covered, as in the previous years, two major areas of research: (a) collection and interpretation of climatological data from different regions of SAT and (b) microclimatological and crop weather modeling studies. In the former areas of research, we put major emphasis this year on revising the SAT maps for India, Africa and Northeast Brazil as per the Troll's approach. We also looked at the climatic environment for pigeonpea in the SAT. As a part of continuing efforts to classify climates, we have initiated some work on the principal component analysis.

Our studies over the past three years showed that data on interception of Photosynthetically Active Radiation (PAR) could be effectively used along with drymatter data to compute growth efficiencies of crops. We have observed significant differences in the growth efficiency of sorghum grown during the rainy and postrainy seasons. Our studies on crop response to moisture stress with sorghum and millet showed that field measurements of transpiration rates are very useful to interpret genotypic responses to water stress.

Our efforts to validate a sorghum growth and development simulation (SORGF) using multilocation collaborative approach yielded encouraging results Several subroutines in the model have been suitably modified to make the model sensitive to the sorghum growing environments of SAT. The correlation coefficient for grain yield between observed data and simulations from the SORGF model and revised SORGF model (0.17 for SORGF and 0.87 for the revised model) showed that the revisions made were useful. These efforts indicate the scope for model improvements and encouraged by these results we initiated work on developing a growth and development model for pearl millet.

Ongoing work on rainfall climatology of West Africa, experiments evaluating the moisture stress responses of groundnut and chickpea are not reported this year. These along with our initial attempts at modeling the millet growth and development will be reported next year.

CHAPTER I

Weather at ICRISAT

1. Rainfall

a) Rainfall amount and distribution

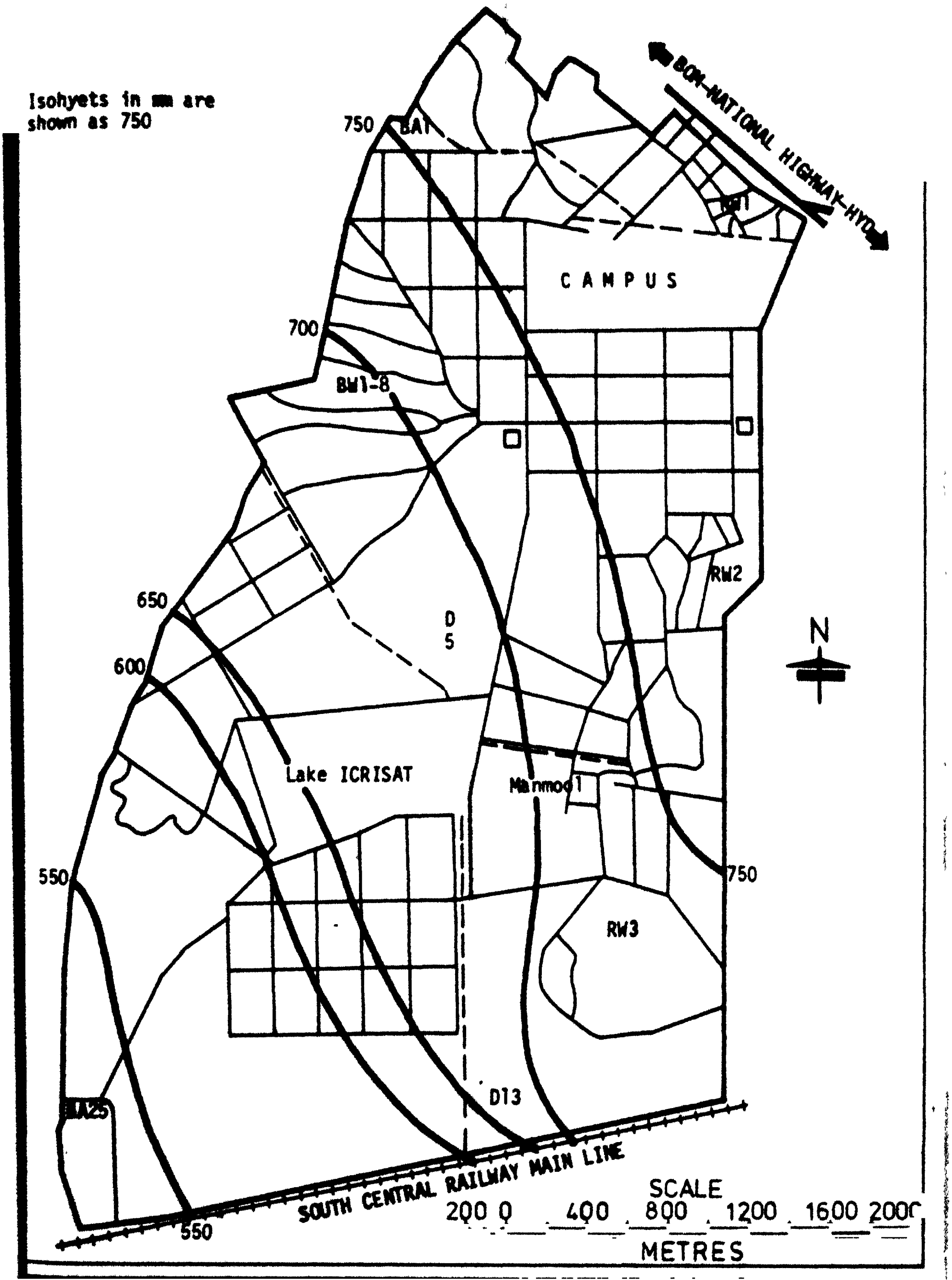
In 1980, the rainy season commenced early by 1 June and receded also very early by 24 September. A total rainfall of 733 mm was recorded at ICRISAT meteorological observatory during June to October (normal 691 mm). However, over ICRISAT Center the rainfall varied from 530 to 780 mm (Fig. 1). Figure 2 depicts the weekly rainfall receipts. Daily rainfall amounts recorded from June to October at ICRISAT Center along with the data of monthly rainfall and average monthly rainfall are presented in Figure 3. While July, September and October received below average rainfall, June and August received above average rainfall. In the first fortnight of June about 135 mm of rainfall was received. Afterwards, from 17 June to 22 July, there was a prolonged break in rains, except for about 20 mm of rain on 1 July and negligible amounts on few other days. The rainfall was well distributed from 22 July to 23 August. However, on any given day the variation of rainfall over ICRISAT Center was very wide. On 20 August the rainfall amounts varied from 10 to 130 mm (Fig. 4). This was reflected in the seasonal rainfall distribution too (Fig.1). The second longest dry spell was during 23 August to 2 September. The effect of this long dry spell was clearly reflected in the variations in other meteorological parameters also. Rainfall amounts exceeding 5 mm were recorded on 31 days while the highest rainfall of about 117 mm occurred on 20 August.

b) Rainfall intensities

In 1980, there were 16 storms with intensity exceeding 20 mm/hr (Table 1) of which the intensity of 11 storms exceeded 40 mm/hr. This year there were three significant storms. The first one on 12 June lasted for about one hour and 42 mm of rain was recorded. The second was on 19 August with 119.5 mm rain in two spells - the first spell of 27 mm lasted for about 45 minutes and the second spell of 90 mm lasted for about four hours. The third storm was on 20 August with about 70 mm rain in two spells - the first spell of 32 mm lasted for about 45 minutes and the second spell of 33 mm lasted for 105 minutes.

2. Moisture environment for crop growth

The generalised trends of simulated available soil moisture in Vertisols and Alfisols with water holding capacities of 230 and 120 mm respectively are depicted in Figure 3. The simulations were made for the maize/pigeonpea (100/180 days) intercrop in deep Vertisol watershed BW3A and for pearl millet (77 days) in the Alfisol watershed RW1. In Alfisol the soil moisture was below 50% of its capacity during second half of July. The soil was at field capacity at the time of harvest of pearl millet. In the case of Vertisols



1. Seasonal (June to October) rainfall distribution over ICRISAT Center, 1980.

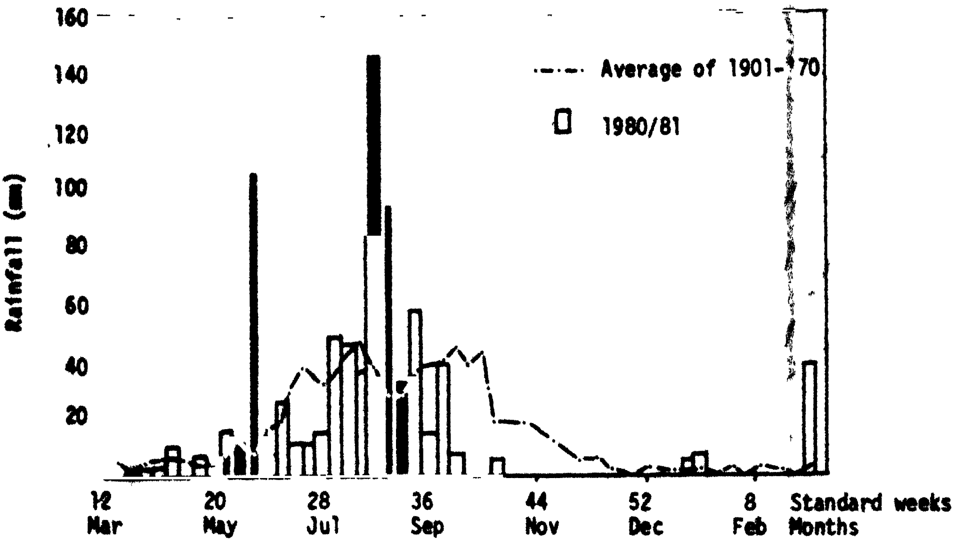


Figure 2. Weekly total rainfall distribution at ICRISAT Center for 1980-81 and average of 1901-'70.

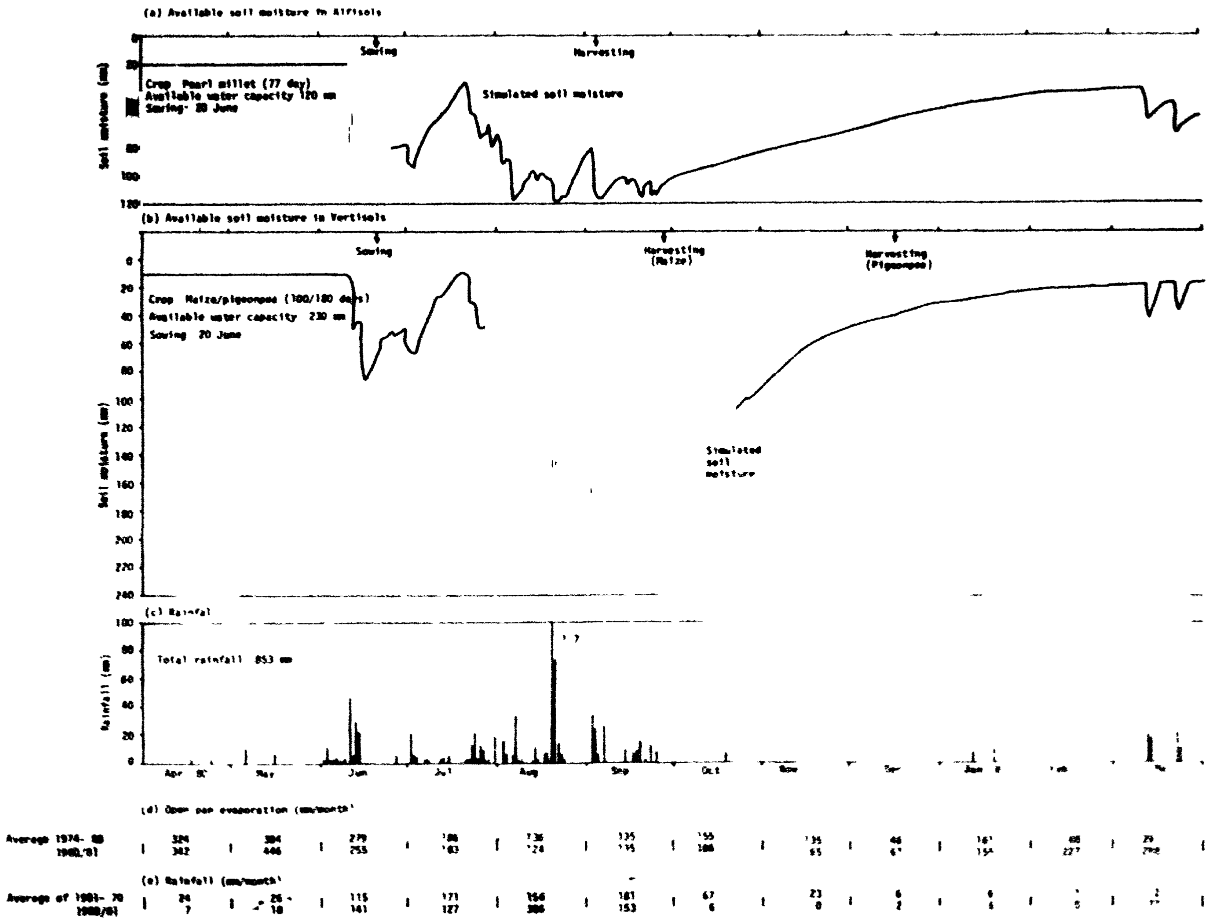


Figure 3. Available soil moisture in deep Vertisols and Alfisols, daily rainfall, and monthly totals of open pan evaporation and rainfall at ICRISAT Center, 1980-81.

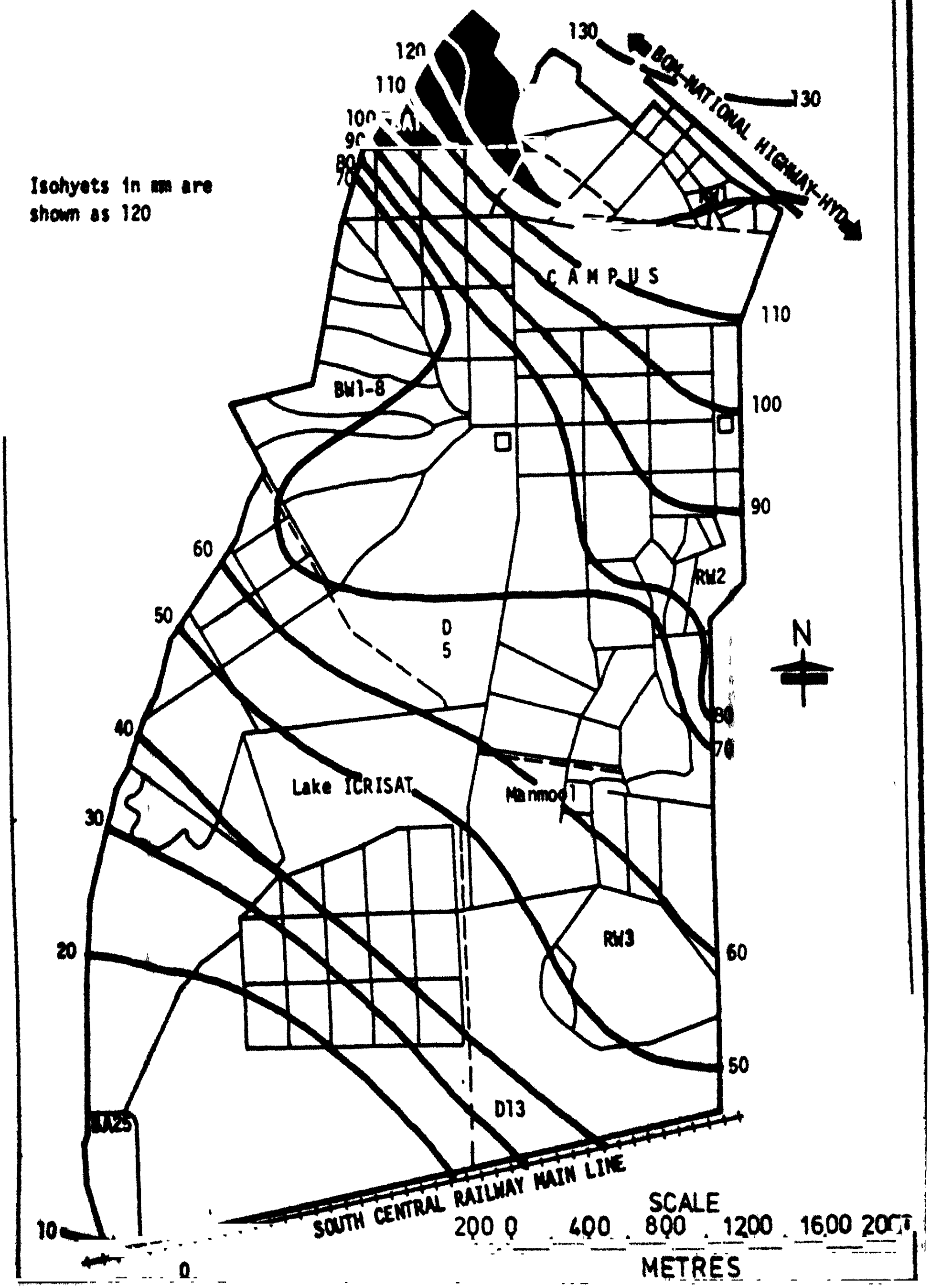

Isohyets in mm are shown as 120

Figure 4. Variability of rainfall over ICRISAT Center as recorded on 20 August 1980.

the soil moisture was below 50% of the available water capacity up to middle of August and in the middle of July the soil moisture was even less than 25% of the available water capacity.

Table 1. Duration and t of intensive rain spells recorded during 1980 rainy season.

Date	Duration (Min.)	Rainfall[1] (mm)	Intensity (mm/hr)
02-6-80	15	10.0	40.0
12-6-80	15	14.0	56.0
15-6-80	15	10.0	40.0
16-6-80	15	6.5	26.0
01-7-80	15	13.0	52.0
22-7-80	15	10.0	40.0
23-7-80	15	12.0	48.0
30-7-80	15	11.5	46.0
06-8-80	15	11.0	44.0
19-8-80	15	14.5	58.0
20-8-80	15	14.0	56.0
03-9-80	15	9.0	36.0
06-9-80	15	15.5	62.0
18-9-80	15	7.0	28.0
22-9-80	15	6.5	26.0
24-9-80	15	5.5	22.0

[1] High intensity spells recording 5 mm/15 minutes are considered.

3. Some important meteorological observations in 1980/81

Daily averages based on weekly totals of air temperatures, relative humidity, wind velocity, open pan evaporation, bright sunshine hours, global solar radiation and net radiation are presented in Figures 5 to 10. Average data for the last seven years for all meteorological elements (1974-80) excepting radiation are also presented and discussed in relation to 1980/81 data.

a) Air temperature Figure 5)

The day temperatures were generally around 40°C during April and May. The highest maximum temperature of 41.9°C was recorded on 27 May and the lowest minimum temperature of 8.8°C was recorded on 8 December. The day temperatures were above average from end of September, 1980 to March, 1981. During the rainy season maximum temperatures fluctuated around the average while minimum temperatures were close to average temperatures.

b) Relative humidity (Figure 6

The relative humidity was above 60% both during morning and evening hours in

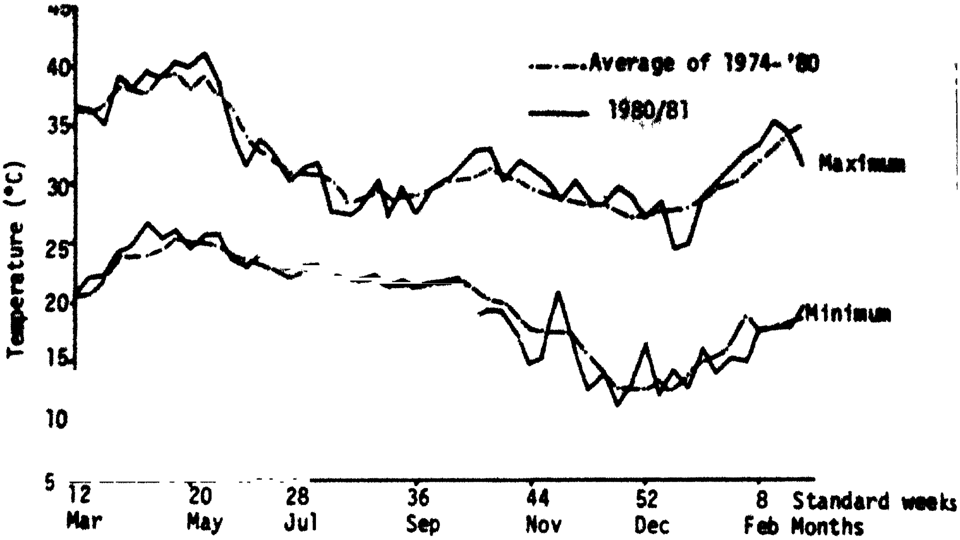


Figure 5. Average weekly air temperature at ICRISAT Center, 1980-81

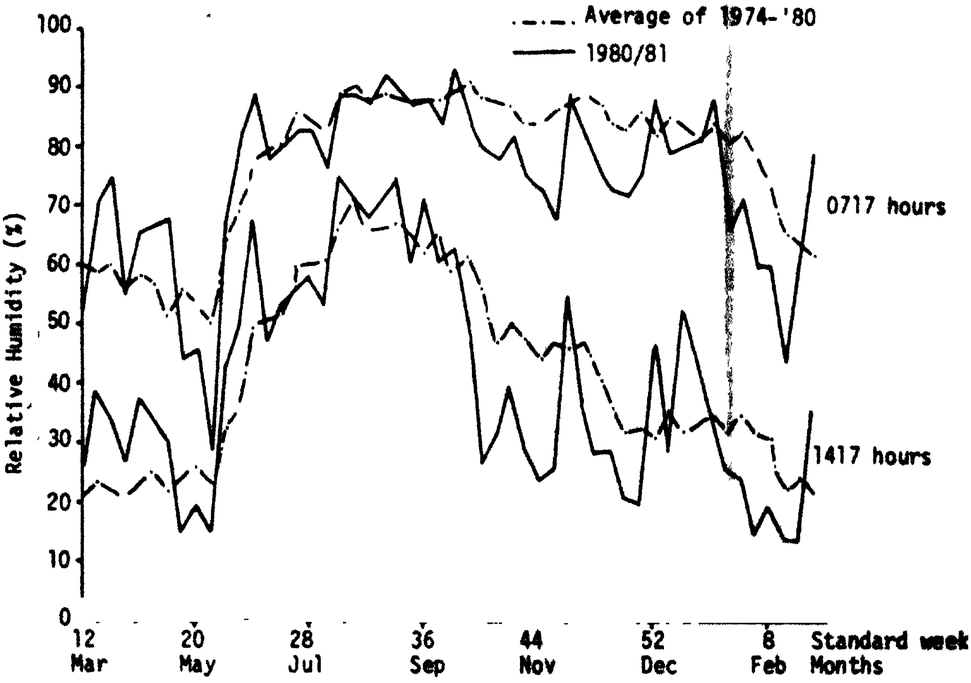


Figure 6. Average weekly relative humidity at ICRISAT Center, 1980-81.

the rainy season -- slightly above average. During October to March the relative humidity was below average.

c) Wind velocity Figure 7)

In June the wind speeds were above average and in the rest of the period the wind speeds were around the average. The highest wind speed of 31.1 km/hr was recorded on 28 June 1980. From the second half of September to March the winds were in 5-10 km/hr range. During the rest of the period the winds were above 10 km/hr.

d) Open pan evaporation Figure 8)

Except for short periods in June, July and August, open pan evaporation was above average. This was mainly due to dry atmospheric conditions prevailing at that time with above average temperatures and below average relative humidities. However, due to low winds evaporation has not reached the abnormal level. The highest value recorded for any 24 hour period was 19.4 mm on 25 May 1980. From October onwards the evaporation was above 4 mm/day.

e) Sunshine (Figure 9)

The sunshine hours were below average during June to August. During September to December these were around the average and on many days the sunshine was more than 10 hours/day.

f) Radiation (Figure 10)

During July and August the global solar radiation was below 400 ly/day. During the rest of the period it was generally above 400 ly/day and in summer it was even above 500 ly/day. Net radiation was in the range of 100-200 ly/day.

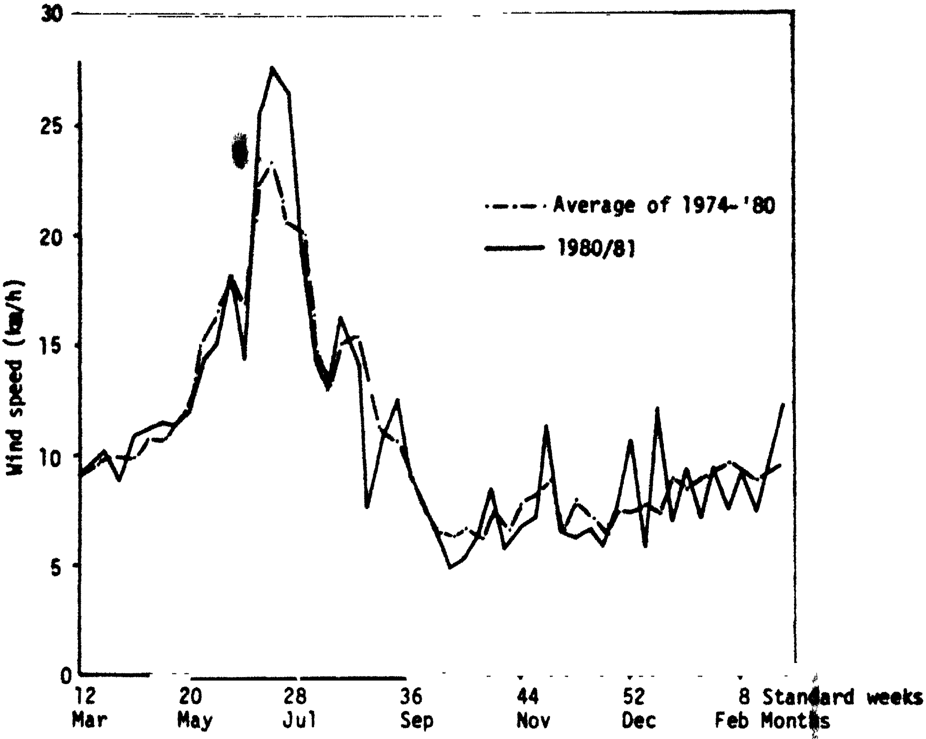


Figure 7. Average weekly wind-speed at ICRISAT Center, 1980-81.

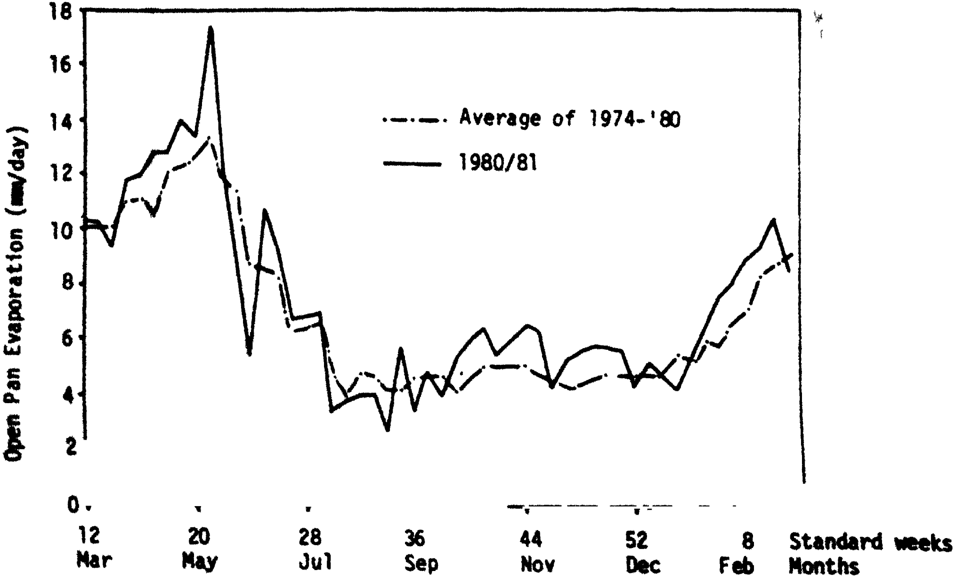


Figure 8. Average weekly open pan evaporation at ICRISAT Center, 1980-81.

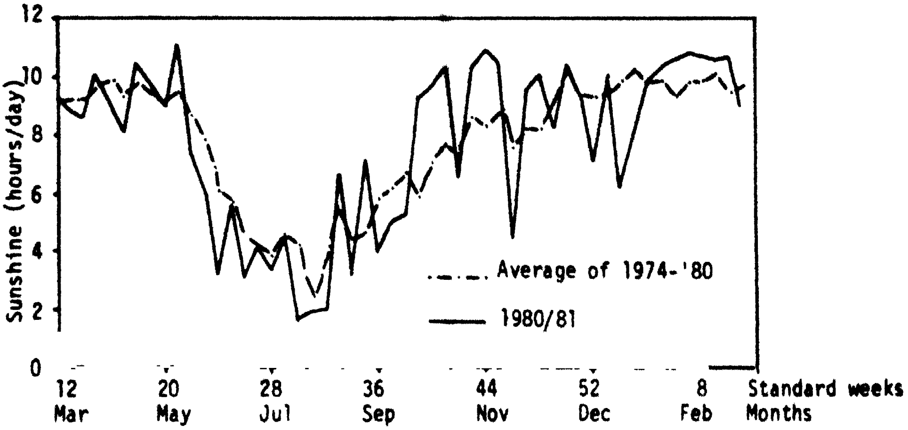


Figure 9. Average weekly bright hours of sunshine at ICRISAT Center, 1980-81.

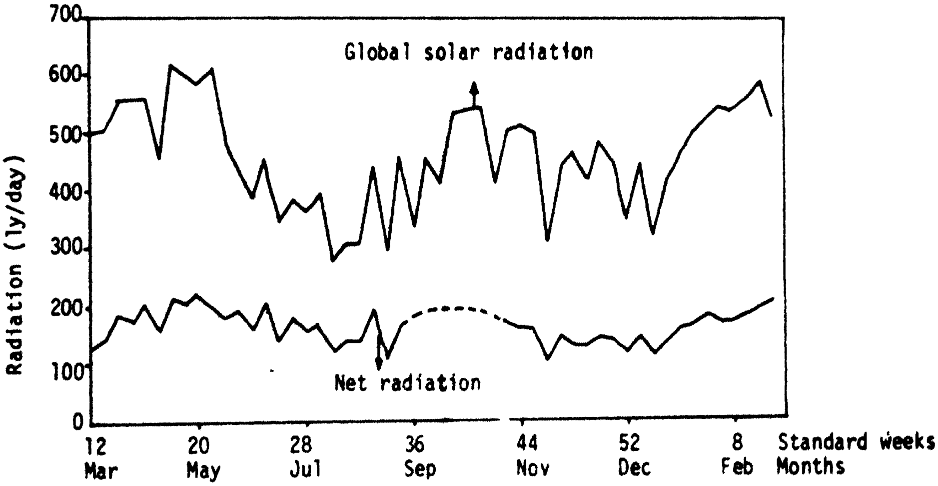


Figure 10. Average weekly global solar radiation and net radiation at ICRISAT Center, 1980-81.

CHAPTER II

Collection and Interpretation of Agroclimatological Data

1. Pigeonpea and its climatic environment

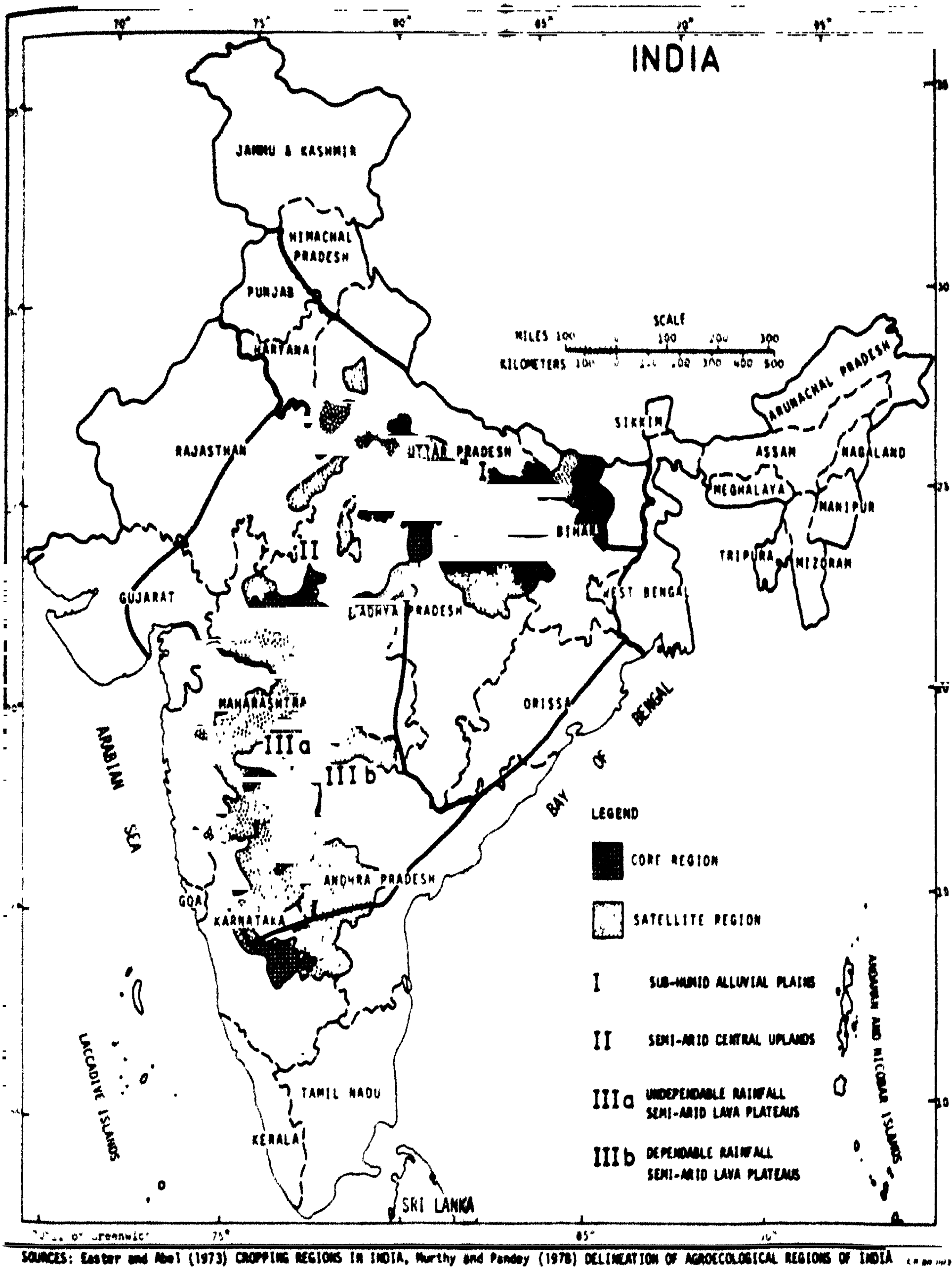
Pigeonpea is a crop predominantly grown in tropical areas. It is cultivated in semi-arid areas in India and Kenya, and in sub-humid regions of Uganda, the West Indies, Burma, and the Carribbean region. About 90% of the world production of pigeonpea is contributed by India. In this country, pigeonpea is the most widely grown grain legume next to chickpea. In view of its economic importance, Reddy and Virmani (1980a) evaluated the agricultural climate of the pigeonpea growing areas of India (Fig. 11). The pigeonpea growing areas broadly fall into three agricultural sub-divisions (I, II and III). Agricultural sub-division III is divided into two parts, namely: IIIa - rainshadow areas of the western ghats, having undependable southwest seasonal rainfall, and IIIb - the area lying outside the rainshadow and having relatively dependable rainfall during rainy season (Fig. 11). Pigeonpea is grown primarily on two soil types: (a) the Entisols, comprising the alluvial soil belt of the Indo-Gangetic regions of agricultural sub-division I, and (b) the Vertisols comprising agricultural sub-divisions II and III (Fig. 12). A small area under pigeonpea is on Alfisols in Southern Karnataka and Andhra Pradesh and eastern Madhya Pradesh.

Pigeonpea is mainly grown in India in regions lying between approximately 14 and 28°N latitude. In this zone the mean temperatures vary from 26 to 30°C in the rainy season and 17 to 22°C in the postrainy season. In northern and northeastern India, although the soil moisture is adequate to sustain the crop in most years, the onset of the cold weather in late November or December limits the growing season.

The amount of daily global solar radiation in pigeonpea growing areas varies from 400 to 430 ly/day during the rainy season and 380 to 430 ly/day in the postrainy season. The amount of solar radiation in the rainy season in the central Indian pigeonpea-growing areas is somewhat lower than in the others

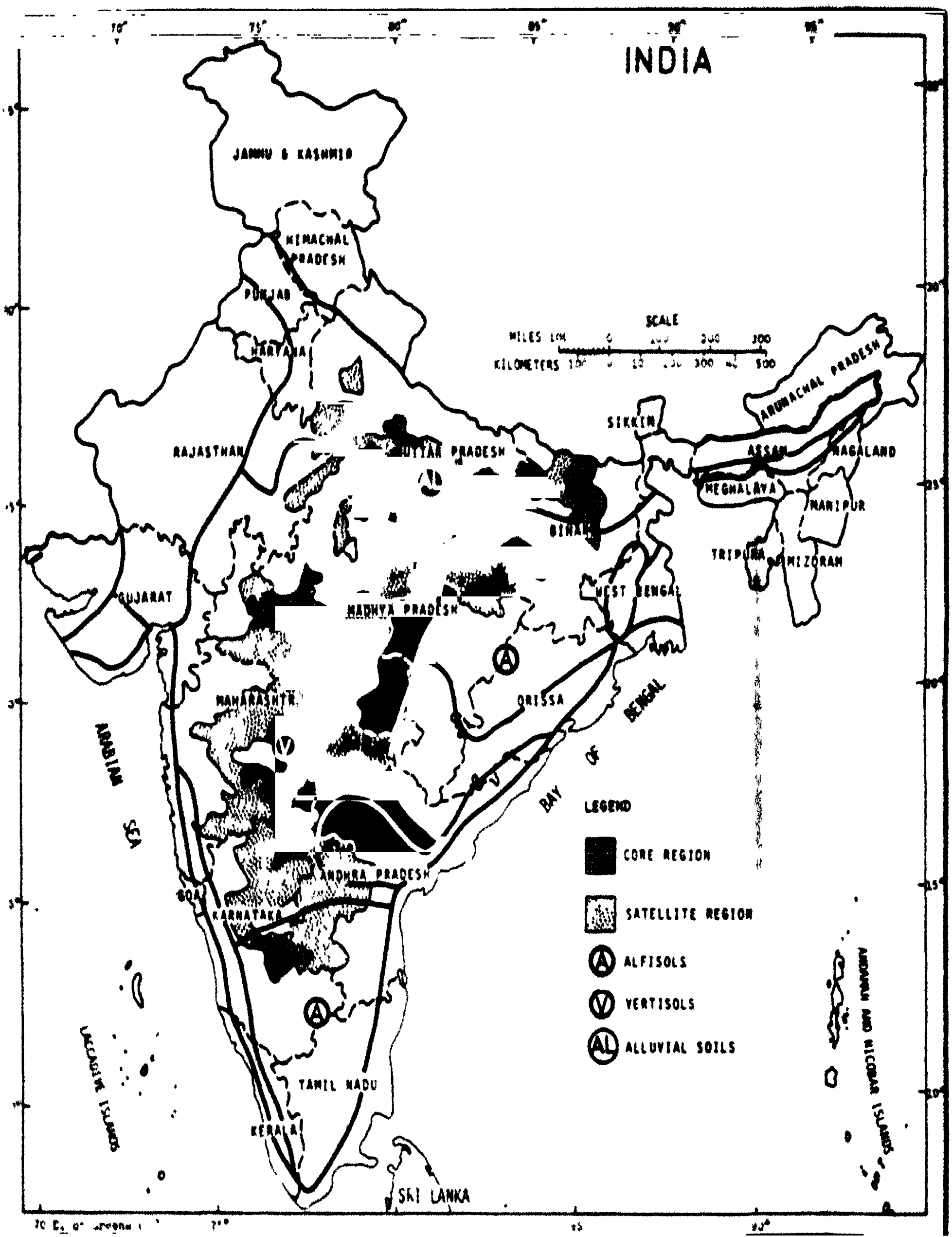
Mean annual rainfall ranges between 600 and 1400 mm, 80 to 90% of which is received during the rainy season. The majority of the principal pigeonpea growing areas in India are endowed with a dependable and high rainfall. The length of the growing season extends from 120 to 180 days. In the zone of low and erratic rainfall in Maharashtra and Karnataka states, the lack of adequate water on a continuous basis is a serious obstacle to stable pigeonpea yields.

A major constraint to stabilized and increased production of pigeonpea is likely to be the exposure of the crop to short-term waterlogging. Efforts should be made to introduce land and water management techniques that will help drain off excessive water from the field.



SOURCES: Easter and Abel (1973) CROPPING REGIONS IN INDIA, Murthy and Pandey (1978) DELINEATION OF AGROECOLOGICAL REGIONS OF INDIA

Figure 11. Agricultural subdivisions of pigeonpea regions of India.



SOURCES: Easter and Abel (1973) CROPPING REGIONS IN INDIA, Murthy and Pandey (1978) DELINEATION OF AGROECOLOGICAL REGIONS OF INDIA

Figure 12. Predominant soil types in pigeonpea-growing regions of India.

Agroclimatic analysis shows that for the states of UP and Bihar it would be advisable to adopt determinate 120-day pigeonpea types. For the central and southern Indian regions, medium to long-duration indeterminate types are likely to be more suitable.

A broad comparison of the climatic attributes of the pigeonpea growing areas in India with agroclimatic characteristics of the West African region showed that the area with a 120 to 180 days growing season is likely to suit pigeonpea cultivation (Fig. 13). This area comprises parts of the Sudan and northern Guinea bioclimatic zones.

Since the growth habit of pigeonpea crop is such that it develops ground cover slowly, intercropping it with cereals would be most advantageous from the view point of resource use. Studies on the light-and-water use patterns of different genotypes in diverse environments should be conducted under intercropping pressure, to evaluate the efficiency of use of climatic resources

2. Revised SAT maps of India, NE Brazil and Africa

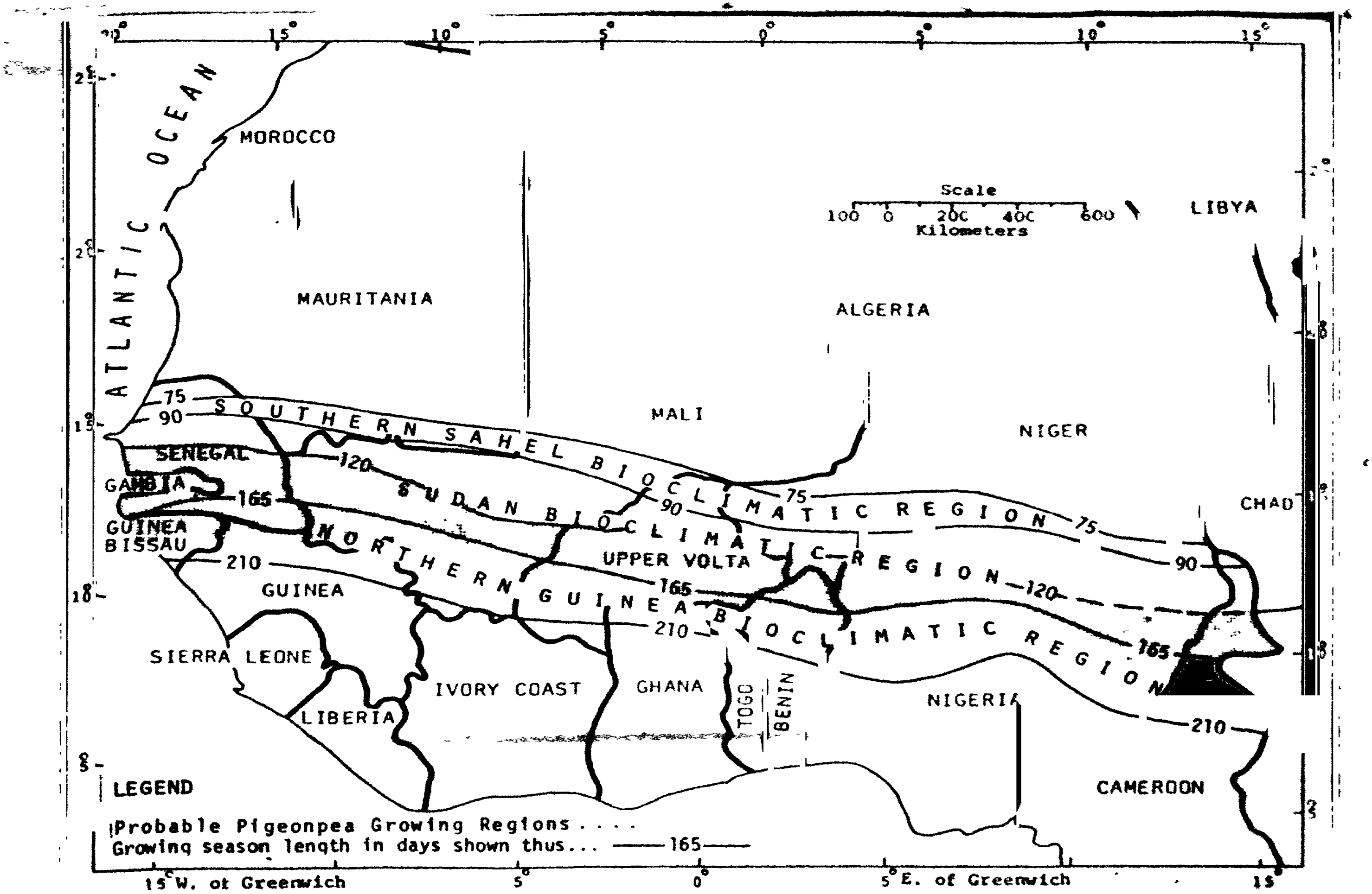
Gray (1970) identified regions with 2-7 humid months on Troll's (1965) map as semi-arids by comparing Troll's map with five ICRISAT crops growing regions in India. In this map most of the desert regions in the northwest India and the northern parts of West Africa etc. were included under 2-4.5 humid months zone i.e. under dry semi-arids. A humid month is defined as the month (h_p) with rainfall (R) exceeding potential evapotranspiration (PE) i.e. $R \geqslant PE$. In the computation of humid months it appears that Troll (1965) used temperature as a simple proxy to PE (i.e. $PE = 2T$, T: average temperature, °C). Because of this, desert regions with very low rainfall were also included under dry semi-arid zone.

The revised SAT map of India (Fig. 14) is based on data for about 300 locations. The rainfall data were taken from IMD (1967) publication and PE data have been given by Rao et al. (1971). Eightyeight percent of geographical area of India comes under tropics. The regions with mean annual temperature exceeding 18°C were identified as tropics following Koppen (1936). Dry semi-arid tropics constitute about 57% of geographical area of India. However, parts of sub-humid and humid regions in Bihar, M.P., U.P., Orissa, Coastal Maharashtra etc. with rainfall amount ⩾ 1300 mm are also included in dry SAT (Fig. 14). Most of the pearl millet and sorghum growing regions of A.P., Maharashtra and Karnataka are eliminated from dry SAT and included under arid.

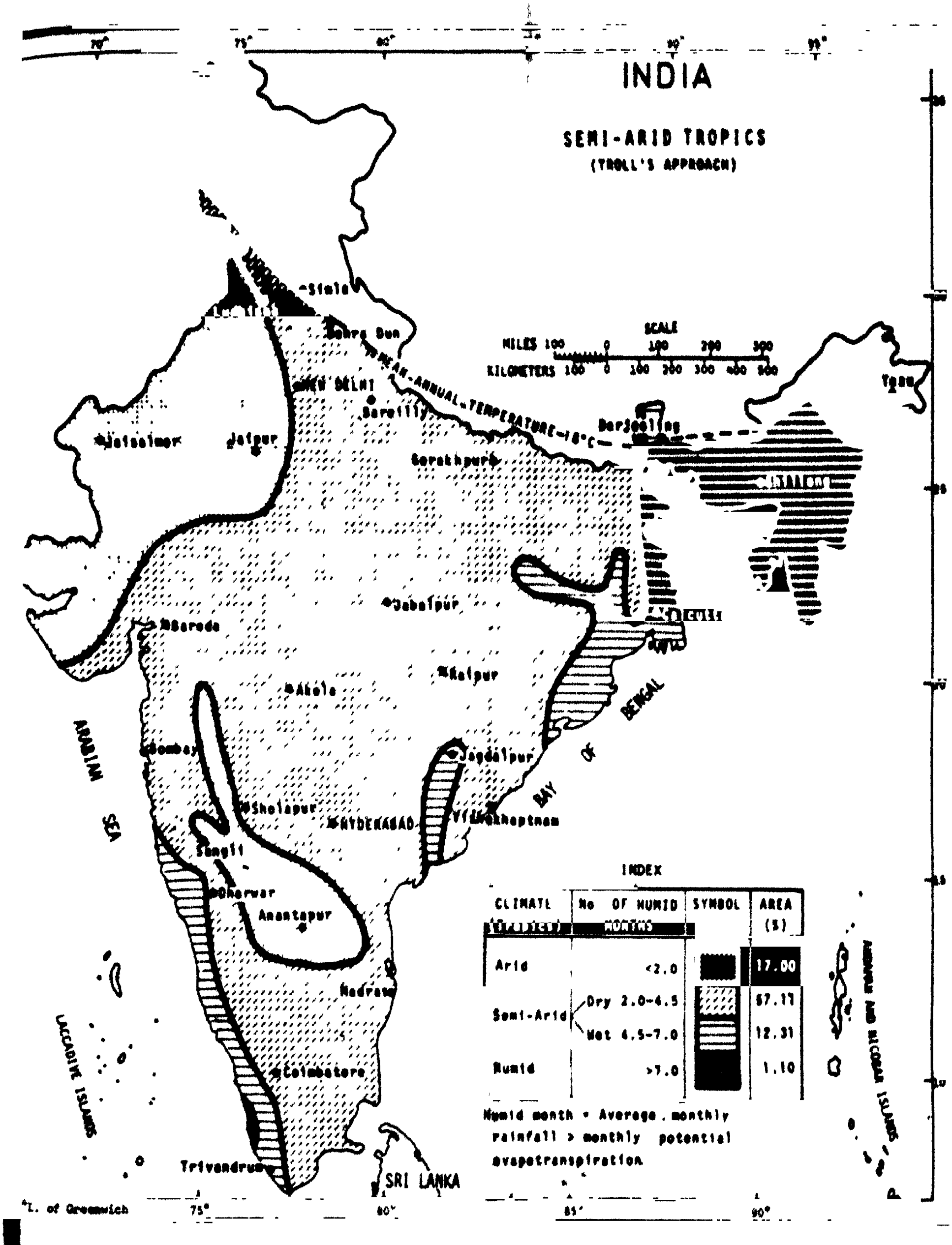
The revised SAT map of NE Brazil (Fig. 15) is based on data from 180 locations. The rainfall and PE data were respectively taken from Hargreaves (1973) and Reddy and Virmani (1981). Figure 16 depicts the mean annual PE distribution over NE Brazil. PE is generally high (⩾ 2000 mm) over NE Brazil.

The revised SAT map of Africa (Fig. 17) is based on the data of 300 locations in West Africa (Virmani et al. 1980, Reddy and Virmani, 1980b) and 180 locations from the rest of Africa (FAO).* (For details see Reddy et al. 1981).

Supplied by Dr. M. Frere, Principal Agrometeorologist, FAO, Rome.



(Adapted from CIEH, 1979)



e 14. Semi-Arid Tropics of India (revised as per Troll's approach).

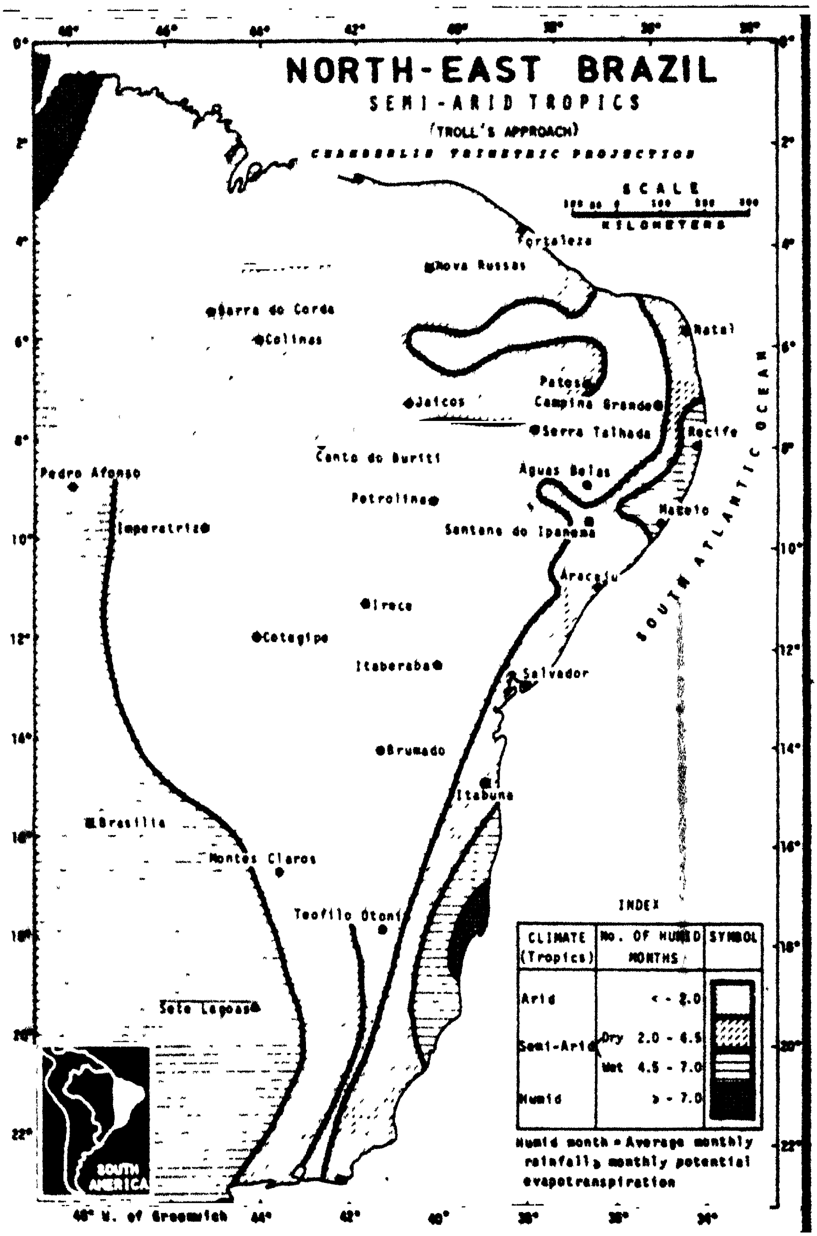


Figure 15. Semi-Arid Tropics of NE Brazil (revised as per Troll's approach).

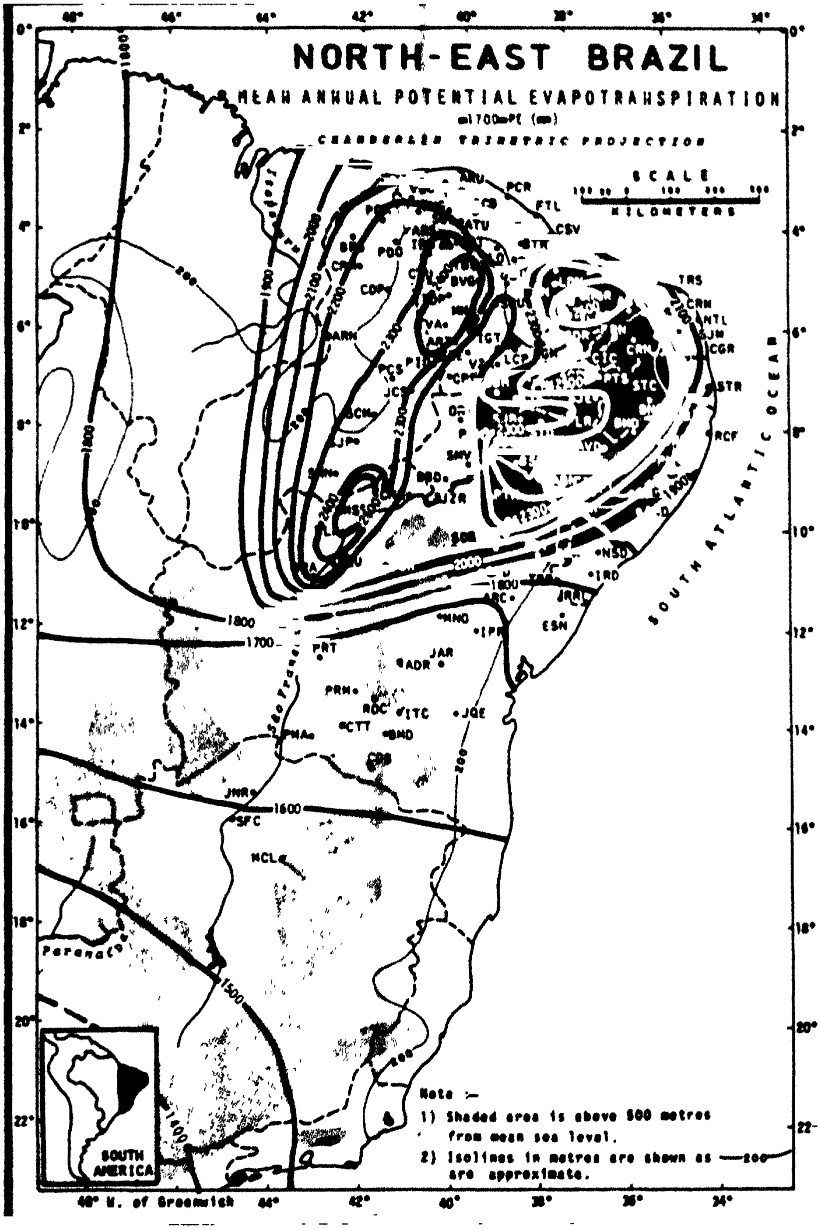


Figure 16. Mean annual potential evapotranspiration distribution over NE Brazil.

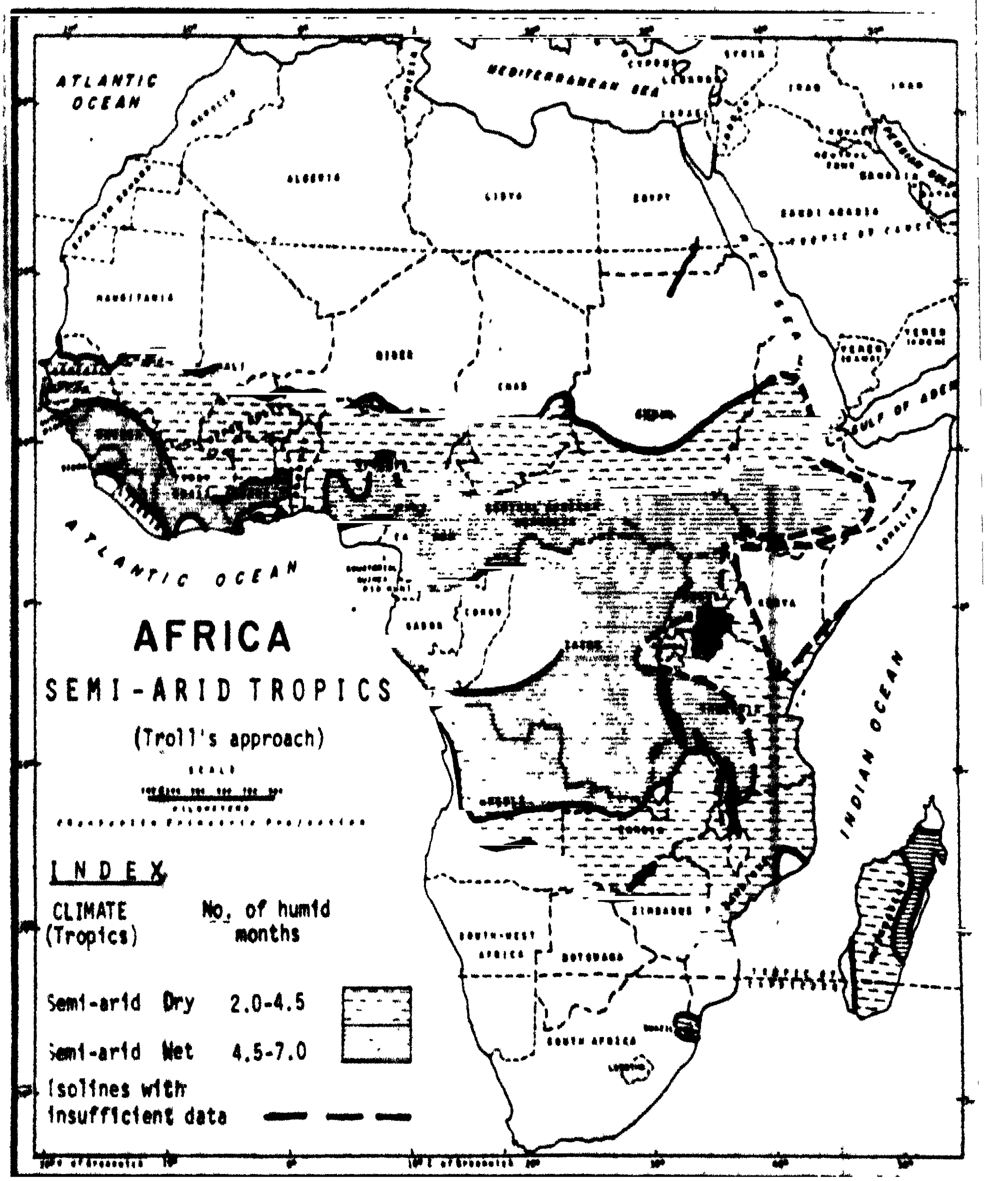


Figure 17. Semi-Arid Tropics of Africa (revised as per Troll's approach).

3. Grouping of climates - principal component analysis

Climate forms a continuum varying in time and space. To study and compare the climates of specific areas and to study the causes of climate variation, numerical classifications provide a fresh approach to this question. There is a wide spectrum of numerical methods that could be applied to climatic data on a global scale in seeking homoclimates for specific stations. Using principal component analysis it was tried to group locations in India and West Africa (Reddy and Virmani, 1981). The climatic attributes used for this purpose were: (1) average weekly rainfall (52 weeks) and (2) weekly initial probability estimates with the limit of 10 mm (52 weeks). Figures 18 and 19 present the normalized first (Z1) and second (Z2) components estimated using initial wet probabilities and average weekly rainfall data of 52 weeks of 81 locations in India and Niger (Table 2). As shown in figures 18 and 19 the two components (Z1 and Z2) together explain about 73 and 66% of variance respectively. It is evident from both these figures that:

i) high rainfall Indian stations are grouped with low rainfall Niger stations;

ii) single peak rainfall stations are separated from double peak rainfall stations but the magnitude of these peaks is not well differentiated; and

iii) in the case of rainfall stations with single peak, the regions that receive slight rain in winter (extreme NW parts of India) are separated from the other stations which donot receive these rains.

However, these results were also achieved even with the monthly data instead of weekly data and also the first two components contributed 77% of variance.

The problem associated with the principal component analysis is that the stations with highly different normals or averages are identified as being similar. The classification or the grouping of entities mainly depends upon the choice of all attributes that are used in the classification of inputs. Therefore, the choice of attributes which explain the climate in realistic sense is very important in the grouping of the entities. Efforts are underway to develop first the methodologies to compute attributes of agronomic relevance which explain the agroclimate of the region.

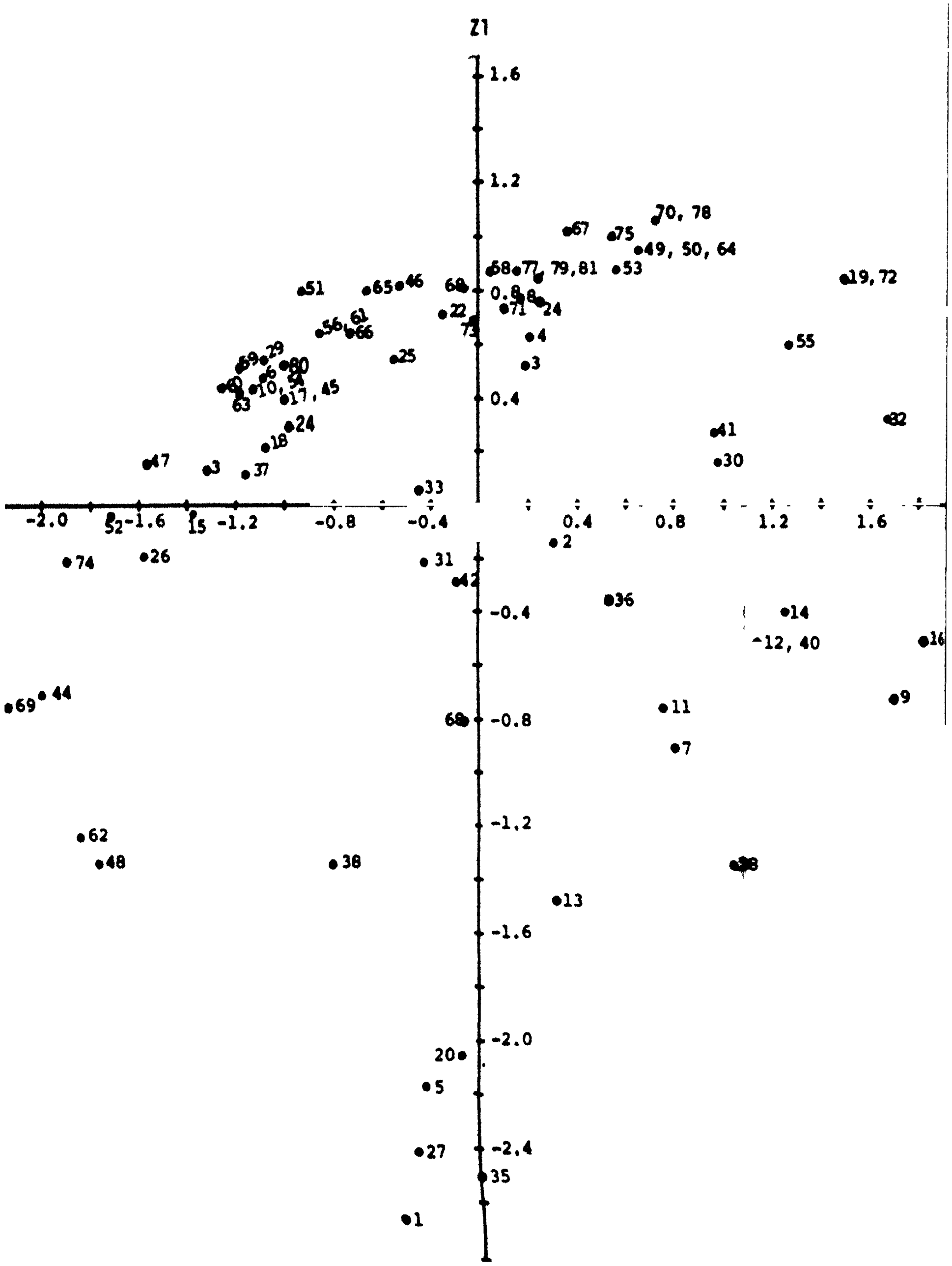


Figure 18. Principal component analysis results based on weekly initial rainfall probability data of India and Niger.

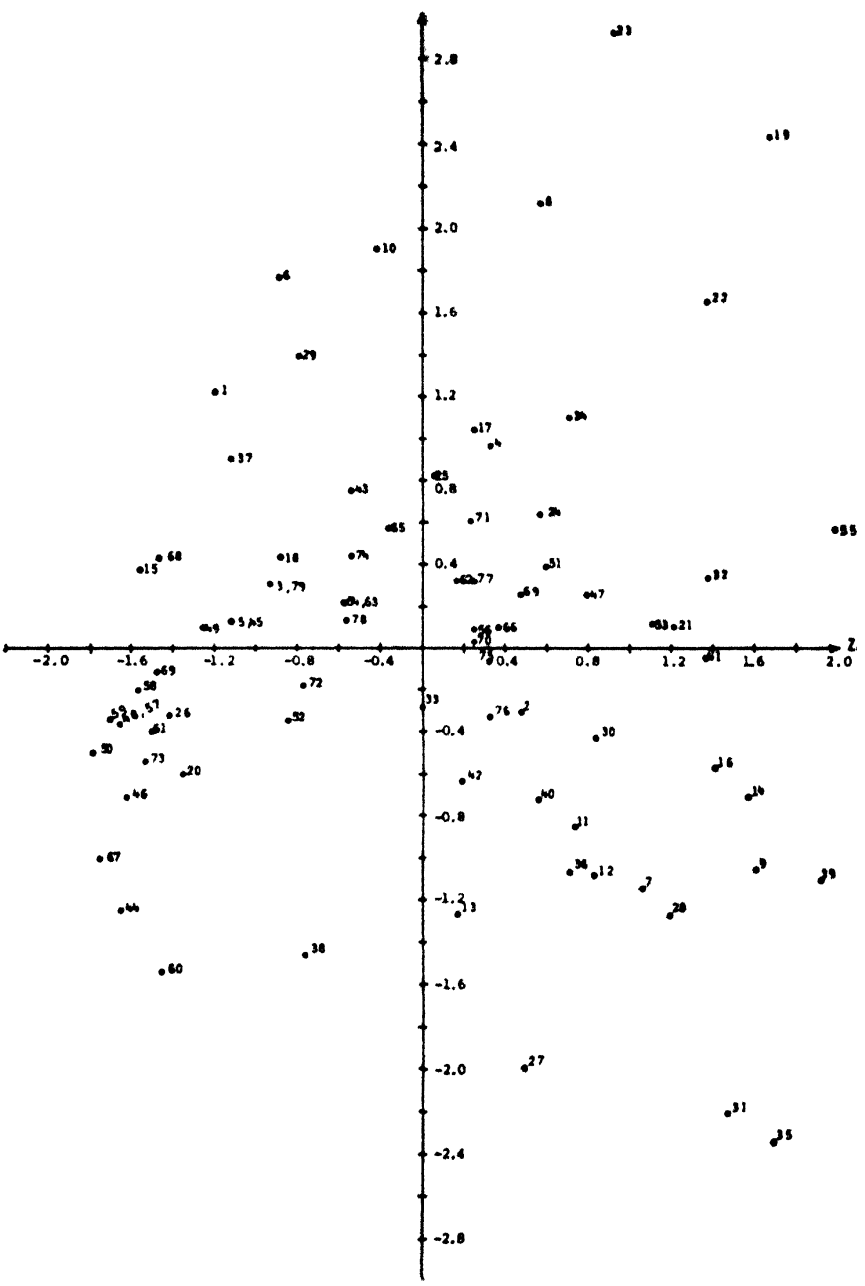


Figure 19. Principal component analysis results bases on average weekly rainfall data of India and Niger.

Table 2. List of stations in India and Niger used in the principal component analysis.

Sl. No.	Station	Lat ° '	Long ° '	Ele (m)
1	Agra	27 10	78 02	169
2	Ahmadnagar	19 05	74 55	657
3	Ajmer	26 27	74 37	486
4	Akola	20 42	77 02	282
5	Amritsar	31 38	74 52	234
6	Anand	22 34	73 01	000
7	Anantapur	14 41	77 37	350
8	Banaras	25 18	83 01	76
9	Bangalore	12 58	77 35	921
10	Banswara	23 33	74 27	218
11	Bijapur	16 49	75 43	594
12	Chitradurga	14 14	76 26	733
13	Coimbatore	11 00	76 58	709
14	Cuddapah	14 29	78 50	130
15	Deesa	24 12	72 12	136
16	Dharwar	15 27	75 00	727
17	Durgapur	23 51	73 43	429
18	Gogha	21 41	71 17	---
19	Gorakhpur	26 45	83 22	76
20	Hissar	29 10	75 44	221
21	Hyderabad	17 27	78 28	545
22	Indore	22 43	75 48	567
23	Jabalpur	23 10	79 57	391
24	Jaipur	26 49	75 48	390
25	Jalgaon	21 03	75 34	201
26	Jodhpur	26 18	73 01	224
27	Jullunder	31 20	75 35	---
28	Kolar	13 08	78 08	---
29	Kota	25 11	75 51	257
30	Kurnool	15 50	78 04	281
31	Ludhiana	30 56	75 52	247
32	Mahboobnagar	16 44	77 59	---
33	Malegaon	20 33	74 32	437
34	Nanded	19 08	77 20	358
35	New Delhi	28 35	77 12	216
36	Padegaon	18 12	74 10	---
37	Rajkot	21 18	70 47	138
38	Ramanathpur	9 23	78 50	7
39	Salem	11 39	78 10	278
40	Sangly	16 52	74 34	534
41	Sholapur	17 40	75 54	479
42	Sikar	27 37	75 08	432
43	Udaipur	24 35	73 42	582
44	Agadez	12 58	07 59	498
45	Ayorou	14 44	00 55	223

Table 2 contd.

Sl. No.	Station	Lat ° '	Long	Ele (m)
46	Bangui	13 43	06 06	350
47	Belbedji	14 39	08 04	400
48	Bilma	18 41	12 55	335
49	Birni N'G	13 05	02 54	188
50	Birni N'K	13 48	05 15	272
51	Bouza	14 25	06 03	300
52	Diffa	13 19	12 37	255
53	Dogondoutch	13 38	04 00	230
54	Dolbel	14 37	00 17	300
55	Dosso	13 01	03 11	218
56	Filingue	14 21	03 19	300
57	Gaya	11 59	03 30	160
58	Gotheye	13 49	01 35	220
59	Goundamaria	13 43	11 10	305
60	Goure	13 59	10 16	450
61	Guidimouni	13 41	09 31	370
62	Iferoune	19 05	08 25	681
63	Kao	15 14	05 45	400
64	Kolo	13 18	02 21	210
65	Madaoua	14 07	05 59	330
66	Maine Soroa	13 13	12 01	339
67	Maradi	13 28	07 25	368
68	Myrriah	13 43	09 09	370
69	N'Guigmi	14 15	13 07	286
70	Niamey Ville	13 30	02 08	216
71	Ouallam	14 19	02 05	250
72	Say	13 06	02 21	200
73	Tahoua	14 54	05 18	385
74	Tanout	14 58	08 53	400
75	Tarna	13 28	07 08	350
76	Tera	14 00	00 45	300
77	Tessoua	13 45	07 59	370
78	Tibiri	13 06	04 00	220
79	Tillabery	14 12	01 27	209
80	Toukounous	14 30	03 17	290
81	Zinder	13 48	08 59	451

CHAPTER III

Microclimatological studies

Microclimatological studies during 1980-81 used an extension of the research conceptualization developed in this area over the past three years. Examination of the relationships between intercepted radiation and drymatter production by sorghum has been extended to cover both the rainy and postrainy seasons. Our efforts to quantify the crop response to moisture stress included this year millet in addition to sorghum. Experiments were initiated to examine the response of groundnut to moisture stress using a line source sprinkler irrigation and the response of chickpea using multiple sowings and differential irrigations. Results of these two studies will be reported next year.

1. Efficiency of conversion of intercepted Photosynthetic Photon Flux Density (PPFD)

Over the past two years, the productivity of different crops/cropping systems was evaluated by means of calculating 'growth efficiency' from the slope of the regression relationship between cumulative intercepted PPFD and drymatter and the calorific value of the crop. For example, during the rainy season of 1979-80 it was observed that the growth efficiencies of CSH-6 and CSH-1 hybrids grown on a Vertisol were 5.9 and 5.2% respectively. This year data were obtained from the trials laid out during the rainy and postrainy seasons to collect congruent data sets to validate the sorghum growth model (SORGF), a detailed account of which can be found in Chapter IV.

During the rainy season, two hybrids CSH-1 and CSH-6 were grown on the Vertisols and Alfisols under uniform management. The experiment on Vertisol included a variety SPV-351 also while the trial on the Alfisol included additional treatments of irrigation and no irrigation. Emergence of the crop occurred on 23 June on the Alfisols and on 4 July on the Vertisol. During the postrainy season the trial was conducted on the Alfisol. The treatments included two genotypes, CSH-8-R a hybrid and M-35-1 a variety, grown under two irrigation regimes. Emergence of the crop occurred on 13 October. PPFD in both seasons was measured on a seasonal basis using four traversing quantum sensors and readout integrators.

The relationship between cumulative intercepted PPFD and drymatter produced for the three sorghum genotypes grown during the rainy season on the Vertisol is shown in Figure 20. The slopes (b) of the regression equation fitted to the observed data were 0.65 g/E for CSH-6 and CSH-1 and 0.56 g/E for SPV-351. Growth efficiencies were calculated from b values, a calorific value of 17.5 KJ/g and a conversion factor of 4.6 µE per J of radiation. Calculated growth efficiencies were 5.2% for the two hybrids and 4.5% for the variety SPV-351.

Growth efficiencies of sorghum hybrids CSH-1 and CSH-6 grown on the Alfisols without irrigation were 5.3 and 5.1% respectively while with irrigation the efficiencies were 4.6 and 5.0% respectively. Frequent rains after irrigations contributed to waterlogging in the irrigation treatment and the waterlogging appeared to have affected the growth efficiency of crops. Results

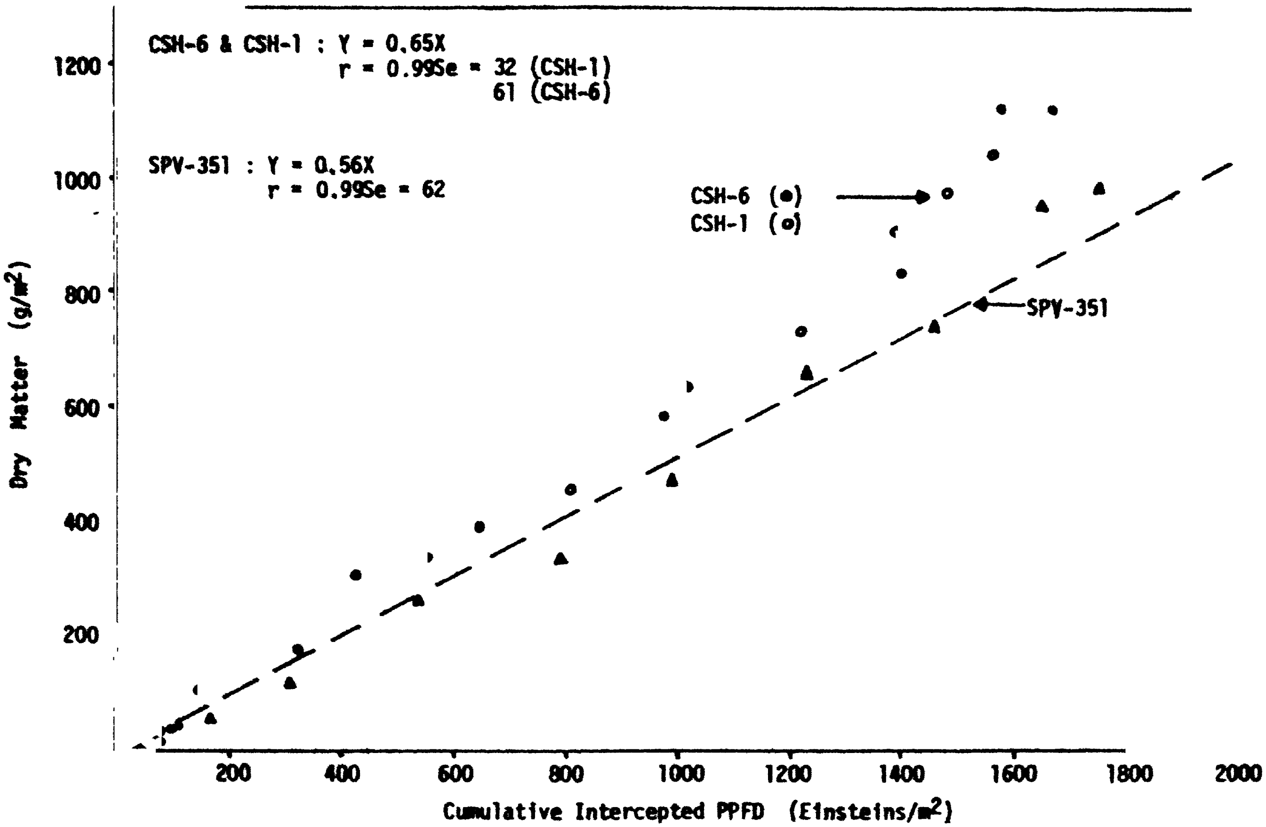


Figure 20. Relationship between cumulative intercepted PPFD and dry matter produced for three sorghum genotypes grown during the 1980 rainy season.

obtained during 1980-81 rainy season on the Vertisols and Alfisols showed that the growth efficiency of CSH-6 hybrid was similar on both soils, while the results of 1979-80 rainy season showed significant difference in the growth efficiency of CSH-6 grown on the two soils. (Agroclimatology Report of Work 1979-80). During the 1979 rainy season due to early sowings, emergence of sorghum on the Vertisols occurred 12 days earlier to emergence on the Alfisols, whereas during the 1980 rainy season emergence on the Alfisols occurred 12 days earlier. Early and timely sowings on the Alfisols seemed to have confierred an advantage during 1980 rainy season considering especially the period from 19 August-22 August when 211 mm of rainfall was received. Heavy rains during this 3 day period caused temporary waterlogging, specially in the Vertisols which affected the crop growth rate. Crop growth rates on the Vertisols a week prior to 19 August were 23 g/m^2/day. But from 19 August-27 August the growth rates dropped down to 7 g/m^2/day. On the Alfisols however the growth rates stood at 17 g/m^2/day from 19 August-2 September. This advantage in growth rates was carried through the growing season to physiological maturity when the final drymatter production was 1251 g/m^2 on the Alfisols while on the Vertisols it was 1129 g/m^2.

Cumulative intercepted PPFD - drymatter relationship for two sorghum genotypes M-35-1 and CSH-8-R grown with and without irrigation during the 1980-81 postrainy season is shown in Figure 21. The slopes of the linear regression through origin showed no significant difference between the two genotypes. Hence the data shown in Figure 21 are pooled over the two genotypes for the irrigated and nonirrigated treatments. Growth efficiency of the two genotypes was 3.8% with irrigation and 2.4% without irrigation. These growth efficiency figures were considerably lower than the growth efficiency observed during the rainy season with hybrids CSH-1, CSH-6 and the variety SPV-351.

These data show that efficient use of the natural resources could be achieved by rainy season cropping as already shown by the farming systems operational research on watersheds over the past eight years (Virmani et al. 1981). Observed growth efficiencies during the postrainy season also suggest that considerable scope exists to achieve higher growth efficiencies by suitable crop management.

2. Quantification of moisture stress in sorghum

Our studies over the past three years with sorghum under varying levels of moisture stress showed that plant measurements such as stomatal conductance, leaf-air temperature differential and transpiration could be effectively used to quantify the moisture stress effects on sorghum. During the postrainy season of 1979-80 studies were conducted on two sorghum genotypes i.e. CSH-8-R and M-35-1 subjected to two moisture treatments i.e., adequate supplemental water and limited supplemental water. Stomatal conductance measurements in the two treatments showed that the absolute values as well as the magnitude of difference in the stomatal conductance between the two treatments were higher in the case of CSH-8-R as compared to M-35-1. CSH-8-R also proved superior in the maintenance of higher leaf-water potential and greater transpiration.

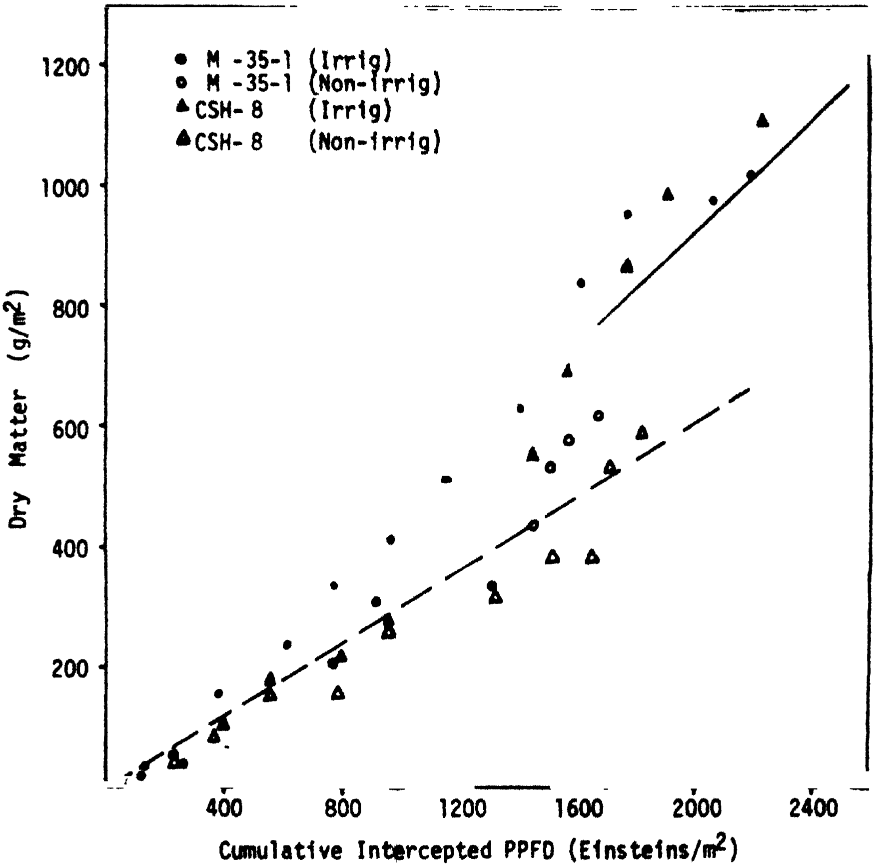


Figure 21. Relationship between cumulative intercepted PPFD and dry matter produced for two sorghum genotypes grown during the 1980-81 post-rainy season.

The above experiment was repeated during the postrainy season of 1980-81. In addition to the two genotypes studies during 1979-80, CSH-6, a sorghum hybrid normally grown during the rainy season, was also included. The crop was sown on 10 October 1980 and emergence occurred on 13 October with an 85 mm irrigation given on 11 October to recharge the profile moisture. Four supplemental irrigations measuring 75, 78, 71 and 50 mm were given to the treatment receiving adequate water (referred to as A) at 10, 28, 39 and 70 DAE. The treatment receiving limited amount of supplemental water (referred to as B) was given two irrigations measuring 60 and 85 mm at 10 and 39 DAE respectively.

Starting from 40 DAE, daily measurements of stomatal conductance, transpiration, leaf and air temperature were taken in all the plots till the crop reached physiological maturity. Stomatal conductance and transpiration were measured with an LI-1600 steady state porometer on the uppermost, fully exposed, fully expanded leaf. Leaf temperatures were measured with a Barnes Infrared thermometer and air temperatures were measured with an Assman Phychrometer. Leaf-air temperature differential (LATD) was calculated from the difference between leaf and air temperatures measured each day. In order to facilitate comparison between different treatments, cumulative values of transpiration, leaf conductance and LATD were computed from the daily values starting from 40 DAE to physiological maturity.

Cumulative LATD for the three genotypes is shown in Figures 22, 23 and 24. It is interesting to notice that although treatment A received 71 mm of additional water prior to the start of the canopy measurements, the treatment effects did not become apparent till 70 DAE when an additional irrigation of 50 mm was given to treatment A. The cumulative LATD for CSH-8-R, CSH-6 and M-35-1 respectively were -240, -241 and -352°C in treatment A and -184, -177 and -266°C in the B treatment. Since the days to physiological maturity were different in the two treatments for the three genotypes, it would be unrealistic to compare the moisture stress response of the genotypes based on the cumulative values. For the measurement period, the average LATD was -3.81, -4.73 and -4.63°C in treatment A and -3.12, -3.93 and -3.64°C in treatment B for CSH-8-R, CSH-6 and M-35-1 respectively. These data show that stress induced increase in leaf temperature averaged over the measurement period was the least in CSH-8-R followed by M-35-1 and CSH-6.

Stomatal conductance measured in the three genotypes on a daily basis was summed over the measurement period and seasonal changes in the cumulative stomatal conductance are shown in Figures 25, 26 and 27. Highest cumulative stomatal conductance of 51 cm/sec was recorded in CSH-8-R under treatment A while for CSH-6 and M-35-1 it was 41 and 44 respectively. It is apparent from the seasonal changes that hybrid CSH-8-R was able to maintain higher stomatal conductance facilitating increased gaseous exchange. The magnitude of the difference between treatments A and B also shows that CSH-8-R exhibits the desirable characteristic of stomatal adaptation to water stress. The order of this adaptation could be given as CSH-8-R > CSH-6 > M-35-1 by examining the average levels of stomatal conductance per day of 0.81, 0.80 and 0.58 cm/sec in treatment A and 0.51, 0.53 and 0.41 cm/sec in treatment B for CSH-8-R, CSH-6 and M-35-1 respectively.

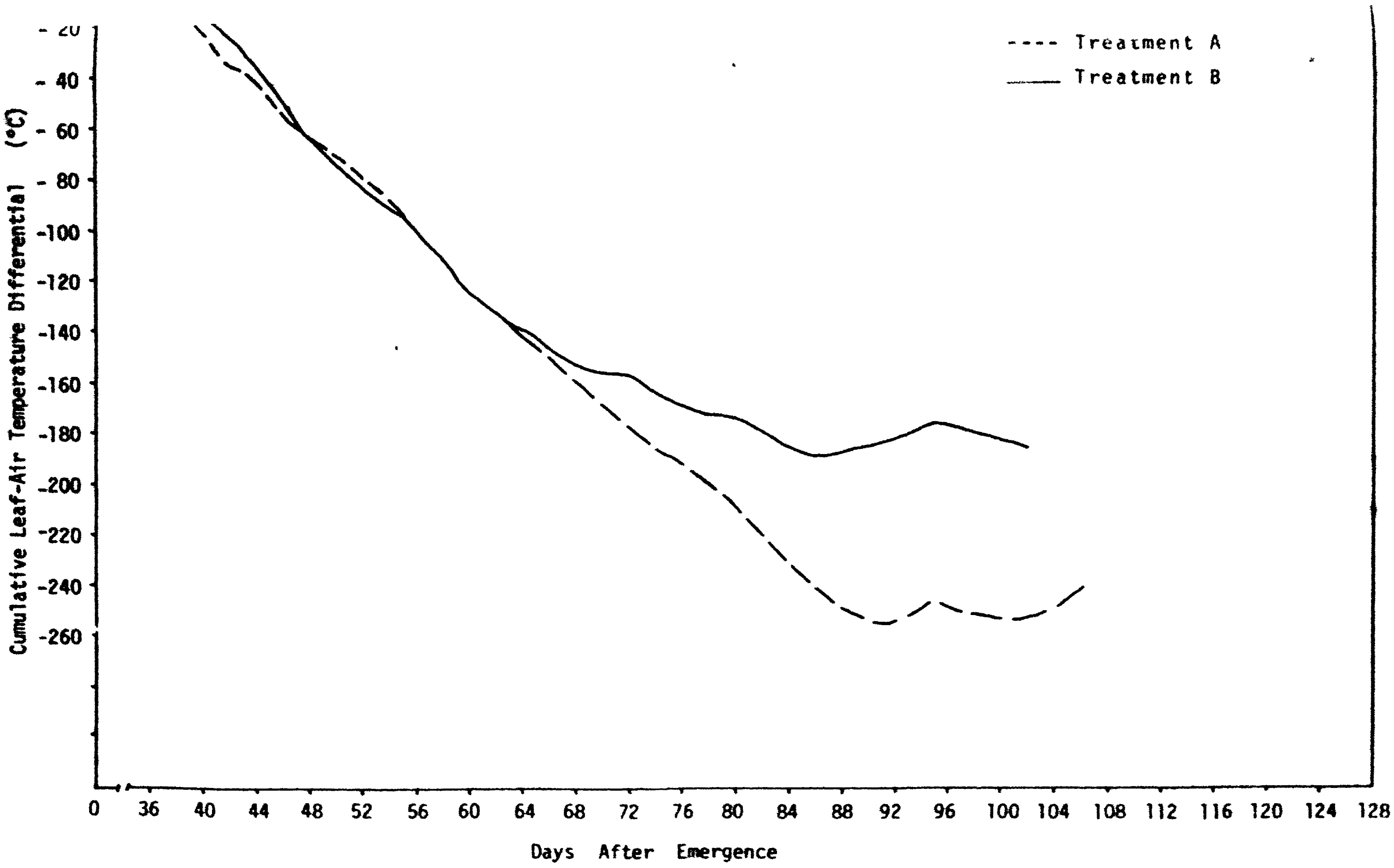
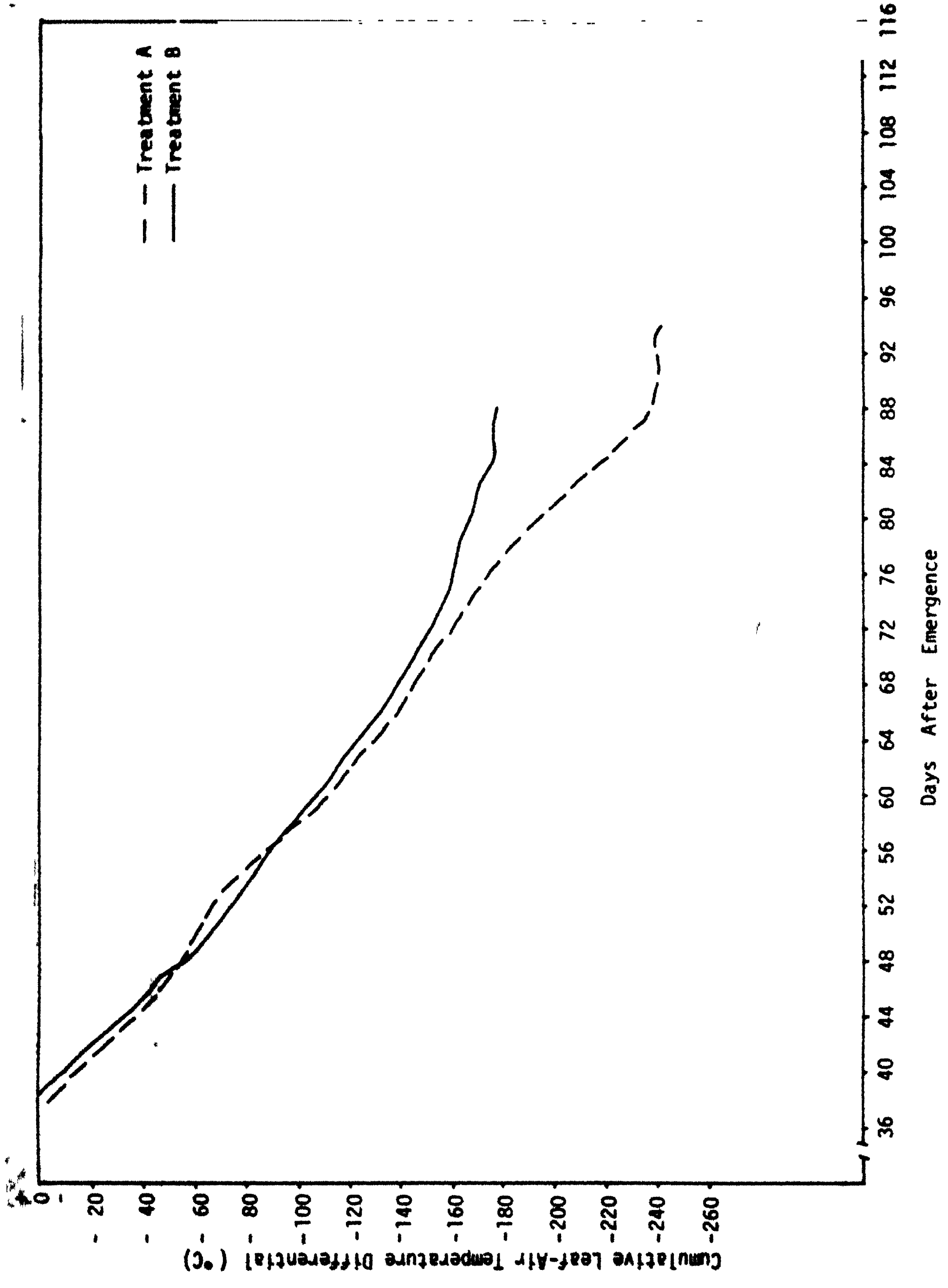


Figure 22. Cumulative leaf-air temperature differential (LATD) for sorghum hybrid CSH-8-P grown under two moisture regimes during the 1980-81 postrainy season.


Treatment A
Treatment B
Cumulative Leaf-Air Temperature Differential (°C)
0
- 20
- 40
- 60
- 80
-100
-120
-140
-160
-180
-200
-220
-240
-260
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
104
108
112
116
Days After Emergence

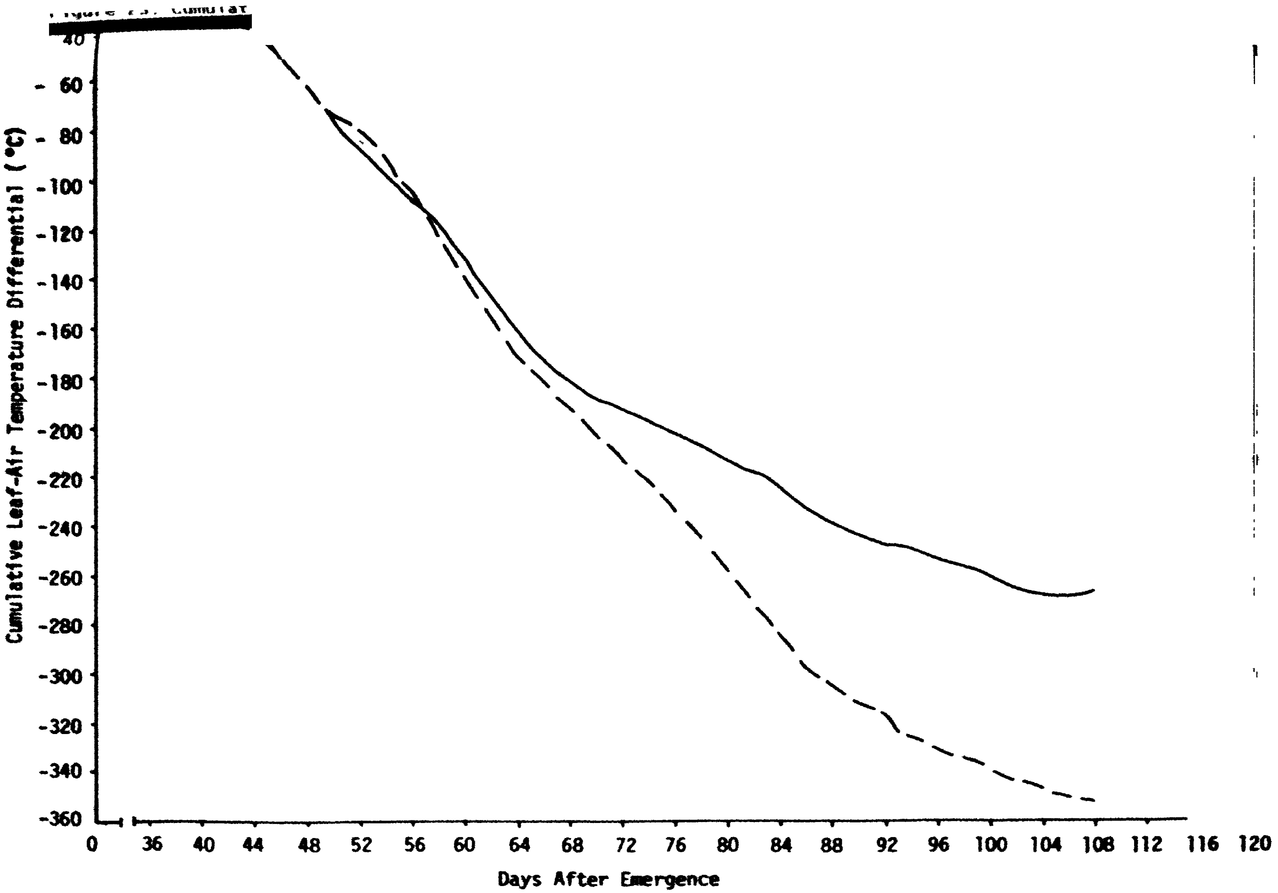


Figure 24. Cumulative leaf-air temperature differential (LATD) for sorghum variety M-35-1 grown under two moisture regimes during the 1980-81 postrainy season.

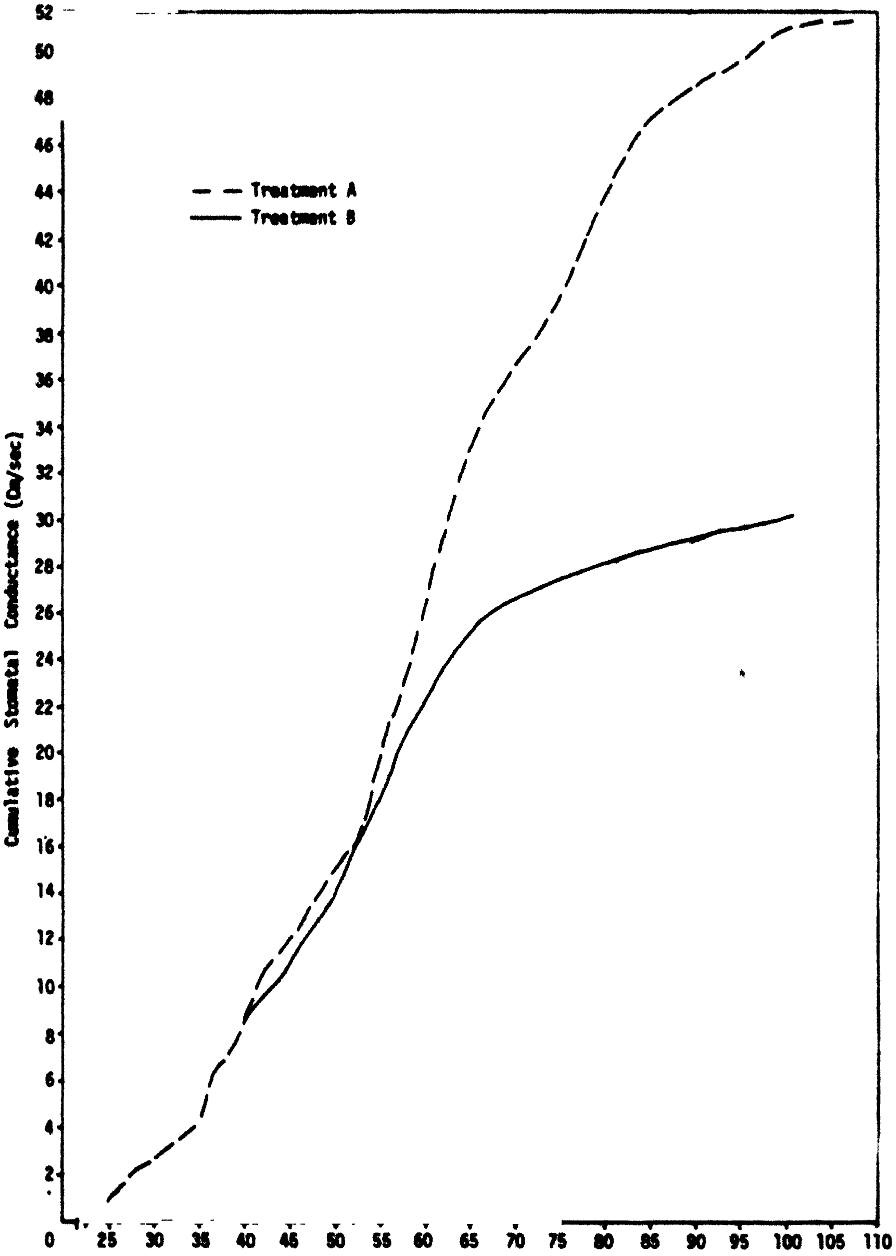


Figure 25. Cumulative stomatal conductance for sorghum hybrid CSH-8-R grown under tw
moisture regimes during the 1980-81 postrainy season.

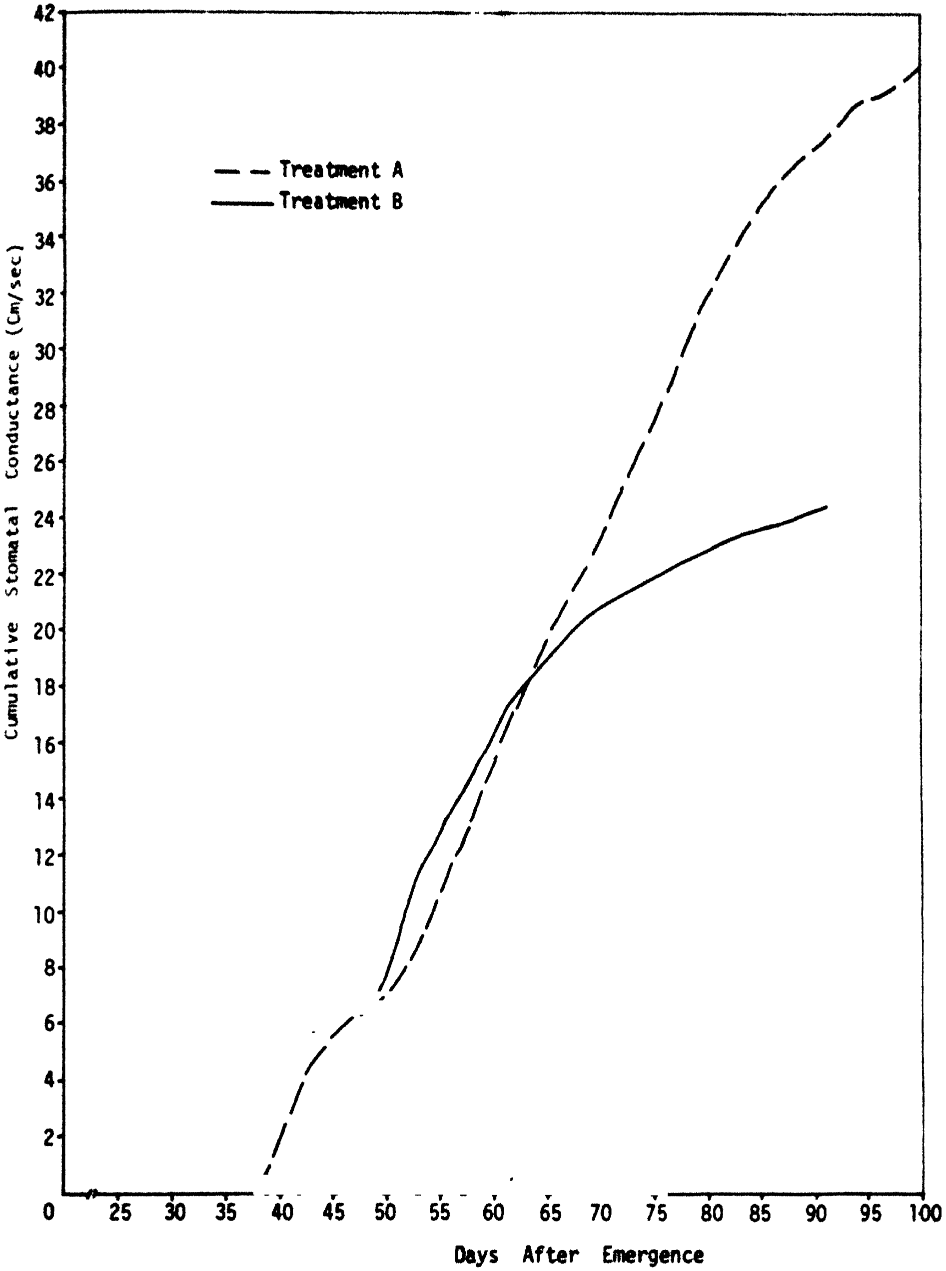


Figure 26. Cumulative stomatal conductance for sorghum hybrid CSH-6 grown under two moisture regimes during the 1980-81 postrainy season.

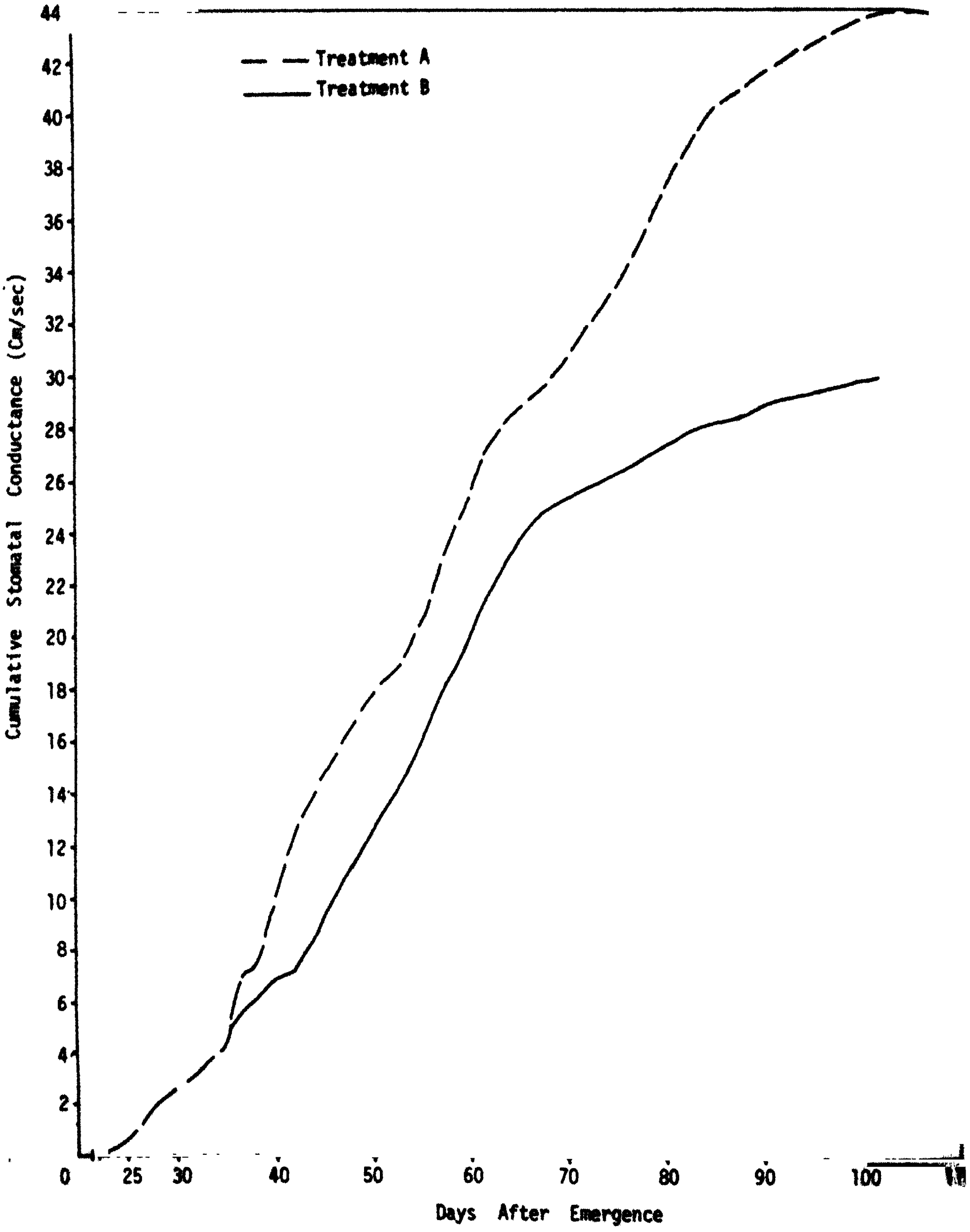


Figure 27. Cumulative stomatal conductance for sorghum variety M-35-1 grown under two moisture regimes during the 1980-81 postrainy season.

Significant differences in the varietal adaptation to moisture stress could be seen in the cumulative transpiration rates (Table 3). Under adequate water supply in treatment II, highest transpiration rates were recorded in CSH-8-R. It follows from stomatal adaptation responses discussed above that CSH-8-R should show the maximum reduction in transpiration rates followed by CSH-6 and M-35-1. Average transpiration rates per day shown in Table 3 amply substantiate the stress induced adaptation ability of CSH-8-R. It will be pertinent to point out here that transpiration rates in µg of water transpired/cm^2/sec were measured on the uppermost leaf in each genotypes. Since the maximum LAI recorded in the three genotypes was different, one useful way of interpreting the transpiration rates measured on the top leaf in terms of canopy response is to compute weighted transpiration rates from the average transpiration rates shown in table 3 using the maximum LAI recorded for each genotype. Interestingly, the weighted transpiration rates show that of the three genotypes tested, CSH-8-R only was able to show adaptation to stress by cutting down the transpiration while CSH-6 and M-35-1 show in fact increased transpiration under limited water application. It is also apparent that CSH-6 was transpiring more water inspite of a low LAI of 1.08.

Table 3. Transpiration and transpiration efficiencies of three sorghum genotypes grown under two moisture regimes during the 1980-81 postrainy season at ICRISAT Center.

Parameter	CSH-8		CSH-6		M-35-1	
	Trt.A	Trt.B	Trt.A	Trt.B	Trt.A	Trt.B
1. Measurement period (days)	63	59	51	45	76	76
2. Cumulative transpiration (µg/Cm^2/sec)	685	405	559	346	541	443
3. Transpiration/day (µg/Cm^2/sec)	10.9	6.9	10.9	7.7	7.1	6.1
4. Maximum LAI	2.96	2.58	1.82	1.08	2.86	2.02
5. Weighted transpiration	3.68	2.67	5.99	7.13	2.48	3.02
6. Transpiration efficiency (gm of dry matter/g/sec)	163	146	166	143	189	140
7. Transpiration efficiency (gm of grain/g/sec)	89	62	84	66	73	38

From the total drymatter recorded at physiological maturity, final grain yield and cumulative transpiration, transpiration efficiencies were calculated. Since the transpiration rates were measured only from 43 DAE, calculated transpiration efficiency values should only be regarded as approximate answers. As shown in table 3, maximum transpiration efficiency in drymatter production in the treatment receiving adequate water was observed in the case of M-35-1; CSH-6 and CSH-8-R did not show any significant difference in the transpiration efficiency. Under stress, however, CSH-8-R showed marginal increase in transpiration efficiency over CSH-6 and M-35-1.

Considerable interest in evaluating the genotypic differences in transpiration efficiency relates to grain yield. Unlike the results observed above for drymatter, transpiration efficiency in grain yield was superior in case of CSH-8-R and CSH-6 in comparison to M-35-1. More striking are the differences in transpiration efficiency between the three genotypes under limited water application. CSH-8-R and CSH-6 showed significantly higher transpiration efficiency over M-35-1.

The relationship of transpiration to drymatter and grain yield pooled over the three genotypes is shown in Figure 28. The data show that with decrease in cumulative transpiration from 685 $\mu g/cm^2/sec$ to 346 $\mu g/cm^2/sec$, the drymatter decrease is linear. However the relationship between cumulative transpiration and yield is not linear. The data in Figure 28 show that between 700 and 500 $\mu g/cm^2/sec$, the decrease in yield with transpiration is almost linear. Further decrease in transpiration to 350 $\mu g/cm^2/sec$ did not show the same magnitude of decrease in yield that was observed for the cumulative transpiration range between 700 and 500 $\mu g/cm^2/sec$. This nature of the relationship of transpiration to drymatter and grain yield shown in Figure 28 is not unexpected especially when data are pooled over different genotypes because harvest indices could vary between different genotypes.

These studies show that plant-water relations of different enotypes could be usefully monitered for meaningful interpretation of plant se to available water.

3.1. Response of earl millet to moisture stress

Over the past three years our efforts to quantify the moisture stress response of crops were mainly limited to sorghum. In order to understand and quantify the effect of timing and duration of stress on the growth, water relations, nitrogen uptake and yield of millet, a study was conducted by the Agroclimatology, Environmental Physics and Soil Fertility subprograms during the summer seasons of 1980 and 1981 on a medium deep Alfisol. Millet variety BK-560 was planted in 75-cm rows on 24 January during the 1980 trial and on 5 February during the 1981 trial and emergence occurred on 30 January and 10 February in the respective seasons. In both the years the treatments imposed on the crop in a split-plot design with three replications were as follows:

Main plot (4 moisture regimes)	Sub-plot (3 Nitrogen levels)
M1 - Irrigation every 10 days	N1 - 0 kg N/ha
M2 - Two irrigations at the time of grain filling	N2 - 40 kg N/ha

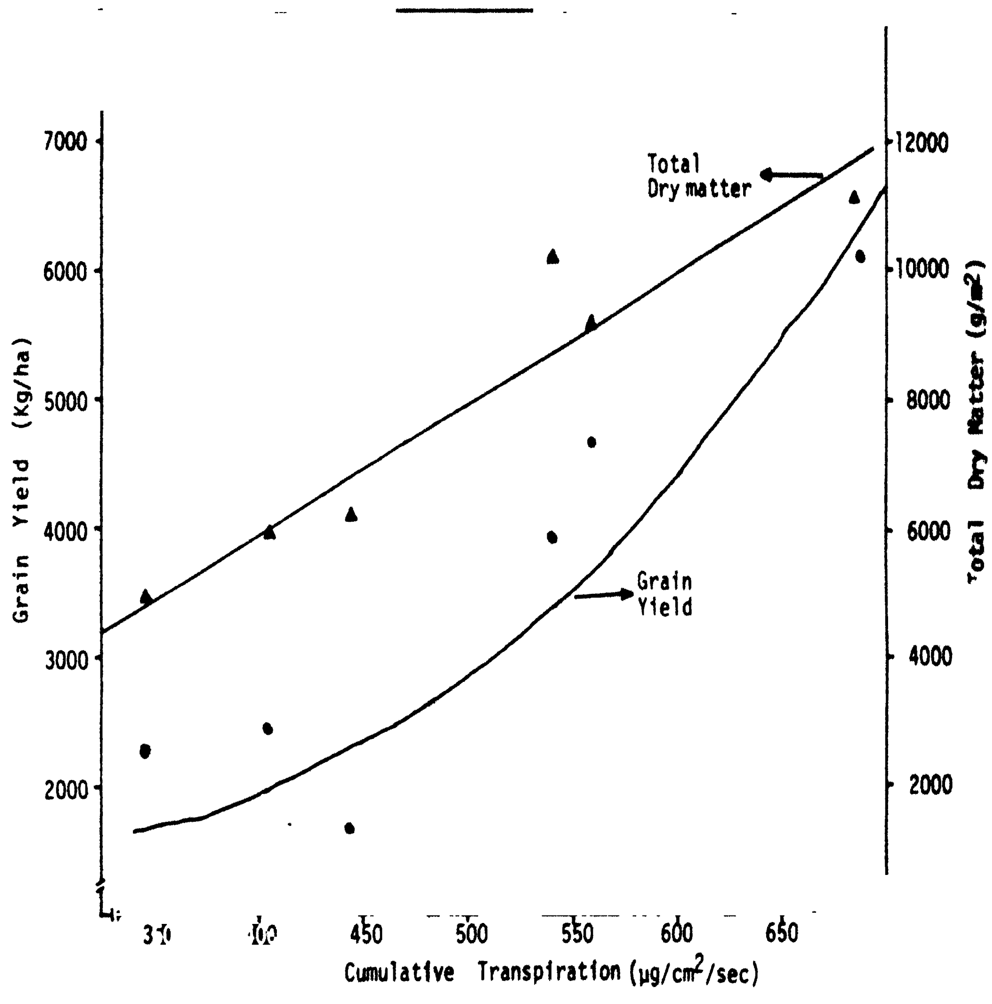


Figure 28. Relationship of total dry matter and grain yield of sorghum to cumulative transpiration (data pooled over 3 genotypes).

M3 - Two irrigations at early vegetative growth stage N3 - 80 kg N/ha

M4 - Two irrigations at the time of flowering

Irrigation schedule in different treatments is shown in Table 4.

Table 4. Schedule of irrigation applied to millet crop under different moisture regimes.

Date	Days after emergence	M1	M2	M3	M4
		1980 summer			
25 Jan	(for germination)	x	x	x	x
11 Feb	12	x	x	x	x
20 Feb	21	x	-	x	-
29 Feb	30	x	-	x	-
10 Mar	40	x	-	-	x
19 Mar	49	x	-	-	x
28 Mar	58	x	x	-	-
07 Apr	68	x	x	-	-
		1981 summer			
06 Feb	(for germination)	x	x	x	x
23 Feb	13	x	x	x	x
02 Mar	20	x	-	x	-
11 Mar	29	x	-	x	-
21 Mar	39	x	-	-	x
30 Mar	48	x	-	-	x
09 Apr	58	x	x	-	-
18 Apr	67	x	x	-	-

Measurements of LAI, leaf number, drymatter distribution in different plant components, and soil water were made on a weekly basis throughout the two growing seasons. In the 1981 growing season additional measurements of canopy conductance, transpiration, leaf temperature and air temperature were made in all the treatments to understand the plant-water relations.

1980 growing season

The effect of irrigation and nitrogen levels at different growth stages on the leaf production per plant is shown in Figure 29. Under frequent irrigations in treatment M1, maximum leaf number per plant was observed at 46 DAE at the highest nitrogen application rate of 80 kg/ha. Two supplemental irrigations during the early vegetative growth (M3) favored better leaf production in comparison to two supplemental irrigations at the time of flowering (M4) or

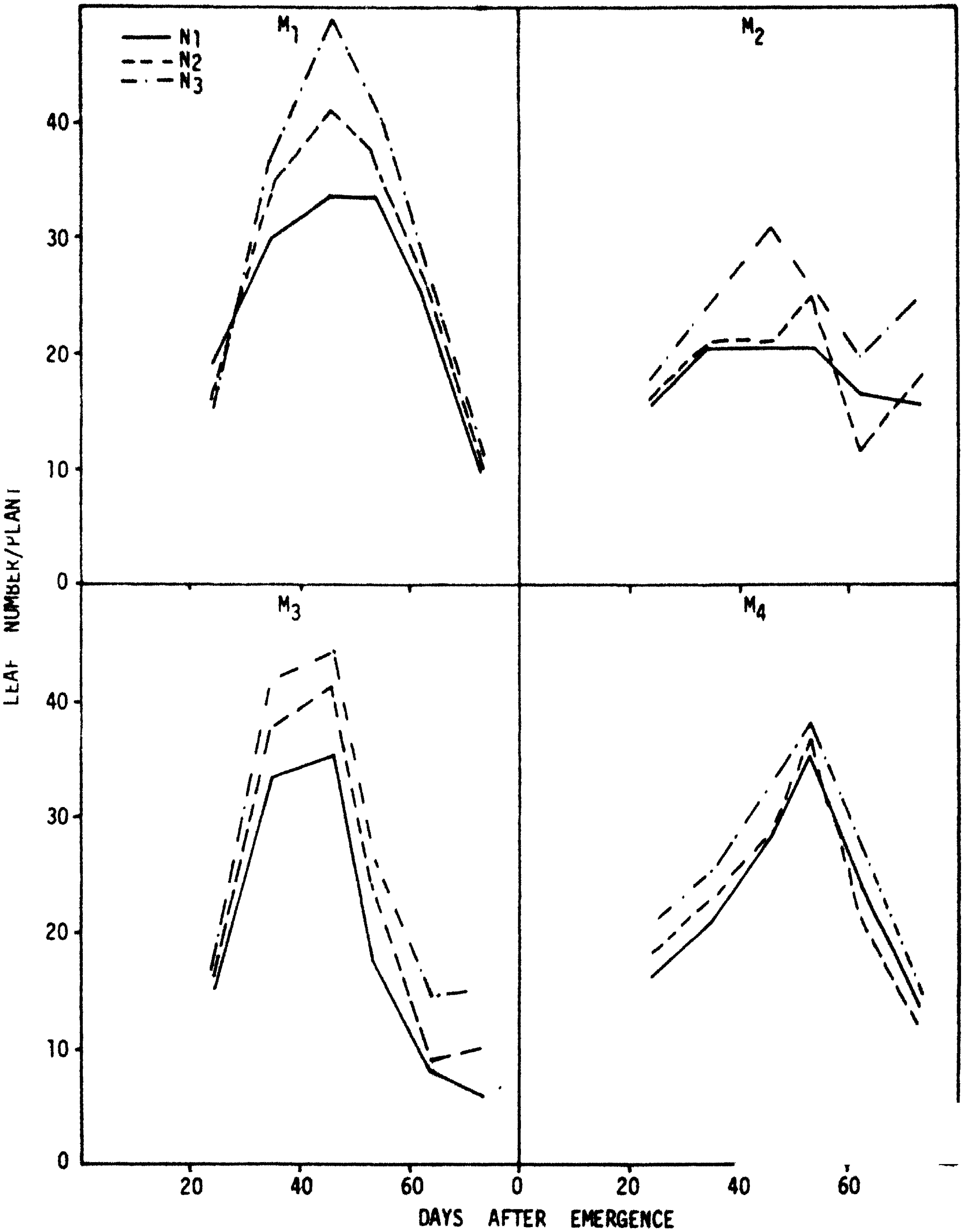


Figure 29. Leaf production in millet grown under different moisture regimes and nitrogen levels during the 1980 summer.

at grain filling (M2). Significant responses to applied nitrogen were noticed in treatments M1 and M3. Application of 80 kg N/ha only showed response in the case of treatment M2.

Delaying the supplemental irrigations till flowering as in treatment M4 resulted in a delay in the attainment of maximum leaf number by about 8 days as compared to the other treatments. This did not however happen in treatment M2 where the irrigations were delayed till grain filling. These data suggest that once flowering is complete and grains start filling, leaf production is complete in millet.

Changes in leaf area index of millet with time (Fig. 30) follow a pattern more or less similar to leaf production observed earlier with treatments M1 and M3 proving superior to M2 and M4. With an adequate nitrogen supply of 80 kg/ha, millet crop under treatment M1 was able to maintain a higher leaf area index till 62 DAE. This was not true however under the other two nitrogen levels. LAI patterns observed in Figure 30 suggest a strong moisture x nitrogen interaction in millet.

Drymatter distribution pattern in the leaf, leaf sheath, stem, head and grain components of millet crop under different treatments in the 1980 growing season is shown in Figures 31 and 32. Maximum drymatter accumulation was observed in treatment M1 at all levels of Nitrogen. The response of millet to nitrogen in terms of increased drymatter accumulation is evident at both levels of 40 and 80 kg N/ha. Most significant effect of moisture stress is apparent in treatment M2 where the irrigations have been withheld till grain filling stage. Maximum drymatter level as well as its distribution among different components indicate that under moisture stress millet shows little response to added nitrogen. This conclusion with respect to nitrogen response is also valid under the other two moisture regimes also as shown in Figure 32. Irrigating the millet crop during the early vegetative growth stage (trt.M3) promoted improved drymatter accumulation in the leaf, leaf sheath and stem components. For example by 50 DAE total drymatter accumulation in treatment M3N1, was about 180 g/m^2 while in treatments M2N1 and M4N1 the total drymatter accumulation was only 70 and 100 g/m^2 respectively. In terms of maximum drymatter accumulation however by 73 DAE irrigating the millet crop at the time of early vegetative growth or at the time of flowering yielded similar response at all the nitrogen levels.

Grain yield response of millet to irrigation and nitrogen level during the 1980 summer is shown in table 5. Mean yield for the moisture regimes over the nitrogen levels shows that irrigating the crop every ten days gave significantly higher yields over the other three moisture regimes. This conclusion is also valid for the comparison of moisture regimes at a given nitrogen level. In, terms of the relative yield advantage attainable by two supplemental irrigations at selected physiological stages, mean yields over the nitrogen levels show that irrigations at early vegetative growth or at the time of flowering resulted in significantly higher yields as compared to irrigating at the time of grain filling. However, at any given nitrogen level, the LSD values for comparison of moisture regimes show that there is no significant difference between the M2, M3 and M4 treatments. Mean yield for the three nitrogen levels over the four moisture regimes showed no advantage of applied nitrogen.

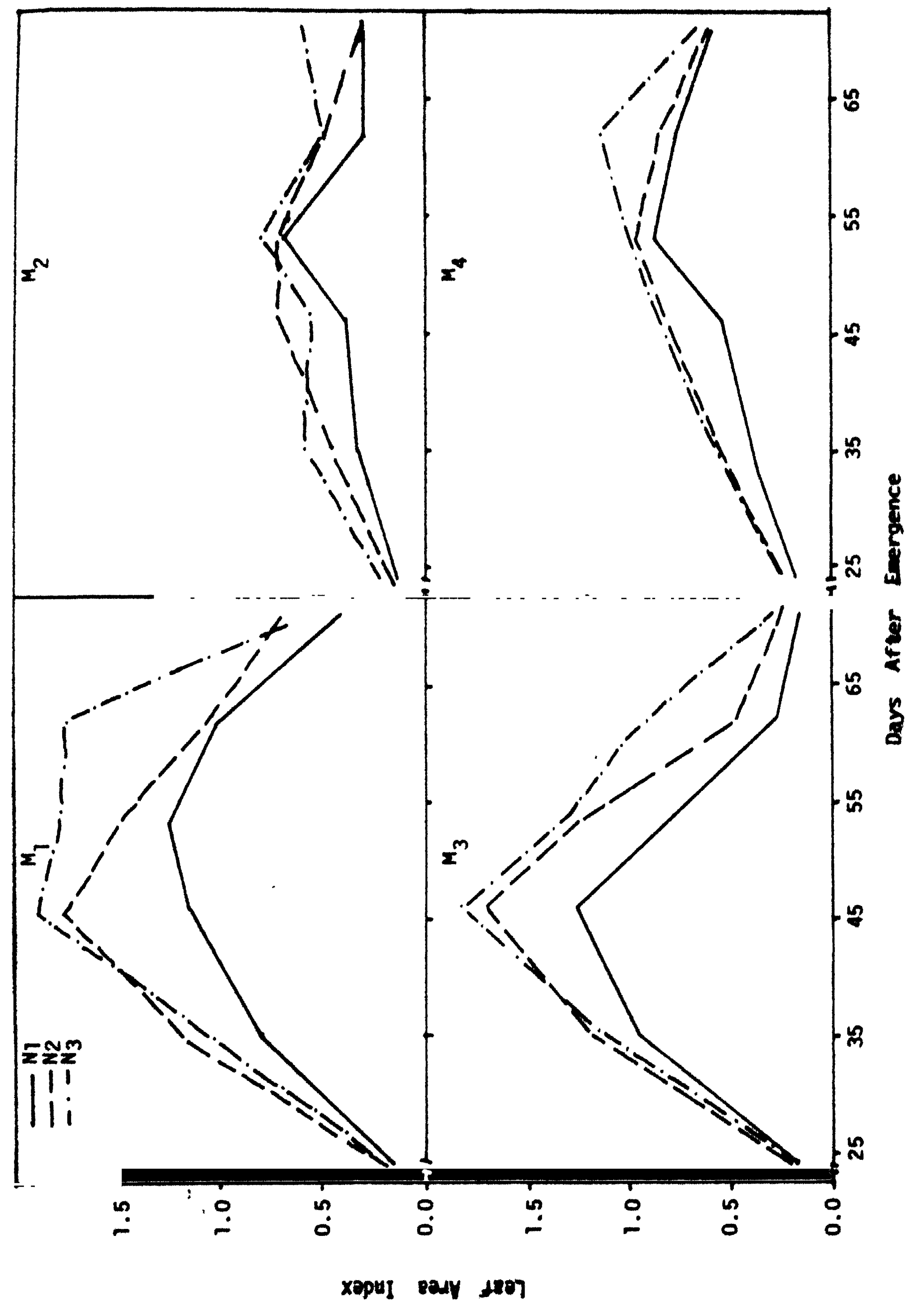


Figure 30. Leaf area index of millet grown under different moisture regimes and nitrogen levels during the 1980 summer.

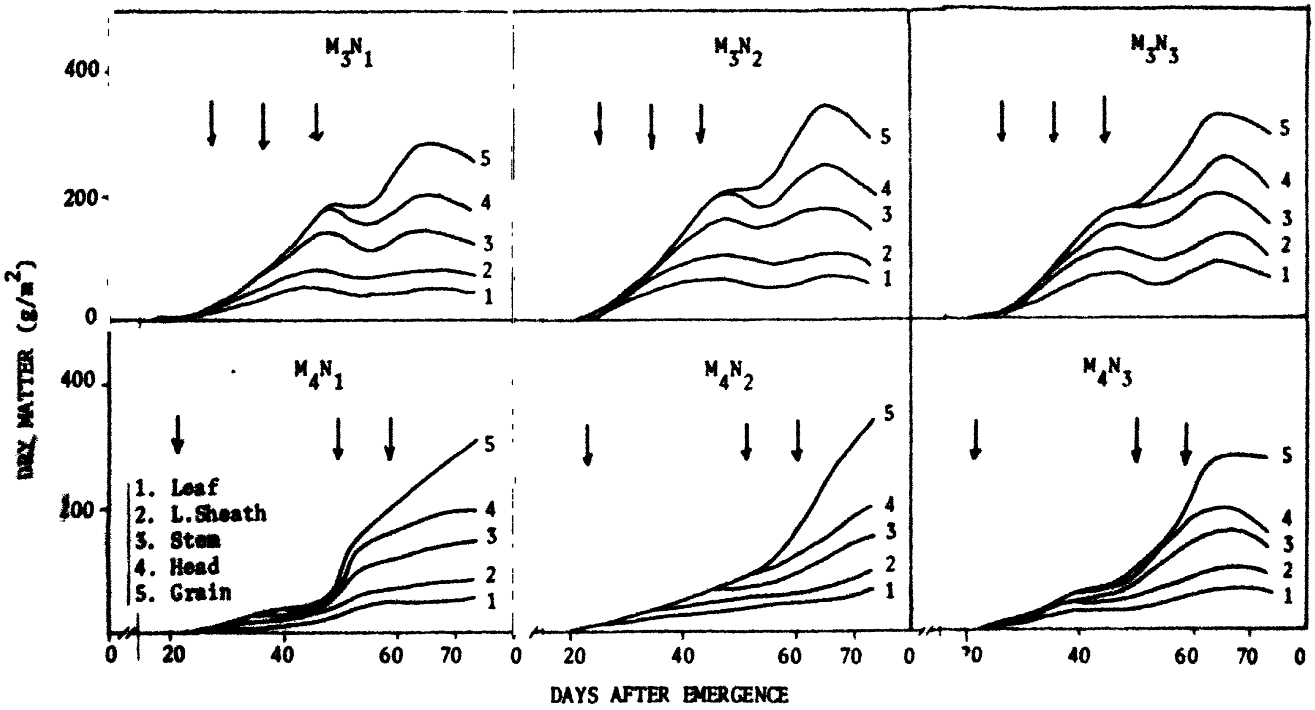


Figure 31. Dry matter distribution pattern in millet grown under different moisture regimes and nitrogen levels during the 1980 summer.

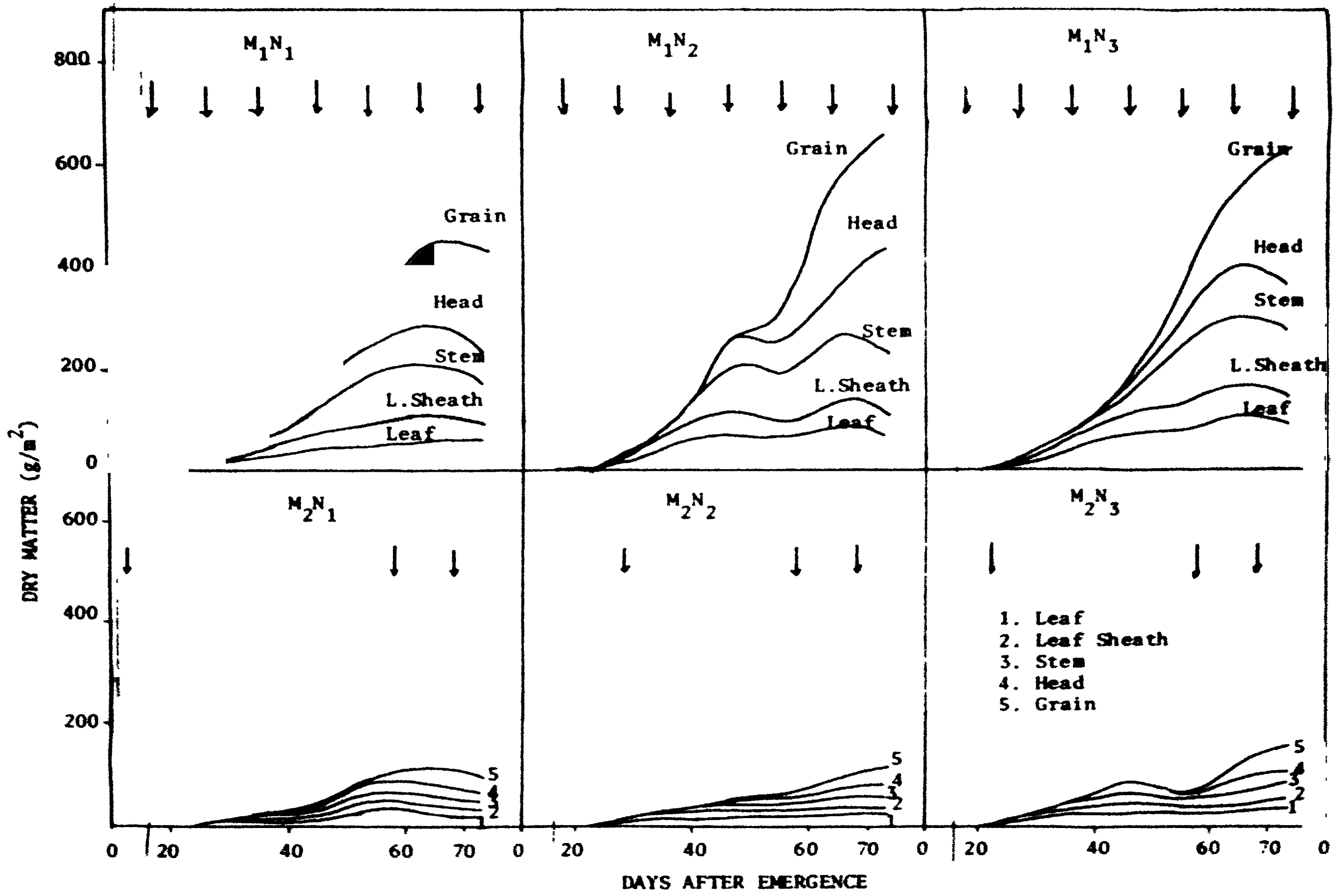


Figure 32. Dry matter distribution pattern in million grown under different moisture regimes and nitrogen levels during the 1980 summer.

Table 5. Grain yield response of millet to irrigation and nitrogen levels during 1980 summer on an Alfisol at ICRISAT Center, Patancheru.

Nitrogen levels	Moisture regimes M1	M2	M3	M4	Mean for nitrogen levels
	---------kg/ha-----------				
N1	1763	364	868	827	956
N2	1922	446	804	945	1029
N3	2173	363	847	873	1064
Means for moisture regimes	1953	391	840	881	

Overall mean: 1016   CV% whole plot: 16   CV% sub-plot: 20

	$S.E_m$ (0.05)	L.S.D. (0.05)
Nitrogen levels	126	266
Moisture regimes	176	430
Nitrogen levels in a moisture regime	251	533
Moisture regimes in a nitrogen level	270	610

Results with respect to final straw yield (table 6) also show that irrigating the crop every ten days gave a significant response over the other moisture regimes. There was no significant difference among the three moisture regimes M2, M3 and M4. Comparison of mean straw yields for the three nitrogen levels shows that application of 40 and 80 kg N/ha proved superior to nitrogen application. Application of 80 kg N/ha gave a significantly higher straw yield over no nitrogen application when two supplemental irrigations were given at the early vegetative growth stage (M3). Nitrogen application rates showed no advantage for the moisture regimes M2 and M4.

1981 growing season

Before discussing the results of the 1981 summer experiment, it will be appropriate to point out an anamoly in the growing season environment. As mentioned earlier millet crop was sown on 5 February and emergence occurred on 10 February The treatments M1 and M3 received supplemental irrigations as per the schedule given in table 4 till 11 March 1981 (29 DAE). On 12, 13 and 14 March rainfall measuring 39 mm was received. A supplemental irrigation was given to treatments M1 and M4 as per schedule on 21 March. Again on 22 and 23 March 38 mm of rainfall occurred. Observed rainfall at this time of the year is very unusual as the probability of even 5 mm in a 7-day period is less than 15 percent during this period (Virmani et al. 1978). In order to observe the response of millet to this mid-season rains and also to provide a comparison with the results obtained in the 1980 summer growing season, irrigations were continued as per the schedule after the rains.

Table 6. Straw yield response of millet to irrigation and nitrogen levels during 1980 summer on an Alfisol at ICRISAT Center, Patancheru

Nitrogen levels	Moisture regimes				Mean for nitrogen level
	M1	M2	M3	M4	
	----------kg/ha----------				
N1	1877	670	873	880	1075
N2	2599	705	1157	1022	1371
N3	2345	681	1252	1047	1332
Means for moisture regimes	2274	685	1094	983	

Overall mean: 1259 CV% whole plot: 18 CV% sub-plot: 14

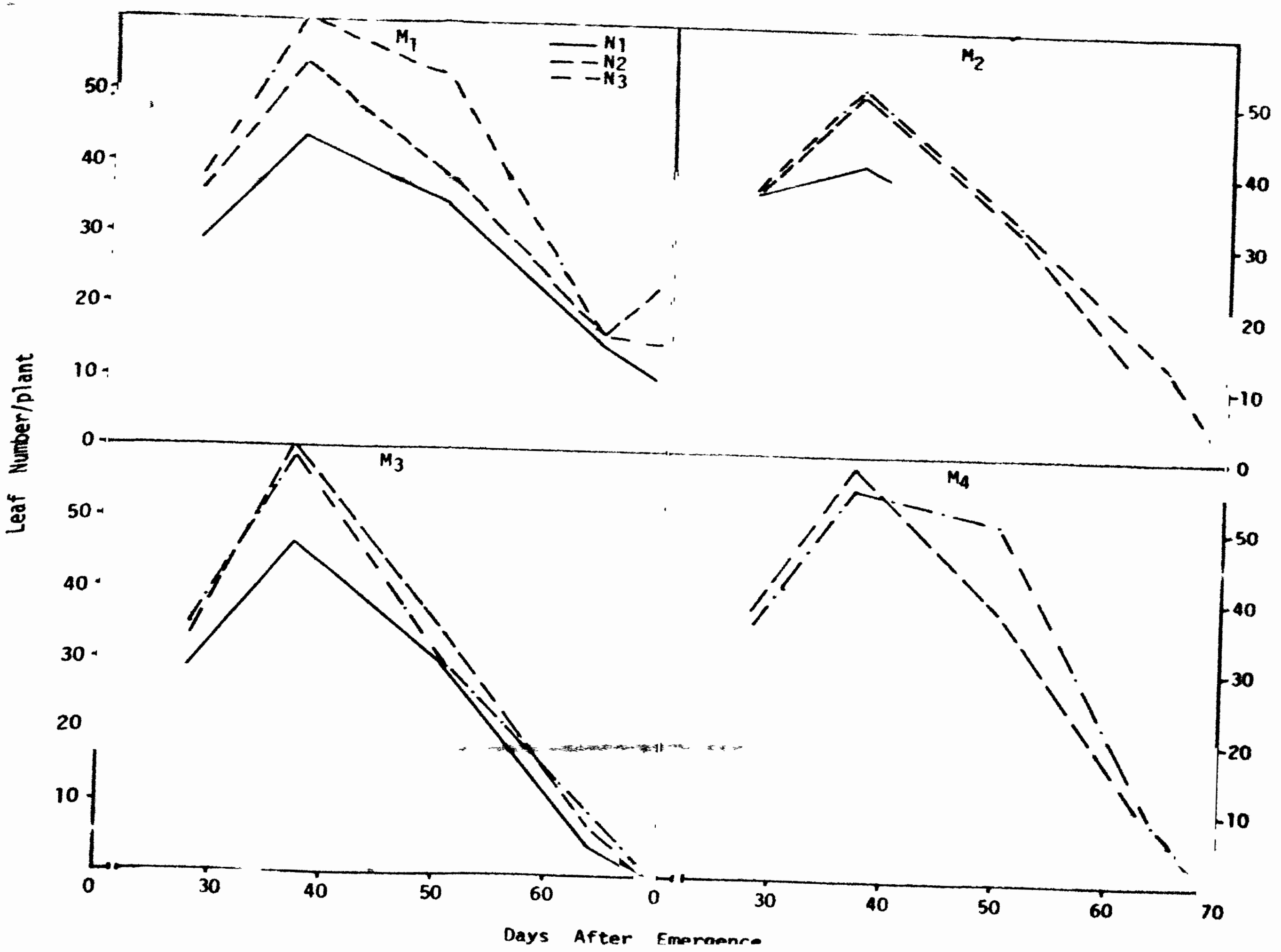
	S.E$_m$ (0.05)	L.S.D. (0.05)
Nitrogen levels	72	153
Moisture regimes	283	694
Nitrogen levels in a moisture regime	144	306
Moisture regimes in a nitrogen level	307	736

Unseasonal rainfall observed in the 1981 summer growing season led to crop responses to stress that were unusual and different from the responses observed in the previous growing season. However, these results permitted us to draw some generalizations on the response of millet to water stress.

Seasonal changes in the leaf number/plant for the four moisture treatments are shown in Figure 33. Rains around 30 and 40 DAE led to leaf production patterns that were more or less similar between different treatments. Better moisture environment during the 1981 growing season resulted in higher leaf number in comparison to leaf production during 1980 summer. Maximum leaf number was almost same in treatments M1, M3 and M4. Because of supplemental irrigations at the time of flowering at a high nitrogen level of 80 kg/ha, leaf number/plant was maximum in treatment M4 as in treatment M1 even at 50 DAE.

As with leaf number, LAI of millet was higher during the 1981 growing season (Figure 34). Treatments M1, M3 and M4 were on par except that in M4 the decline in LAI occurred a little earlier. Responses to applied nitrogen were maximum in treatment M1 and M3. The strong moisture x nitrogen interactions observed during the previous season were not evident during the 1981 growing season.

Drymatter accumulation in different plant components of millet under different treatments is shown in Figures 35 and 36. As in the previous season, maximum accumulation of drymatter occurred in treatment M1 at all levels of nitrogen. As opposed to the results during 1980 summer, two supplemental irrigations given at the time of flowering resulted in maximum drymatter accumulation as compared to M2 and M3 treatments. For example by 65 DAE, millet crop receiving 80 kg N/ha


M1
N1
N2
N3
M2
M3
M4
Leaf Number/plant
Days After Emergence
0
10
20
30
40
50
60
70

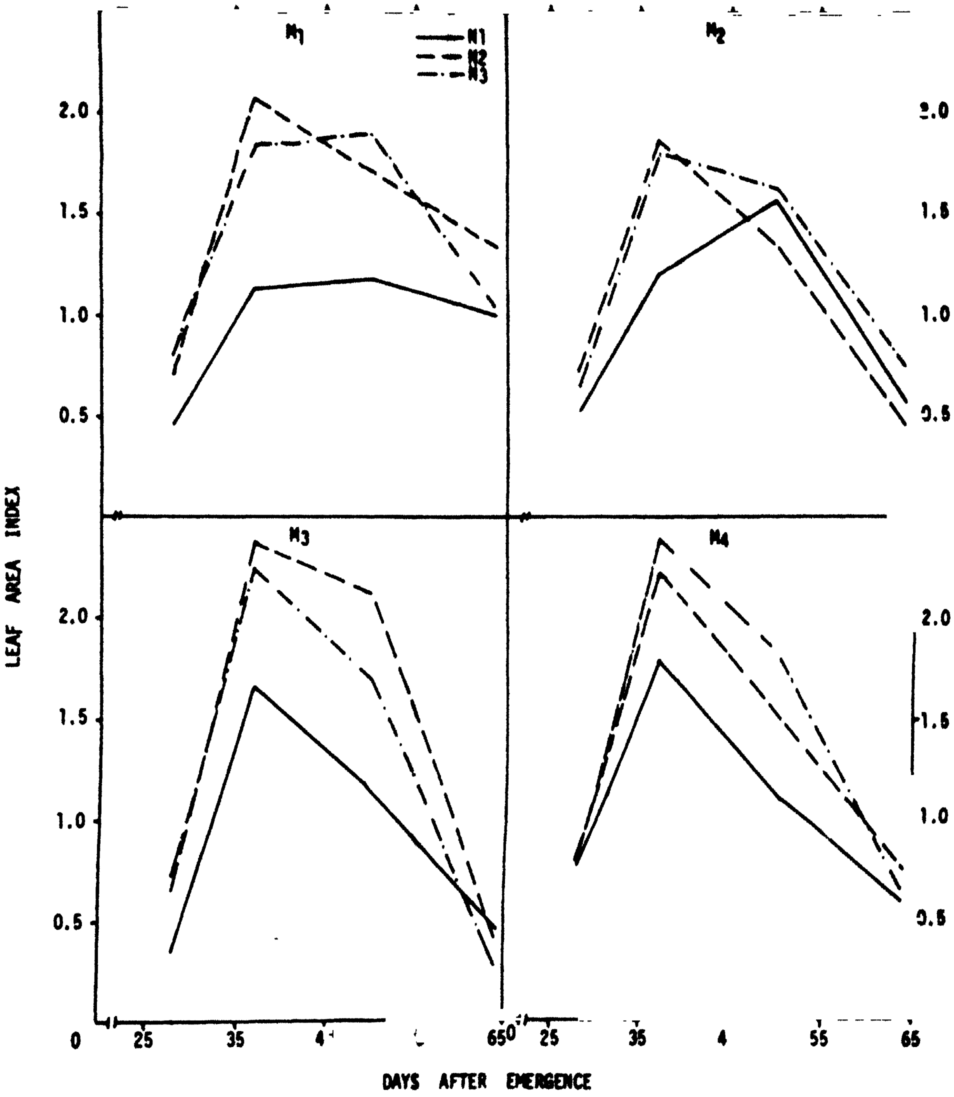


Figure 34. Leaf area index of millet grown under different moisture regimes and nitrogen levels during the 1981 summer.

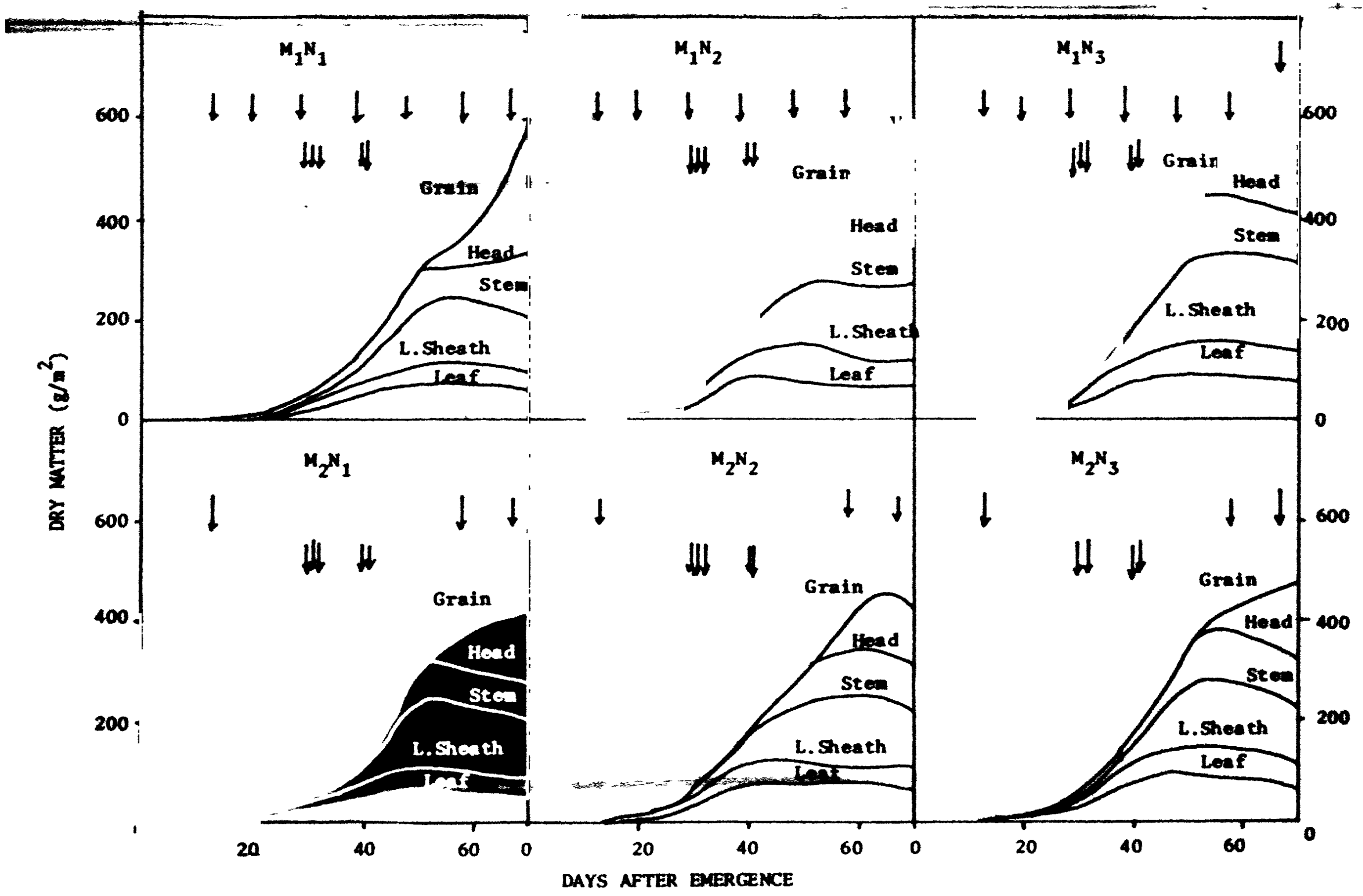


Figure 35. Dry matter distribution pattern in millet grown under different moisture regimes and nitrogen levels during the 1981 summer.

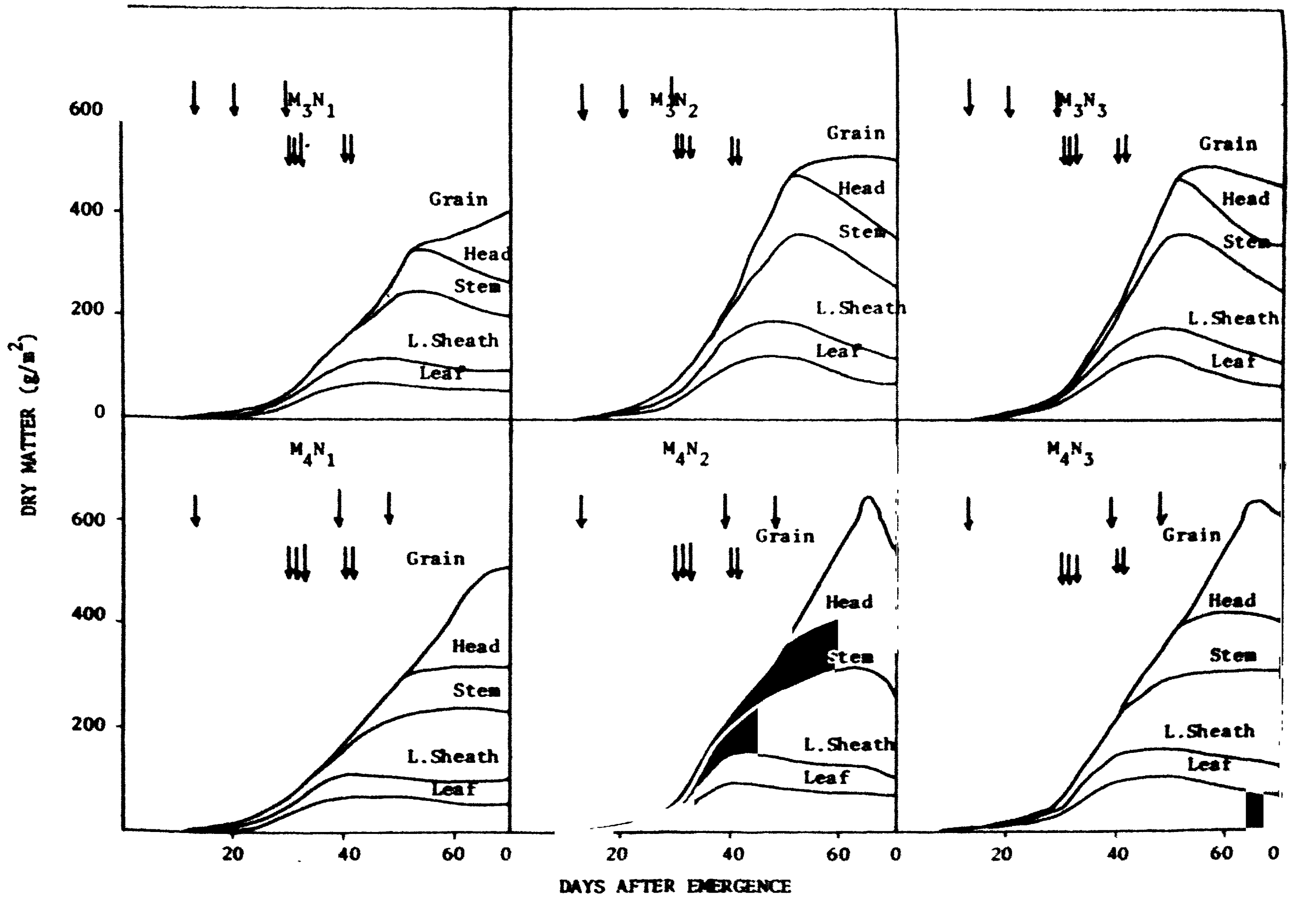


Figure 36. Dry matter distribution pattern in millet grown under different moisture regimes and nitrogen levels during the 1981 summer

produced 650 g/m^2 in treatment M4 while in treatment M2 and M3 the drymatter production was 475 and 470 g/m^2 respectively.

Cumulative leaf-air temperature differential of millet under the four moisture regimes at the nitrogen level of 80 kg/ha is shown in Figure 37. The measurements depict data taken for a continuous period of 15 days from 16 March (34 DAE) to 31 March (49 DAE). Treatments M1 and M3 received two supplemental irrigations on 2 March and 11 March prior to these measurements. During the period of these measurements M1 and M4 received supplemental irrigations on 21 March and 30 March.

Data in Figure 37 show clearly the influence of different moisture regimes on the plant response under an adequate nitrogen supply. Two days prior to these measurements, rainfall measuring 39 mm occurred, hence the treatment differences were not apparent till 4 days after the measurements started. Treatment M1 receiving supplemental irrigations every 10 days showed the least effect of moisture stress as the cumulative LATD was consistently lower. The early advantage of supplemental irrigations given to treatment M3 lasted for a period of 20 days i.e., till 48 DAE (just around the time of flowering) by which time treatment M4 showed superior responses to available water as indicated by the lower LATD. A sharp contrast is provided by treatment M2 which showed consistently higher LATD indicating maximum stress effects.

Stomatal conductance and transpiration data of millet under different moisture regimes at the nitrogen level of 80 kg/ha for selected days are shown in Table 7. When these data are examined in the context of the irrigation schedule in different treatments (table 4), it is apparent that millet shows a significan adaptability to moisture stress. Under significant stress till 1 April, millet in treatment M2 showed a significant stomatal closure and reduction in transpiration. The recovery due to two supplemental irrigations on 9 April and 18 Apri to treatment M2 is indicated by improved stomatal conductance and transpiration. Similar are the responses observed in the case of treatment M4 on 25 March and 1 April after the supplemental irrigations on 21 March and 30 March. Significan reductions in stomatal conductance and transpiration of millet from 25 March til. maturity were observed in treatment M3.

Final yields of millet under different treatment (table 8) reveal some interesting features when compared to results of 1980 (table 5). One noticeable feature is that the overall mean yield during 1981 summer was 2389 kg/ha while in 1980 it was only 1016 kg/ha. This improvement could be solely attributed to 77 mm of rainfall during 1981. Treatment M1 gave significantly higher grain yield only over treatment M3 but not over treatments M2 and M4. The reasons for this response are apparent when the length of the dry period is examined for the three treatments M2, M3 and M4. In the case of treatment M2 there was a 17 day dry spell before the rains and another spell of 15 days before the two supplemental irrigations late in the growing season. In treatment M4 the dry spell of 17 days before rains was followed immediately by rains and supplemental irrigations and then there was 27 day dry spell. In both M2 and M4, the length of dry spell after completion of flowering was short. However, in treatment M3 after the second rains there was an uninterrupted 34-day dry spell which must have affected grain filling.

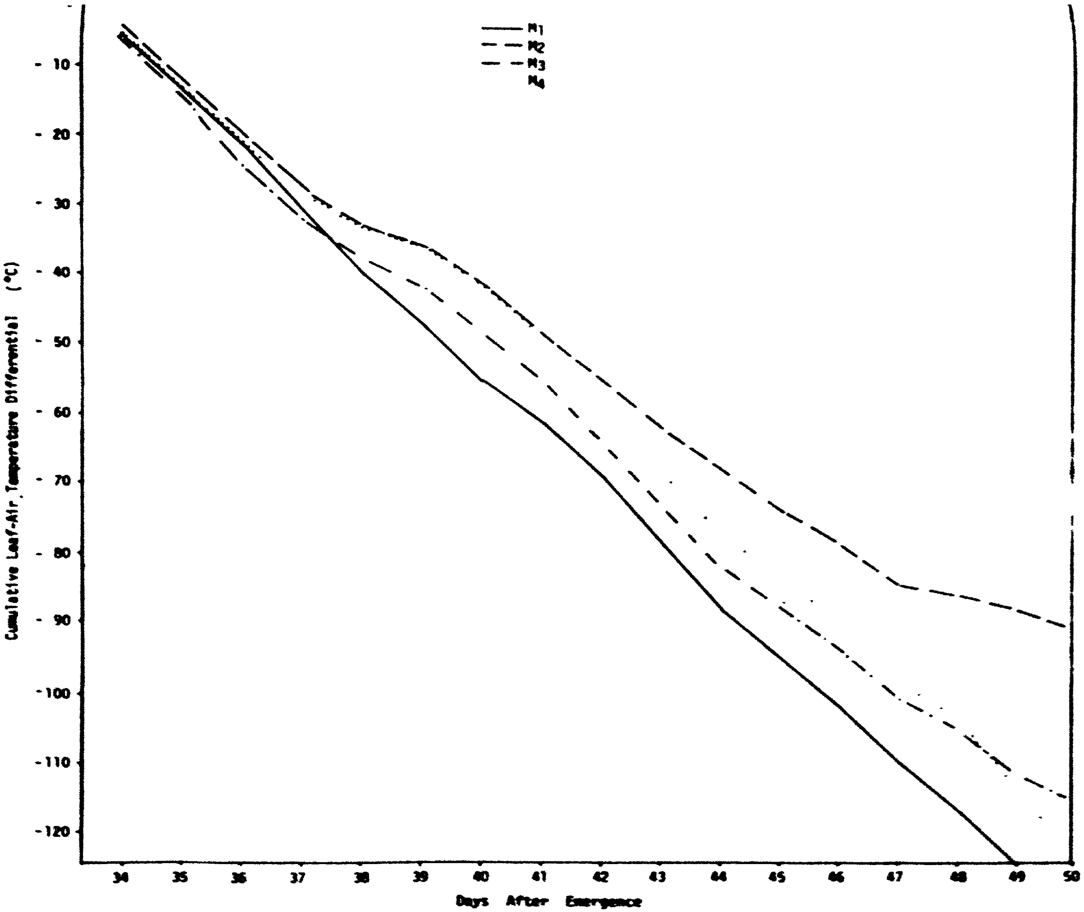


Figure 37. Cumulative leaf-air temperature differential (LATD) measured from 16 March to 31 March 1981 for millet grown under different moisture regimes at a nitrogen level of 80 kg/ha.

Table 7. **Stomatal conductance and transpiration of millet crop grown under different moisture regimes at 80 kg N/ha.**

Date	M1		M2		M3		M4	
	Cond.	Transp.	Cond.	Transp.	Cond.	Transp.	Cond.	Transp.
16 March	0.53	14	0.43	11	0.57	15	0.31	8
25 March	0.89	24	0.42	12	0.50	13	0.55	17
01 April	0.53	26	0.17	6	0.19	10	0.69	24
10 April	0.29	14	0.30	16	0.12	11	0.16	9
20 April	0.14	7	0.29	15	0.00	0	0.04	2

Table 8. Grain yield response of millet to irrigation and nitrogen levels during 1981 summer on an Alfisol at ICRISAT Center, Patancheru.

Nitrogen levels	Moisture regimes				Means for nitrogen levels
	M1	M2		M4	
N1	2416	2219	1718	2167	2130
N2	3167	2148	2122	2493	2483
N3	2711	2411	2248	2600	2493
Mean for moisture regime	2765	2260	2030	2420	

Overall means: 2369   CV% Main plot: 24   CV% Sub-plot: 11

	$S.E_m$ (0.05)	L.S.D. (0.05)
Nitrogen levels	107	228
Moisture regimes	265	647
Nitrogen levels in a moisture regime	215	455
Moisture regime in a nitrogen level	317	745

Straw yield responses of millet (table 9) show that the treatment M3 gave significantly lower straw yield when compared to treatments M1 and M4. There was no significant difference between treatments M1 and M4. Except for treatment M1, there was no response to applied nitrogen.

Table 9. Straw yield response of millet to irrigation and nitrogen levels during 1981 summer on an Alfisol at ICRISAT Center, Patancheru.

Nitrogen level	Moisture regimes				Means for Nitrogen levels
	M1	M2	M3	M4	
N1	1969	1489	1124	1892	1619
N2	2650	1350	1144	1824	1742
N3	2234	1166	1031	1847	1570
Nitrogen for moisture regimes	2285	1335	1100	1854	

Overall mean: 1643 CV% Main plot: 24 CV% Sub-plot: 20

	$S.E_m$ (0.05)	L.S.D. (0.05)
Nitrogen levels	135	287
Moisture regimes	191	468
Nitrogen levels in a moisture regime	270	573
Moisture regime in a nitrogen level	292	660

When the results of the 1980 summer season are compared with those of 1981 summer, two factors emerge clearly that modulate the response of the millet crop to water and nitrogen stress.

1. A prolonged spell of water stress during the stage of both early vegetative growth and flowering could reduce the yield of the millet crop substantially. Millet could recover from stress imposed at early growth if supplemental irrigations are provided before and around the time of flowering is completed. Availability of water around the time of flowering seems to be crucial for subsequent grain filling.

2. Millet would respond to applied nitrogen only when sufficient water is available for good vegetative growth and for promoting active flowering. Application of nitrogen beyond 40 kg/ha does not show economic responses.

CHAPTER IV

Crop Weather Modeling: Sorghum Modeling Experiments

Over the past three years a multilocation collaborative project is being conducted at ICRISAT and at other cooperating centers in the SAT. Scientists from different disciplines are actively involved in collecting congruent data sets on soils, crops, weather and management with the following main objectives:

(i) To develop and test dynamic sorghum simulation models by integrating information on different aspects of crop growth and development.

(ii) To develop a quantitative understanding of crop response to environment.

(iii) To identify areas where quantitative knowledge is lacking and plan a future course of action to fill the gaps in knowledge.

(iv) To use models as research tools in the development and transfer of technology.

Preliminary tests with SORGF (Arkin et al. 1976) showed that several subroutines in the model need modification for its adoption to the SAT regions. These subroutines deal with emergence, soil water, leaf area development, phenology, light interception and drymatter partitioning. Based on limited data sets, some preliminary revisions were made in SORGF during the year 1979-80 (Agroclimatology Report of Work, 1979-80). The revised SORGF model referred to as SORGF-1 showed some improvements in simulating sorghum growth and development.

Data collected from the sorghum modeling experiments during the rainy and postrainy seasons of 1979 and 1980 were used to further examine the SORGF model. The revised model is now referred to as SORGF-2. The revisions made and the simulation results from SORGF and SORGF-2 are described in this report.

Experimental Methods

Replicated trials involving two standard sorghum genotypes, CSH-1 and CSH-6 during the rainy season and CSH-8 and M-35-1 during the postrainy season, were conducted at most of the locations. Additional moisture treatments of adequate water and water stress at certain critical stages were included in the postrainy season experiments. Standard data sets on crop, soil, weather and management required to test the model were collected. Details of the nature of data and method of data collection were described by Huda et al. (1980).

Details of Multilocation Trials

The experiments were conducted at ICRISAT Center, Coimbatore, Delhi, Hissar, Ludhiana, Parbhani, Pune and Rahuri in India and at Khon Kaen in Thailand. Data obtained at each of these locations during the 1980 rainy season, and 1979-80 and 1980-81 postrainy seasons, are described in detail by Huda et al. (1981). A brief description of the trials is given below.

1. ICRISAT Center

a) 1979-80 Postrainy Season

The trials were conducted on both Alfisol (RP-4) and Vertisol (BP-12) soils.

RP-4: The response of two sorghum genotypes CSH-8 and M-35-1 to available soil moisture was studied by creating two levels of soil moisture depletion. The available water holding capacity of the soil is 8.5 cm. Crops were sown on 19 November and the soil was recharged to capacity just after planting. Emergence occurred on 22 November. Two differential moisture regimes were created by giving four supplemental irrigations at 19, 39, 57, and 76 DAE (referred to as treatment A) and only two supplemental irrigations at 39 and 76 DAE (referred to as treatment B). Final plant populations/ha for CSH-8 were 143,000 and 125,000 in treatments A and B respectively and for M-35-1 in both treatments they were 150,000.

BP-12: This experiment involved comparison of five different row spacings of sorghum hybrid CSH-8 i.e., 30-, 60-, 90-, 120-, and 150-cm at two different moisture regimes. The crop was sown on 22 November. After a 'come-up' irrigation of 4-cm on 23 November the emergence occurred on 26 November. The available water holding capacity of the soil is 14 cm. The moisture regimes included three supplemental irrigations measuring 6, 6 and 4.5 cm at 15, 35 and 55 DAE (treatment A) and no supplemental irrigation (treatment B).

b) 1980 Rainy Season

Alfisol (RP-4): Two sorghum hybrids CSH-1 and CSH-6 were tested under supplemental irrigation (treatment A) and under rainfed situation (treatment B). The crops were sown on 19 June and emergence occurred on 23 June. After giving two supplemental irrigations to treatment A at 5 and 28 DAE it was noticed that rains following irrigations led to waterlogging and no further irrigations were given. This waterlogging led to decreased total drymatter and grain yield for CSH-6 as will be discussed later.

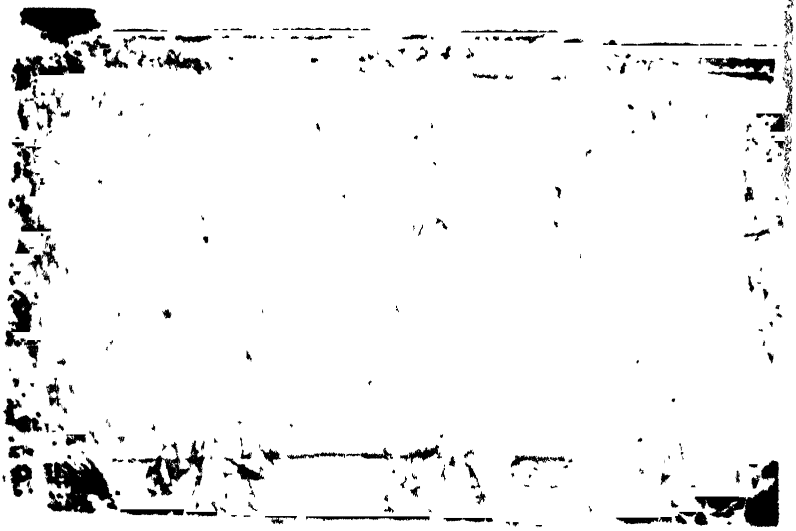
Vertisol (BW-3): This trial involved three sorghum genotypes CSH-1, CSH-6 and SPV-351 which were sown on 18 June and emergence occurred on 4 July because of dry seeding. Plant populations at harvest were 117,000, 130,000 and 114,000 for CSH-1, CSH-6 and SPV-351 respectively.

c) 1980-81 Postrainy Season

Experiments were conducted on both Alfisols and Vertisols with the specific objective of quantifying the effect of moisture stress on leaf area development, phenology, drymatter production and its partitioning in various genotypes.

Alfisol (RP-4): Three sorghum genotypes CSH-6, CSH-8, and M-35-1 were grown under two moisture treatments A and B. The crop was sown on 10 October. A common irrigation was given to both treatments on 11 October to recharge the profile. Emergence occurred on 13 October. Treatment A received four supplemental irrigations at 10, 28, 39 and 70 DAE while treatment B was irrigated at 10 and 39 DAE (Plate 1).

A: Well-watered.
Front: CSH-8, Middle CSH-6, Rear M-35-1.



B: Stressed
Front: CSH-8, Middle: CSH-6, Rear: M-35-1.

Plate 1: A view of sorghum modeling experiment with three genotypes under two moisture treatments grown at ICRISAT Center on an Alfisol (RP-4) during 1980-81 postrainy season.

Vertisol (BW-5): An unreplicated trial involving four genotypes (CSH-6, CSH-8, M-35-1 and CSV-5) and two moisture treatments A and B was conducted. Sowing was done on 24 November. The entire field was irrigated after sowing to recharge the profile holding 200 mm available water. Treatment A was given irrigations at 36, 65 and 81 DAE while in treatment B no supplemental water was applied to the crop.

2. Coimbatore

Sorghum modeling experiment was initiated in Coimbatore from the 1980-81 post-rainy season. CSH-6 was sown on [illegible] November. The soil contained [illegible] cm available water at sowing against the capacity to hold [illegible] cm available water. Emergence occurred on 12 November. A total of [illegible] mm of rainfall was received in this growing season. Five irrigations each of [illegible] cm were given at 28, 44, 58, 74, and 90 DAE. Population was 140,000/ha.

3. Delhi

At Delhi, both CSH-1 and CSH-6 were sown on 28 June during the 1980 rainy season. The soils at Delhi are recent alluvial soils with a maximum water holding capacity of 18.7 cm. The available soil water at sowing was 8.5 cm. Two irrigations were given on 27 August and 16 September each with 5 cm. This treatment is referred to as A. The other treatment involves growing crops under rainfed situation and is referred to as treatment B.

4. Hissar

In the 1979 rainy season CSH-6 performed considerably better with grain yield of 3590 kg/ha compared to 1580 kg/ha for CSH-1 due to damage caused by shootfly for the later hybrids. Therefore, only CSH-6 was grown in 1980 rainy season with two moisture treatments. The crop was sown on 20 June. In one treatment three additional irrigations each amounting 8 cm were applied on 9 July, 20 July and 16 August (treatment A) and the other treatment involves growing crops under rainfed situation (treatment B).

5. Khon Kaen

Sorghum genotype Hegari was sown on 13 August 1980. The available water at sowing was 11.5 cm indicating the fully recharged profile. Emergence occurred on 16 August. No irrigation was given.

6. Ludhiana

CSH-1 and CSH-6 were sown on 1 July 1980. The soil profile was almost full at the time of sowing. The available water holding capacity of the soil is 12.8 cm Emergence occurred on 4 July. A total of 74.5 cm rainfall was received during the growing season. The crop was grown in rainfed situation.

7. Parbhani

a) 1979-80 Postrainy Season

CSH-8 and M-35-1 were sown on 7 October. The available water holding capacity was 15 cm at sowing indicating 75 percent recharge of the profile. Emergence occurred on 12 October. Crops were grown with the residual moisture with 25 mm precipitation received in this growing season.

b) 1980 Rainy Season

CSH-1 and CSH-6 were sown on 23 June. The soil having 20 cm available water holding capacity was about 50 percent recharged at sowing. It took 3 days for emergence. No supplemental irrigation was given.

c) 1980-81 Postrainy Season

CSH-8 and M-35-1 were sown on 20 October. The available soil water at sowing was 16 cm. Emergence occurred on 23 October. Two irrigations each of 5 cm were given on 25 October and 11 November. The stand of M-35-1 was very poor and therefore no data are reported for this variety.

8. Pune

a) 1979-80 Postrainy Season

CSH-1 and M-35-1 were sown on 1 December. The available soil water at sowing was 8.6 cm against the capacity of the soil to hold 12.5 cm available water. Row to row spacing was maintained at 45 cm while this was 75 cm for almost all other locations. Five irrigations each amounting 7 cm were given on 15 November, 12 December, 4 January, 23 January and 7 March.

b) 1980 Rainy Season

CSH-1 and CSH-6 were sown with 45 cm row spacing on 17 July. The available water holding capacity of the soil was 10 cm. An irrigation was given to recharge the profile at sowing.

c) 1980-81 Postrainy Season

CSH-8 and M-35-1 were sown on 16 November with a presowing irrigation after recharging the profile with a capacity to hold 10 cm available water. Emergence occurred on 19 November. Three more irrigations each measuring 10 cm were given on 21 December, 14 February and 4 March. The stand of M-35-1 was not good and therefore data for this genotype were not reported.

9. Rahuri

a) 1980 Rainy Season

CSH-1 and CSH-6 were sown on 12 July. The soil at the time of sowing contained 10 cm available water against its capacity of 12 cm. Emergence occurred on 15 July. There were two moisture treatments. In one treatment 100 mm water was applied through irrigation. This is referred to as treatment A. In treatment B crops were grown under rainfed situation.

b) 1980-81 Postrainy Season

CSH-8 and M-35-1 were sown on 13 October when the available soil water was 10 cm. Two more irrigations each amounting to 10 cm were given on 4 and 6 December.

Results

1. Summary of Weather Data

The normal and seasonal rainfall data along with seasonal potential evaporation at different locations for the 1980 rainy season are given in table 10. Above normal rainfall was received at Delhi, Parbhani and Ludhiana. The seasonal rainfall at ICRISAT Center was normal and was 28 percent higher than the PE requirement. Rainfall at Hissar, Khon Kaen, Pune and Rahuri was below normal. However at Khon Kaen the PE requirements could be adequately met through the seasonal rainfall.

Table 10. Summary of weather data for 1980 rainy season.

Location	Seasonal rainfall	Normal rainfall	Open pan evaporation (Eo)	PE*
	----------------------	----------------------	mm ----------------------	----------------------
ICRISAT Center	591	587	658	461
Delhi	724	617	568	398
Hissar	200	304	804	563
Khon Kaen	455	557	392	274
Parbhani	1050	830	698	489
Pune	248	516	500	350
Rahuri	291	538	565	396
Ludhiana	745	528	528	370

*PE = Eo x 0.7

2. Summary of Experimental Results

Detailed data on phenology, maximum and final LAI, total drymatter and grain yield observed for different sorghum genotypes at ICRISAT and the phenological data observed at other cooperating locations are given in the section under simulation results. Summary of genotypic performance under different treatments at each of the locations is given below.

a) ICRISAT Center

(i) 1979-80 Postrainy Season: There was no difference in the days to physiological maturity (PM) between the two moisture treatments A and B for both CSH-8 and M-35-1 in an Alfisol (RP-4) experiment. However, it was observed from other experiments that hastening of the maturity depends on the degree of moisture stress which prevails during the grain filling period. The available soil moisture at PM in this experiment was 2.0 cm for M-35-1 in both treatments while it was 1.9 and 1.5 cm in treatments A and B for CSH-8. Thus both A and B treatments had the same order of moisture stress during the later part of grain filling period. CSH-8 performed better than M-35-1 under both adequate and limited moisture stiuations.

(II) 1980 Rainy Season: In the trial on the Alfisols (RP-4), total drymatter and grain yield for CSH-6 in treatment A were lower than in treatment B. Observed reductions show that CSH-6 is susceptible to waterlogging in the rainy season. Since total drymatter and grain yield for CSH-1 were higher in treatment A than in B it can be surmised that CSH-1 is tolerant to waterlogging.

In the Vertisol experiment, CSH-6 performed better than CSH-1 and SPV-351, although the leaf area index and total drymatter were maximum in SPV-351. Partitioning of drymatter to grain component which seems to be important here is discussed later.

(III) 1980-81 Postrainy Season: Early maturity because of moisture stress in treatment B was notable for all the three genotypes CSH-6, CSH-8 and M-35-1 tested on the Alfisols (RP-4) in two moisture treatments. Leaf area index, total drymatter and grain yield were maximum in treatment A for all the genotypes (Plate 2) Highest grain yield was recorded for CSH-8 in both treatments. However, under limited water availability in treatment B, M-35-1 was superior in total drymatter production as compared to CSH-8 and CSH-6. Total water use and water use efficiencies for different treatments are shown in table 11.

In the trial on Vertisols (BW-3) early maturity was observed due to the effect of moisture stress. CSH-6 showed early maturity followed by CSV-5, CSH-8 and M-35-1. The performance rankings in terms of grain yield for treatment A is CSH-8 > CSV-5 > CSH-6 > M-35-1 and for treatment B it is CSH-8 > CSH-6 > CSV-5 > M-35-1. Maximum total drymatter in treatment A was recorded for CSH-8 while in treatment B, CSV-5 proved superior.

Results from both the Alfisols and Vertisols show that CSH-8 proved superior to the other genotypes tested.

Table 11. Water use and water use efficiency of three sorghum genotypes grown during the 1980-81 postrainy season at ICRISAT Center.

Observation	CSH-8		CSH-6		M-35-1	
					A	B
1. Water use (mm)	289	210	281	198	291	210
2. Water use efficiency (kg of TDM/ha/mm)	38.6	30.8	32.9	25.3	35.2	32.3

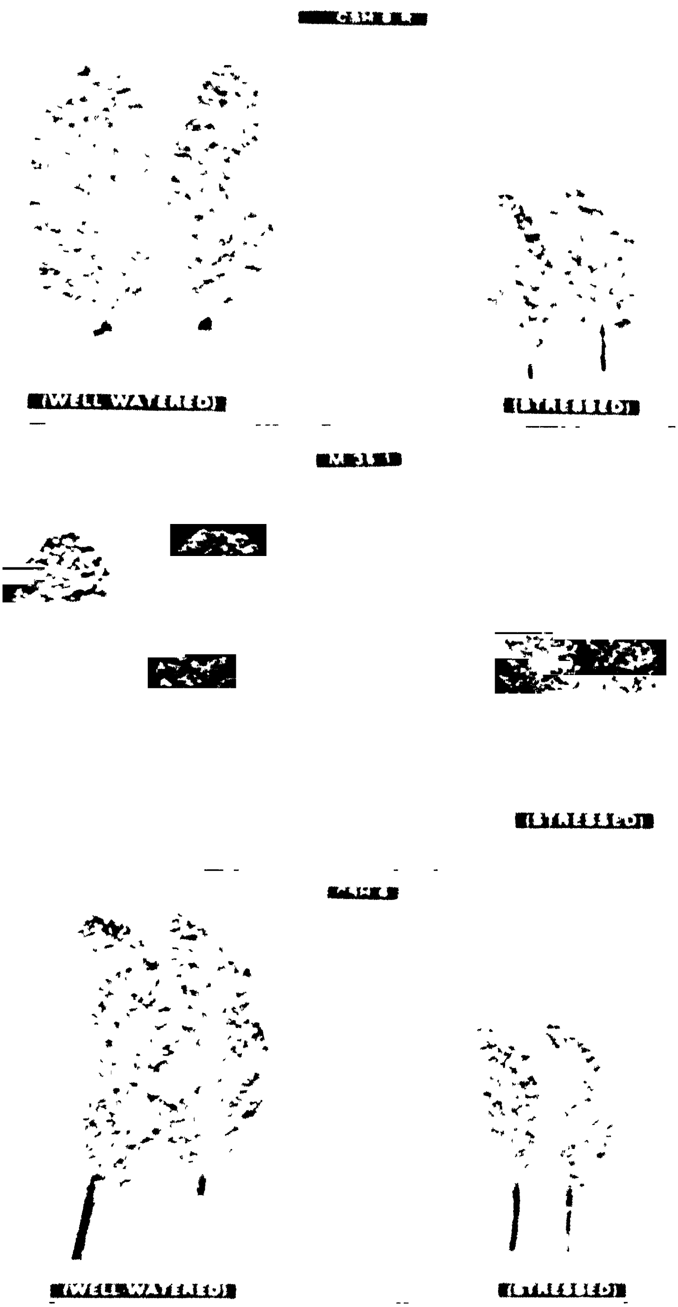


Plate 2: Comparison of heads for three sorghum genotypes grown at ICRISAT Center on an Alfisol (RP-4) during 1980-81 postrainy season.

b) Cooperating Centers

A summary of crop data for all the cooperating centers is given in table 12. The data indicate that during rainy season, CSH-6 performed consistently better than CSH-1 at all locations excepting Rahuri during the 1980 rainy season. Supplemental irrigations given to treatment A totalled 100 mm at Rahuri and this led to waterlogging. CSH-6 yielded less than CSH-1 in treatment A while in treatment B (rainfed), CSH-6 proved superior. This observation confirms the susceptibility of CSH-6 to waterlogging observed in the Alfisol trial at ICRISAT Center during the same season. In the postrainy season at all locations CSH-8 showed its superiority over M-35-1.

Table 12. Summary of crop data collected at cooperating centers.

(1) Delhi (1980 Rainy Season)

	CSH-1 (A)	CSH-1 (B)	CSH-6 (A)	CSH-6 (B)
Final plant population	140,000	140,000	160,000	160,000
Total drymatter (kg/ha)	11,586	9,016	12,810	11,430
Grain yield (kg/ha)	3,850	3,550	4,500	[illegible],900
Maximum LAI	5.92	5.92	5.15	5.15
Final LAI	3.39	1.69	2.49	1.43

(2) Hissar (1980 Rainy Season)

	CSH-6 (A)	CSH-6 (B)
Final plant population	175,000	167,000
Total drymatter (kg/ha)	23,420	20,316
Grain yield (kg/ha)	3,310	2,756

(3) Ludhiana (1980 Rainy Season)

	CSH-1	CSH-6
Final plant population	80,000	80,000
Total drymatter (kg/ha)	14,200	14,200
Grain yield (kg/ha)	1,437	2,467
Maximum LAI	1.09	1.08
Final LAI	0.54	0.32

(4) Khon Kaen (1980 Rainy Season)

	Hegari
Final plant population	119,000
Total drymatter (kg/ha)	4,750
Grain yield (kg/ha)	950
Maximum LAI	1.04
Final LAI	0.91

Table contd..

(A) Adequate moisture supply
(B) Rainfed

Table 12 Contd.

(5) Coimbatore (1980-81 Postrainy Season)

	CSH-8
Final plant population	140,000
Grain yield (kg/ha)	3,167

(6) Rahiri (1980 Rainy Season)

	CSH-1 (A)	CSH-1 (B)	CSH-6 (A)	CSH-6 (B)
Final plant population	130,000	140,000	140,000	140,000
Grain yield (kg/ha)	3,913	3,203	2,694	3,595

(7) Rahuri (1980-81 Postrainy Season)

	CSH-8	M-35-1
Final plant population	90,000	140,000
Grain yield (kg/ha)	7,158	4,071

(8) Parbhani (1979-80 Postrainy Season)

	CSH-8	M-35-1
Final plant population	70,000	68,000
Total drymatter (kg/ha)	5,800	5,300
Grain yield (kg/ha)	2,000	1,400
Maximum LAI	2.32	1.87
Final LAI	1.59	1.43

(9) Parbhani (1980 Rainy Season)

	CSH-1	CSH-6
Final plant population	112,000	115,000
Total drymatter (kg/ha)	11,240	13,020
Grain yield (kg/ha)	2,600	3,050
Maximum LAI	3.72	3.36
Final LAI	1.4	1.23

(10) Parbhani (1980-81 Postrainy Season)

	CSH-8
Final plant population	92,300
Total drymatter (kg/ha)	5,150
Grain yield (kg/ha)	3,080
Maximum LAI	4.62
Final LAI	1.07

Table contd.

Table 12 Contd.

(11) Pune (1979-80 Postrainy Season)

	CSH-8	M-35-1
Final plant population	180,000	150,000
Total drymatter (kg/ha)	8,657	4,000
Grain yield (kg/ha)	5,360	1,766

(12) Pune (1980 Rainy Season)

	CSH-1	CSH-6
Final plant population	70,000	120,000
Total drymatter (kg/ha)	5,133	8,205
Grain yield (kg/ha)	1,233	2,138

(13) Pune (1980-81 Postrainy Season)

	CSH-8
Final plant population	100,000
Total drymatter (kg/ha)	6,296
Grain yield (kg/ha)	2,759

3. Revised Subroutines in SORGF

a) *Phenology*

The time from emergence to floral differentiation is computed in the SORGF model as the period midway between the stages when five leaves expanded and when the flag leaf is visible in the whorl; time from emergence to anthesis is calculated as the computed date the flag leaf was expanded plus 0.86 times the computed number of days from differentiation to flag leaf appearance; time from emergence to physiological maturity (PM) is calculated as 1.4 times the computed number of days from emergence to anthesis.

In the revised version of SORGF instead of Accumulated Daily Heat Units, Growing Degree Days (GDD) are used to estimate the phenological events with a base temperature of 7°C and a cutoff temperature of 30°C. Data collected at ICRISAT Center show that 390 GDD are required to reach panicle initiation (PI) for hybrids like CSH-1, CSH-6 and CSH-8. GDD for varieties like SPV-351 and M-35-1 are 420 which is a little higher. These values are referred to as base GDD for PI. Emergence to anthesis is computed as 2.68 times GDD required for PI. Similarly emergence to physiological maturity is computed as GDD required for PI times 4.15.

The simplicity of the method of GDD computation may cause errors in calculating GDD. Some criticisms of calculating GDD using maximum and minimum temperatures with base and cutoff temperature are as follows:

- The threshold temperatures are not constant but change with advancing age of the plant (Wang, 1960); the narrower the range between daily maximum and minimum, the faster the development rate is at the same average temperature (Arnold 1971); and

- the day length bias is also incorporated in computing GDD in a north-south direction (Newman 1971). Stapper and Arkin (1980) used a day length correction factor for computing GDD to determine the phenology of corn.

It is suggested that these points be considered and a sound method of GDD computations be evolved in due course of time. However, the following correction factor is used in the revised version for computing phenology.

$$\text{GDD for PI} = \text{Base GDD}\ \{1-(13-\text{Day length}) \times .2\}$$

A base day length of 13 hours was chosen because the average day length for the emergence to PI in the rainy season is 13 hours at ICRISAT Center. Emergence to anthesis and PM for other locations is computed in a similar manner for ICRISAT Center.

b) Leaf Area

Total number of leaves and maximum area for individual leaf are two of the input data requirements for driving SORGF model. The number of leaves given as input data for a genotype determine its maturity duration depending on the environmental condition. It needs 50 HU above 7°C base temperature for a new leaf to emerge and then attainment of its maximum area is also a function of temperature. It is assumed that in the present model each leaf will achieve its maximum area irrespective of water stress. Also it is assumed that senescence will start after 11th leaf fully expands. These are some of the limitations in the computation of leaf area index.

It would be useful to simulate area for each leaf using environmental information instead of using them as input data. Data collected from ICRISAT indicate that senescence occurs after seventh leaf has expanded. So this information is included in the revised version. It is also assumed that the final LAI at PM will be 0.5 of its maximum under no moisture stress situation; 1/3 under mild water stress conditions (at WATSCO -- ratio of current available water and water holding capacity -- between 1.0 and 0.5). In severe moisture situation (WATSCO < 0.5) the final LAI will be nearly zero. Critical evaluation of the effect of moisture stress on leaf development is presently underway Reasonable estimation of leaf area index is important because this information is used in other subroutines like light interception and soil water.

c) 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 day length. Examination of our data show that model computation of solar declination and day length are quite accurate resulting in sufficiently accurate estimation of hourly solar radiation. The quantum flux density (PAR) in Einsteins m^{-2} day^{-1} is estimated in SORGF from the energy flux density (RS) in cal $cm^{-2} day^{-1}$ as

$$PAR = RS\ (0.121)$$

However our results indicate that the constant relating PAR to solar radiation (RS) should be altered. In the revised version, PAR is thus calculated as 0.09 times RS.

Light transmission is calculated from the relationship of extinction coefficient and maximum light transmission using information on row spacings and 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. The model breaks down for row spacings greater than 137 cm because the computed light transmission exceeds 100 percent. Thus the functions for estimating extinction coefficient (X2) and maximum light transmission (X1) were revised. These are:

$$X2 = 0.0065 * \text{Row spacing} - 0.6469$$

$$X1 = 0.4711 * \text{Row spacing} + 67.2642$$

$$\text{Light transmission} = X1 * \text{Exp}\ \{X2 * \text{DLAI (I)}\}$$

Both SORGF and the revised equations simulate light transmission within 15 percent of observed light transmission, with the revised equations performing better for wider row spacings. This indicates scope for further improvement of this subroutine.

d) Soil Water

Daily available water for the entire soil profile (single layered) is computed 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 computing 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 computed from albedo, maximum solar radiation reaching the soil surface (Ro), and sky emissivity. Ro is calculated using a site-specific sine function as follows for ICRISAT Center:

$$Ro = ([illegible] + [illegible] * (Sin (0.0172 * (I-80)))$$

and Ro is not allowed to exceed 690 cal $cm^{-2} day^{-1}$

However, results indicate that Ro is underestimated. It may be useful to include open pan data as an input requirement of the model so that by multiplying these data with a suitable constant PE could be estimated. In the revised version open pan data times 0.7 has been included to compute PE.

However, several other subroutines of soil water are available in the literature. At present an exercise is underway to compare the performance of these subroutines. The subroutine giving accurate estimates of available soil water will be included in the model. These subroutines are:

(i) Ritchie model (1972) with appropriate modification for computing PE.

(ii) Ritchie model (1972) with the procedure developed by Williams and Hann (1976) to account for an effective rooting depth and consider a multi-layered profile.

(iii) I[illegible]WAB (Reddy, [illegible]).

Reasonably accurate computation of soil water is important because it determines the moisture stress index which influences LAI, phenology, drymatter and its partitioning.

e) Drymatter and its Partitioning

In SORGF potential photosynthate is calculated from intercepted PAR. Net photosynthate is computed after accounting for the water and temperature stress as well as for respiration. At ICRISAT Center we do not have facilities to study the photosynthesis and respiration in detail. So it was felt that it would be desirable to develop a relationship between total drymatter (TDM) and intercepted PAR. Our data indicate that [illegible] g of drymatter is produced per MJ of PAR absorbed when water and temperature stress do not occur. From the daily potential drymatter, actual drymatter increase is estimated as a function of temperature and water stress using the TEMPCO and WATSCO coefficients. This has been included in the revised version of the model.

The average Harvest Index was found to be 0.50 for the hybrids like CSH-1, CSH-6 and CSH-8; and 0.36 for varieties like M-35-1 and SPV-351 under no moisture stress conditions. However, these values were lower depending on the degree of moisture stress. In the revised version the harvest index used was 0.40 for hybrids and 0.26 for varieties under moisture stress conditions. Assumptions are made that HI per day holds a linear relationship from anthesis to PM. Further examination of the data is required to come up with a more satisfactory partitioning coefficients.

4. Summary of Simulation Results

The revised SORGF version is referred to as SORGF-2. The following comparision of SORGF and SORGF-2 results are made with the observed data.

a. Phenological events.
b. Leaf area index as a function of time.
c. Drymatter and its partitioning to grain yield.
d. Statistical analysis.

a) Phenological Events

Observed and simulation results for the days required from emergence to anthesis and PM for different genotypes, locations, seasons and treatments are compared in tables 13 and 14. Observed data indicate that rainy season hybrids like CSH-1 and CSH-6 took about 52-56 DAE to reach anthesis and 85-88 DAE to reach PM, while SPV-351 took about 62-63 DAE to reach anthesis and about 90-95 DAE to reach maturity. In early October plantings during the postrainy season CSH-8 matured a little earlier than M-35-1. It took about 60-66 DAE to reach anthesis and 98-106 DAE to reach PM. M-35-1 reached anthesis by 67-71 DAE and PM by 105-113 DAE. When plantings were delayed till late November on deep Vertisols days to anthesis and PM were extended for CSH-8. M-35-1 also took longer to reach anthesis (80 DAE) and PM (115 DAE).

Simulation results indicated that SORGF underestimated the maturity duration while the estimation by the revised version was reasonably close to the observed data.

b) Leaf Area Index as a Function of Time

Data on leaf area index were collected at 7-10 days interval in all the treatments for every experiment conducted at ICRISAT Center. Simulation results are compared with the observed data, and the maximum LAI and final LAI at PM for all these experiments are given in table 15. Seasonal changes in LAI for selected experiments are shown in Figures 38 to 41.

Results indicate that both SORGF and SORGF-2 overestimate the maximum LAI. Suggestions are made in the preceding section regarding future revisions in computing LAI in the early growth stages. Modifications made so far in this regard account for leaf senescence after the expansion of the 7th leaf (instead of after the 11th leaf as is done in SORGF) and include the effect of moisture stress in the grain filling period. The revised version of SORGF improved the computation of LAI in the grain filling period. However, further improvements are envisaged in the overall leaf area development computation.

c) Drymatter and its Partitioning to Grain Yields

Total drymatter (kg/ha) and grain yields (kg/ha) for all experiments conducted at ICRISAT Center are compared with simulation results (table 16), and seasonal patterns in observed and simulated drymatter and grain yield for selected genotypes are shown in Figures 42 to 45.

Observed and simulated drymatter and grain yield pooled over all the treatments are shown in Figures 46 and 47 to examine the degree of correspondence between observed and simulated results. Results indicate that some improvements in simulating TDM and grain yields were achieved through revisions and considerable scope exists for further improvement.

Table 13: Observed and Simulated Phenological Events at ICRISAT Center.

Location	Season	Genotype/ Treatment	Days from emergence to					
			Anthesis			PM		
			O	S_1	S_2	O	S_1	S_2
RP-4	1979 Rainy	CSH-1	56	54	53	87	76	83
		CSH-6	55	54	53	85	76	83
BW3-A	1979 Rainy	CSH-6	52	62	53	81	76	82
		SPV-351	63	54	57	89	76	88
RP-4	1979-80 Post-rainy	CSH-8 A	60	69	72	98	97	103
		CSH-8 B	62	69	72	97	97	103
		M-35-1 A	67	69	76	105	97	109
		M-35-1 B	63	69	76	105	97	109
RP-4	1980 Rainy	CSH-1 A	52	51	54	88	76	85
		CSH-1 B*	52	51	54	88	76	85
		CSH-6 A	53	51	54	86	76	85
		CSH-6 B*	53	51	54	86	76	85
BW3-A	1980 Rainy	CSH-1	54	51	57	87	80	87
		CSH-6	54	51	57	84	79	87
		SPV-351	62	52	61	94	73	94
RP-4	1980-81 Post-rainy	CSH-8 A	66	56	66	106	80	108
		CSH-8 B	64	56	66	102	80	108
		M-35-1 A	71	64	72	113	87	116
		M-35-1 B	70	64	72	111	87	116
BW3-A	1980-81 Post-rainy	CSH-8 A	73	74	74	110	104	104
		CSH-8 B	73	74	74	107	104	104
		M-35-1 A	80	75	78	115	106	110
		M-35-1 B	80	75	78	111	106	110

O = Observed
S_1 = SORGF
S_2 = SORGF-2
A = Adequate moisture supply
B = Limited moisture supply
PM = Physiological maturity
* = Rainfed

Table 14: Observed and simulated phenological events for cooperating centers

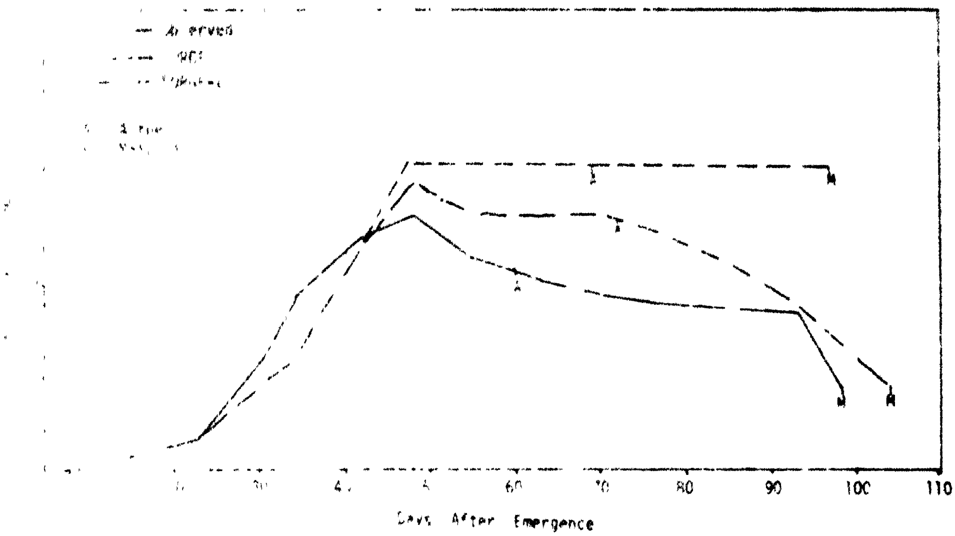
Location	Season	Genotype	Days from emergence to					
			Anthesis			PM		
			0	S_1	S_2	0	S_1	S_2
Parbhani	1979-80 Postrainy season	CSH-8	56	54	60	96	76	101
		M-351	66	54	64	106	76	106
Pune	" "	CSH-8	61	75	79	111	105	112
		M-351	69	75	82	114	105	117
Delhi	1980 Rainy season	CSH-1	58	49	62	99	69	95
		CSH-6	56	49	62	95	69	95
Parbhani	" "	CSH-1	58	53	53	88	75	84
		CSH-1	54	53	53	86	75	84
Khonkaen	" "	Hegari	52	38	52	92	54	80
Parbhani	1980-81 Postrainy season	CSH-8	59	56	69	111	79	115
Coimbatore	" "	CSH-8	58	55	61	96	76	93
Rahuri	" "	CSH-8	59	56	68	91	79	115
		M-351	63	61	73	96	86	121

0 = Observed
S_1 = SORGF
S_2 = SORGF-2
PM = Physiological Maturity

Table 15: Observed and Simulated Maximum and Final Leaf Area Index

Location	Season	Genotype/ Treatment	Maximum LAI			Final LAI		
			0	S_1	S_2	0	S_1	S_2
RP-4	1979 rainy	CSH-1	2.86	2.98	2.66	2.05	2.98	1.03
		CSH-6	2.70	3.29	2.86	1.93	3.29	1.11
BW3-A	1979 rainy	CSH-6	3.47	3.38	3.07	1.40	3.3[illegible]	1.58
		SPV-351	3.46	3.38	3.04	1.83	3.34	1.55
RP-4	1979-80 post-rainy	CSH-8A	2.74	3.64	3.14	1.10	3.59	0.95
		CSH-8B	2.25	3.18	2.74	0.42	3.14	0.25
		M-35-1A	3.04	3.74	3.20	0.92	3.69	0.76
		M-35-1B	2.29	3.74	3.20	0.27	3.69	0.23
RP-4	1980 rainy	CSH-1A	2.93	3.88	3.13	1.23	3.81	1.61
		CSH-1B*	3.06	4.40	3.57	1.77	4.32	1.82
		CSH-6A	3.54	4.53	3.94	0.96	4.53	2.01
		CSH-6B*	3.52	4.53	3.94	1.57	4.53	2.01
BW3A	1980 rainy	CSH-1	2.83	3.93	3.12	1.07	3.87	1.60
		CSH-6	2.76	3.63	3.12	1.52	3.59	1.60
		SPV-351	3.50	3.64	3.30	1.10	3.64	1.69
RP-4	1980-81 post-rainy	CSH-8A	2.96	4.98	4.48	1.92	4.97	1.45
		CSH-8B	2.58	3.81	3.36	0.46	3.80	0.23
		M-35-1A	2.86	3.95	3.53	0.84	3.92	1.03
		M-35-1B	2.02	2.80	2.50	0.45	2.78	0.17
BW3A	1980-81 post-rainy	CSH-8A	3.88	4.12	3.63	1.98	4.12	1.68
		CSH-8B	3.16	4.12	3.63	0.79	4.12	0.33
		M-35-1A	3.71	4.04	3.44	2.77	4.04	1.46
		M-35-1B	2.35	3.50	2.98	0.61	3.47	0.28

0 = Observed
S_1 = SORGF
S_2 = SORGF-2
A = Adequate moisture supply
B = Limited moisture supply
* = Rainfed



[illegible] leaf area index for sorghum hybrid CSH-6 grown under adequate [illegible] during the [illegible] rainy season on Alfisol at ICRISAT Center

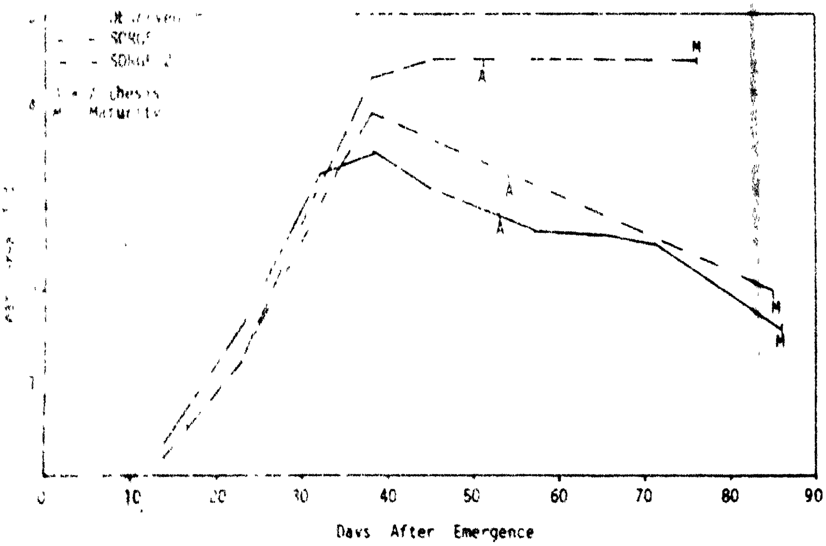


Figure 19. Observed and simulated leaf area index for sorghum hybrid CSH-6 grown under rainfed situation (Trt B) during the 1980 rainy season on Alfisol at ICRISAT Center

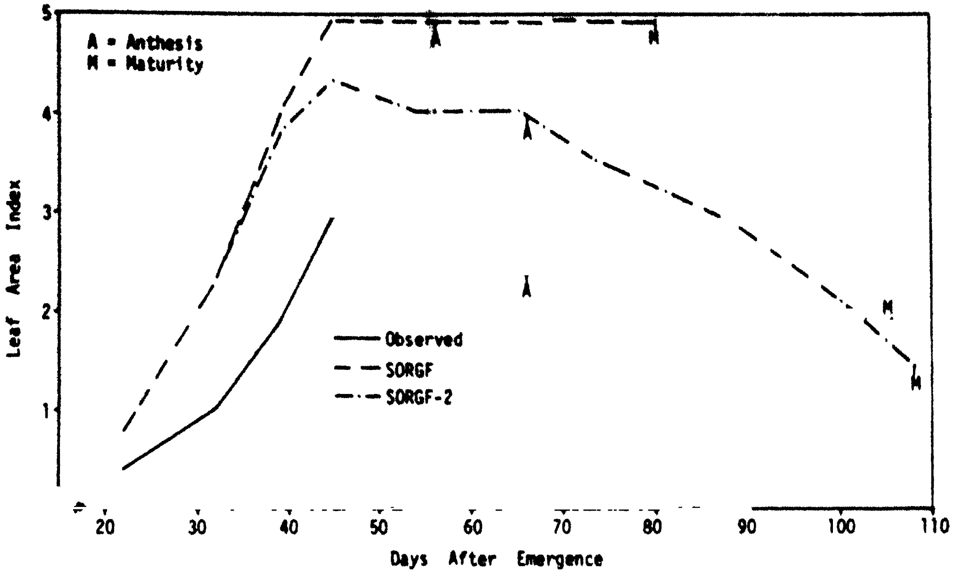


Figure 40. Observed and simulated leaf area index for sorghum hybrid CSH-8 grown under adequate water supply (Trt.A) during the 1980-81 postrainy season on an Alfisol at ICRISAT Center

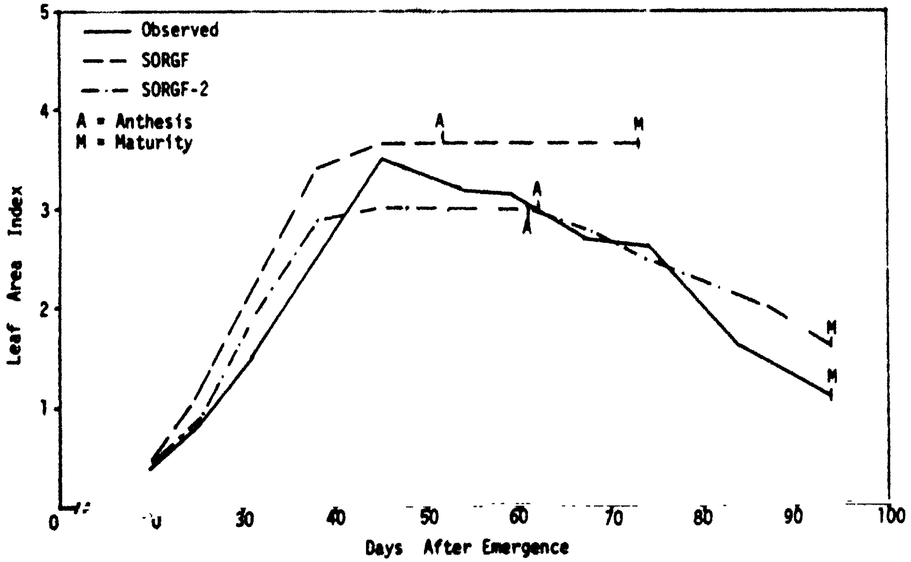


Figure 41. Observed and simulated leaf area index for sorghum variety SPV-351 grown under rainfed situation during the 1980 rainy season on a deep Vertisol at ICRISAT Center.

Table 16: **Observed and simulated total dry matter (kg/ha) and grain yield (kg/ha)**

Location	**Season**	**Genotype/ Treatment**	Total dry matter			Grain yield		
			0	S_1	S_2	0	S_1	S_2
RP-4	1979 Rainy **season**	CSH-1	9490	9145	7415	3490	4133	3497
		CSH-6	10440	9631	7630	4100	4333	3599
BW3-A	1979 **Rainy** **season**	CSH-6	11730	10892	10013	4190	5148	5007
		SPV-351	11660	10916	10665	4220	5135	3839
RP4	1979-80 post-**rainy** season	CSH-8 A	7650	11958	9378	3830	6086	4220
		CSH-8 B	4700	9257	5191	2080	3807	2093
		M-351 A	8330	12212	9226	2100	6128	2734
		M-351 B	4950	10130	5108	1300	4125	1328
RP4	1980 Rainy **season**	CSH-1 A	11300	9829	8784	5540	4365	4392
		CSH-1 B*	10585	9662	8595	5110	4483	4297
		CSH-6 A	11937	10374	9403	5640	4665	4701
		CSH-6 B*	12510	9726	8842	5880	4616	4421
BW3-A	1980 Rainy season	CSH-1	10430	11019	9891	4545	5244	4945
		CSH-6	11290	10471	9768	5310	4983	4884
		SPV-351	12348	9440	11928	4260	4393	4294
RP-4	1980-81 post-rainy season	CSH-6 A	9259	5800	8730	4695	2389	4063
		CSH-6 B	5008	5454	5067	2276	2268	2027
		CSH-8 A	11149	9534	9497	6118	3772	4330
		CSH-8 B	6464	8508	4977	2495	3406	1991
		M-351 A	10234	9250	8568	3948	3988	2645
		M-351 B	6780	7678	4458	1691	3183	1159
BW3-A	1980-81 post-rainy season	CSH-6 A	11143	7746	12700	5345	4138	6350
		CSH-6 B	6590	7555	7146	2992	4026	2907
		CSH-8 A	12631	13944	13487	6136	7606	6564
		CSH-8 B	7452	12767	6365	3115	6452	2579
		M-351 A	12150	14548	14013	3801	7607	4738
		M-351 B	6767	12564	6573	2543	6065	1750

0 = Observed
S_1 = SORGF
S_2 = SORGF-2
A = Adequate moisture supply
B = Limited moisture supply
* = Rainfed

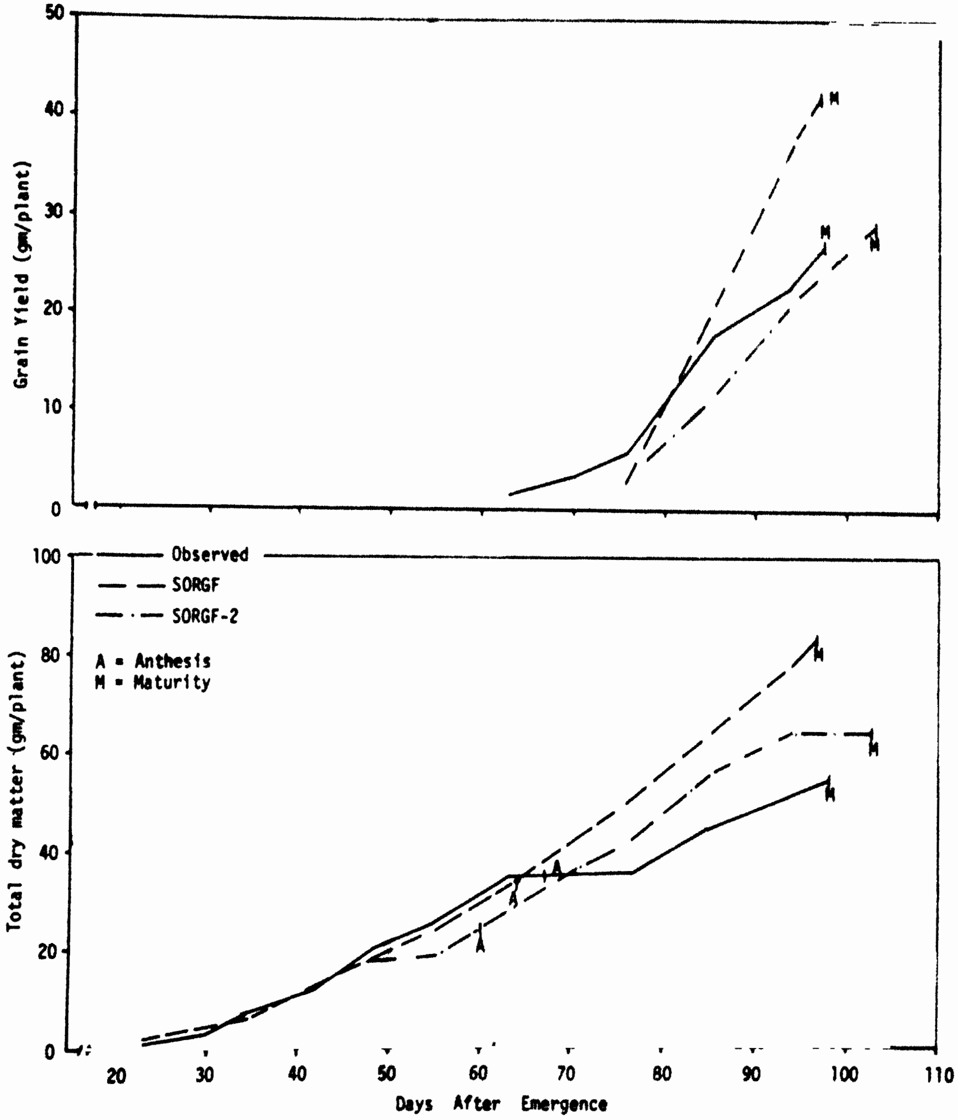


Figure 42. Observed and simulated total dry matter and grain yield for sorghum hybrid CSH-8 grown under adequate water supply during the 1979-80 postrainy season on an Alfisol at ICRISAT Center.

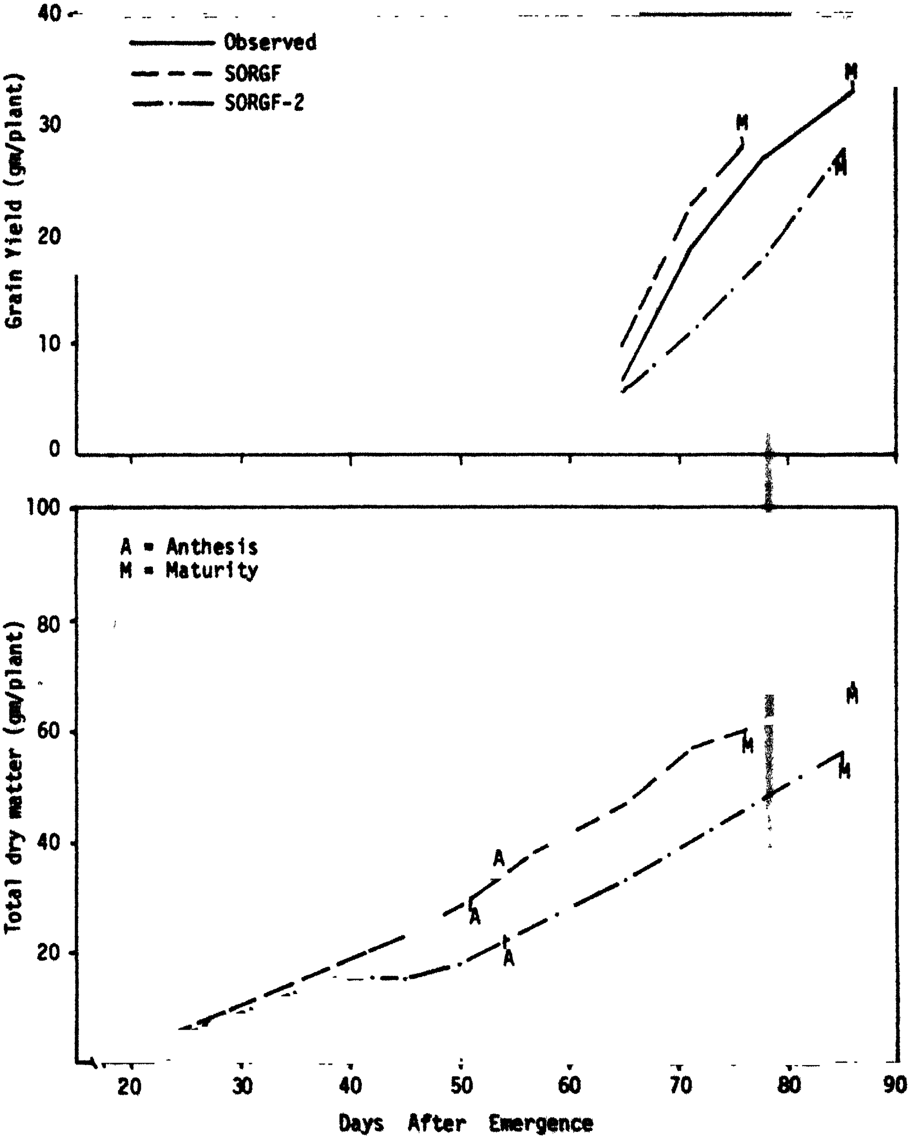


Figure 43. Observed and simulated total dry matter and grain yield for sorghum hybrid CSH-6 grown under rainfed situation (Trt.B) during the 1980 rainy season on an Alfisol at ICRISAT Center.

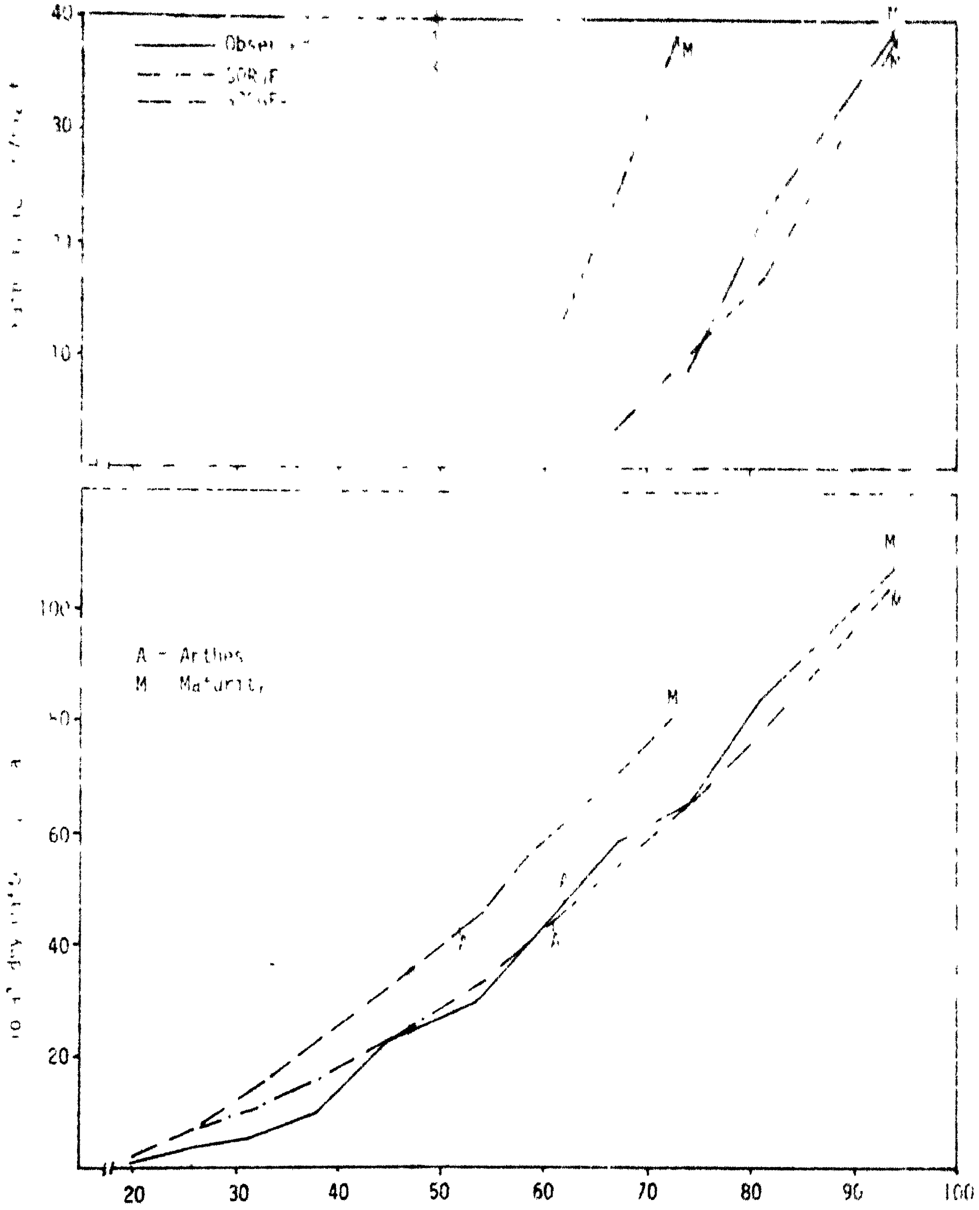


Figure 44. Observed and simulated total dry matter and grain yield for sorghum variety SPV-351 grown under rainfed situation on a deep Vertisol at ICRISAT Center.

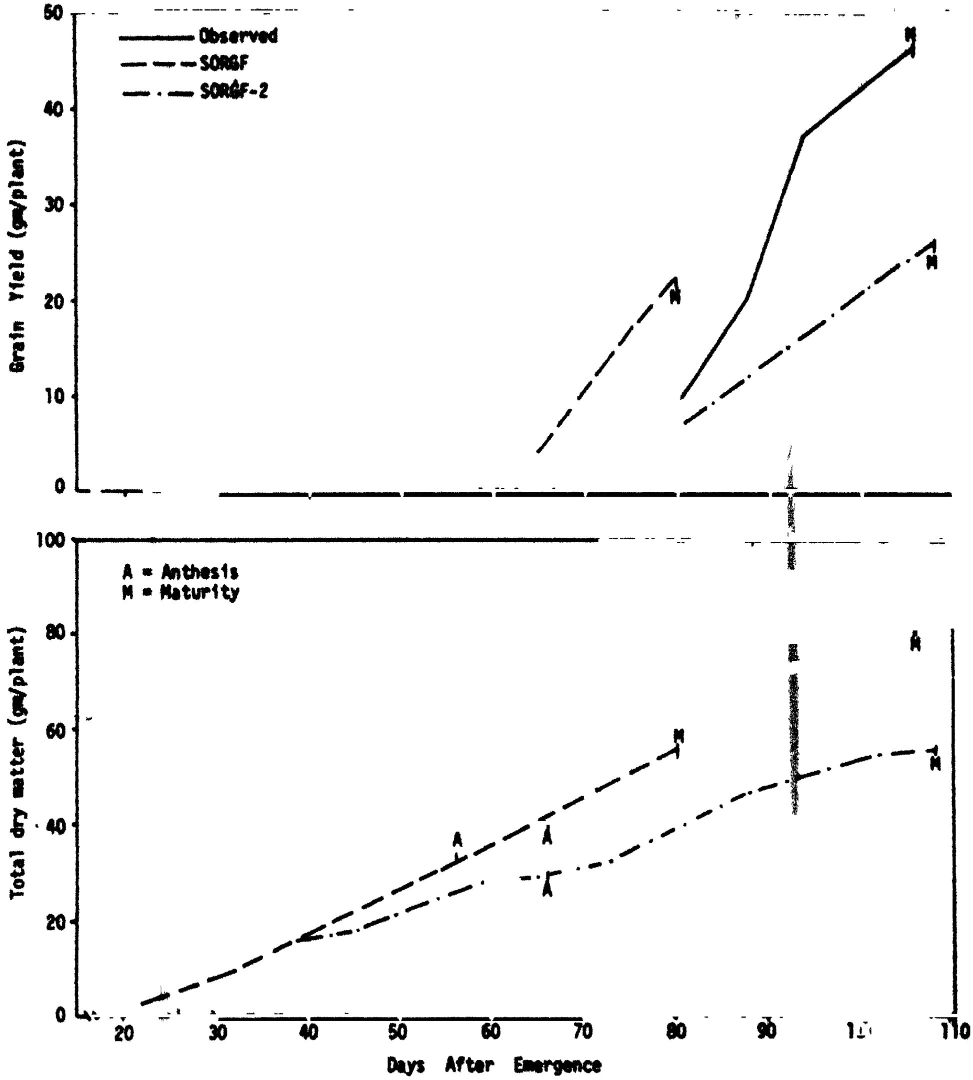


Figure 45. Observed and simulated total dry matter and grain yield for sorghum hybrid CSH-8 grown under adequate water supply (Trt.A) during the 1980-81 postrainy season on an Alfisol at ICRISAT Center.

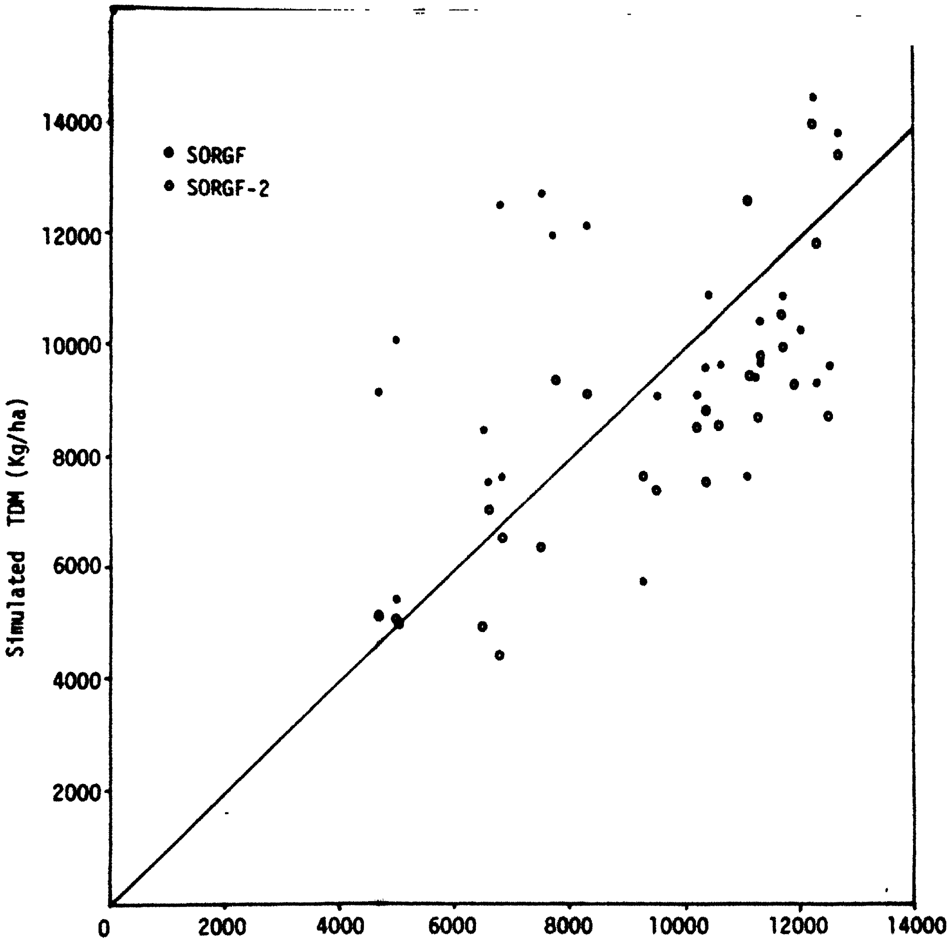


Figure 46. Correspondence between observed and simulated total dry matter (data pooled over all experiments).

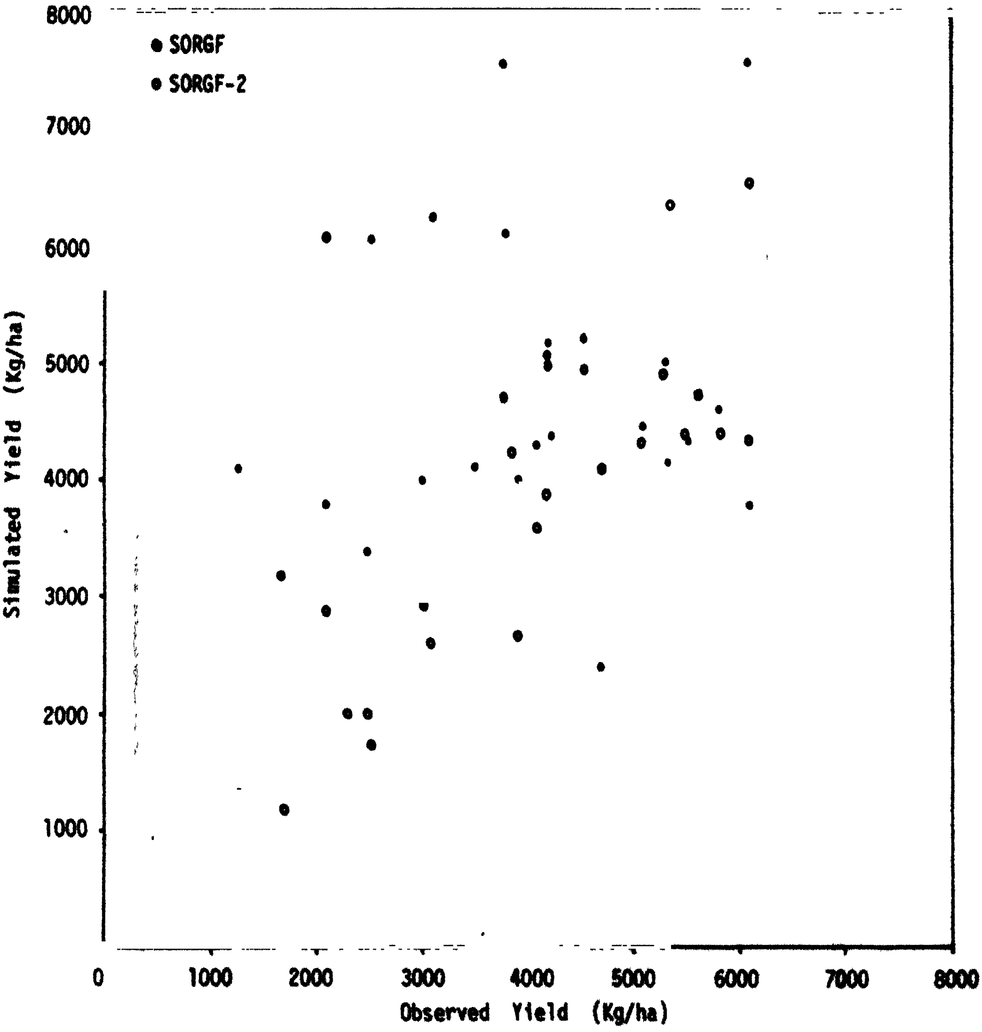


Figure 47. Correspondence between observed and simulated grain yield (data pooled over all experiments).

e) Statistical Analysis of Simulation Results

Selected crop data pooled over 27 data sets were used to compare the performance of SORGF and SORGF-2 models (table 17). The observed TDM (kg/ha) ranged from 4950 for the genotype M-35-1 grown under moisture stress to 12510 for CSH-6 grown in rainy season. Grain yields (kg/ha) ranged from 1300 for M-35-1 under moisture stress to 6136 for CSH-8 under adequate moisture supply treatment in the postrainy season. Simulation results show that SORGF model overestimated particularly the grain yields at both the highest and lowest ends. SORGF-2 improved the simulation.

Table 17. Statistical analysis of simulation results (n = 27)

(a) Highest, mean and lowest response of observed and simulated data

Crop data	Observed			SORGF			SORGF-2		
	Highest	Mean	Lowest	Highest	Mean	Lowest	Highest	Mean	Lowest
Total drymatter (kg/ha)	12510	9444	4950	14548	10000	5454	14013	8645	4458
Grain yield (kg/ha)	6136	3954	1300	7607	4687	3183	6564	3680	1159
Physiological maturity (DAE)	115	97	81	106	85	76	116	98	83
Maximum LAI	3.88	2.89	1.73	4.98	3.68	2.28	4.48	3.2	2.14
Final LAI	2.77	1.24	0.27	4.97	3.65	2.28	2.01	1.12	0.13

(b) Correlation coefficient

	SORGF	SORGF-2
Total drymatter	0.32	0.83
Grain yield	0.17	0.87

(c) Root mean square error (RMSE)

	SORGF	SORGF-2
Total drymatter (kg/ha)	2779	1619
Grain yield (kg/ha)	1886	766
Physiological maturity (DAE)	13	3

It can be noted that the data represent genotypes with a range of maturity duration from 81-115 DAE. SORGF underestimated maturity duration while SORGF-2 estimated closely for the entire range of duration. No major change has yet been made in computing maximum LAI which is evident from the overestimation of the data by both models. The effect of moisture stress factors on leaf expansion and senscence should be further examined and incorporated in the model in computing the daily LAI. The observed final LAI data range between 0.27 to 2.77 while SORGF model overestimated final LAI, SORGF-2 improved the estimates.

Correlation coefficient between observed and simulated results (table 17) show that revisions in the model resulted in improved estimates of TDM and grain yield. SORGF could explain only 4 percent variation associated with grain yields in the present data set while SORGF-2 could explain 76 percent variation.

Error analysis of the simulation results indicates that RMSE for TDM, grain yields and PM was reduced due to revisions in the model (table 17).

Conclusions and Future Plans of Work

Revisions in the model did show some improvement in simulation results. Systematic examination of the data is underway not only to improve the predictive nature of the model but also to investigate reasons why in certain individual cases the model performance was poor. At the end of the 1981 rainy season there will be multilocation data sets from five seasons representing various genotypes grown under different treatments. Critical examination of half of the data sets will be undertaken to revise the model and the other half would be used to validate the revised model.

Collaborative work with the soil fertility group is underway to develop a nutrient subroutine for inclusion in the model. It is difficult to develop pest and disease subroutines. However, in the 1981 rainy season an experiment is taken up in the unsprayed plots at ICRISAT Center with five genotypes (CSH-1, CSH-5, CSH-6, CSH-8 and SPV-351) with 40 kg N/ha to evaluate the model performance under medium fertility and no pest and disease control conditions.

Experiments on three pearl millet genotypes (BJ-104, WC-C75 and ICMS-7703) have been taken up from 1981 rainy season to collect standard data sets to develop a dynamic simulation model for pearl millet.

CHAPTER V

Looking Ahead

As referred to by the Technical Advisory Committee (TAC) while reviewing the Farming Systems Research (FSR) at International Centers (TAC, 1978), base data analysis is inimical to the success of any program using the FSR approach. Climate evaluation which includes presentation of general climatic characteristics of different regions and assessment of crop potential is an important first step in planning for the resource-based technologies for improved crop-production in the SAT. Our reports of rainfall probabilities (Virmani et al. 1978), rainfall climatology (Sivakumar et al. 1980, Virmani et al. 1980) and estimation of PE (Reddy and Virmani, 1980) are directed at providing the first approximation answers to the question of climate evaluation.

Coupled with the aspect of evaluation is the question concerning meaningful classification of climates. We found that Troll's classification of SAT (Troll, 1965) was based on limited data and hence the boundaries given by Troll were inaccurate. We have undertaken the task of establishing climatic data banks and prepared revised maps of SAT based on the enlarged data base. We will continue our efforts to provide meaningful climate evaluation for outlining cropping potentials for different regions.

Microclimatic studies and crop weather modeling efforts give us the scope to assess the crop potential at the field scale. These studies provide an understanding of the climatic control of the plant growth and development. This understanding enables us to establish the laws of growth and production in the light of meteorological factors as they fluctuate in the field during the vegetative cycle. It is logical that the end result should be a model that simulates effectively the crop growth and development under several climatic constraints. We have made considerable progress in studying the crop response to the ambient environment by using collaborative approaches in studying the soil-plant-atmosphere continuum. As described in Chapter IV our ability to predict the sorghum growth and development is now fairly satisfactory, but we envisage further improvement and extension of our ideas to other crops.

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