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Collaborative Multilocation Sorghum Modeling Experiment

(COOPERATORS' MEETING - 12-13 NOVEMBER 1982)

REPORT FOR 1978-82

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

NOVEMBER 1982

NOTE TO THE READER

This is an informal report of the Collaborative Multilocation Sorghum Modeling Experiment for 1979-1982. The report is designed to stimulate thinking and comments from professional colleagues and is not a formal publication bearing the endorsement of the Institute.

CREDIT LINE

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PROGRAM OF THE COOPERATORS' MEETING ON MULTILOCATION SORGHUM MODELING RESEARCH, 12-13 NOVEMBER 1982

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venue: training class room # 2

THURSDAY 11 NOVEMBER

Participants arrive

FRIDAY 12 NOVEMBER

Session I: Overall validation of SORGF Model
Chairman : RW Gibbons
Rapporteur : MVK Sivakumar

0830 *Welcome address: RW Gibbons*

0840 *Need and relevance of crop modeling research in the context of farming systems research - SM Virmani*

0900 *Presentation of the report on collaborative multilocation sorghum modeling experiment - validation of the SORGF model in the SAT - AKS Huda*

1000 *BREAK*

1030 *Discussion*

Session II: Discussion on specific SORGF subroutines
Chairman : GF Arkin
Rapporteur : N Seetharama

1100 *Evaluation of subroutines on light interception, dry matter accumulation and soil water - MVK Sivakumar*

1145 *Discussion*

1300 *LUNCH*

1400 *Effects of moisture stress on phenology, leaf area, dry matter accumulation and partitioning - AKS Huda*

1430 *Discussion*

Session III: Improvements in SORGF - Review by cooperators, Demonstration on the use of SORGF on ICRISAT computers.
Chairman : SM Virmani
Rapporteur : Sardar Singh/JG Sekaran

1600 The participating cooperating scientists from Temple, Coimbatore, Delhi, Hissar, Kenya (KARI), Khon Kaen, Ludhiana, Parbhani, Patancheru (ICRISAT), Pune, Rahuri and Sholapur present the progress made in sorghum modeling research. If time permits, the use of SORGF model will be demonstrated to the cooperating scientists in 302 seminar room.

1700 Adjournment

SATURDAY 13 NOVEMBER

0830 Session III continued

Session IV : Planning future strategies
Chairman : JN Peacock
Rapporteur : G Alagarswamy

0930 Environmental and genotypic effects on sorghum yield components - N Seetharama

1000 Discussion

1030 BREAK

1045 Discussion on proposal of pearl millet modeling research - AKS Huda

1145 Identifying gaps in knowledge and planning for future research - SM Virmani/MVK Sivakumar

1245 Vote of thanks - AKS Huda

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REPORT OF THE COLLABORATIVE MULTILOCATION SORGHUM MODELING EXPERIMENT
(1978-1982)

Prepared on behalf of the Cooperators

by

A.K.S. Huda, M.V.K. Sivakumar, S.M. Virmani and J.G. Sekaran

cooperators

INDIA

Tamil Nadu Agricultural University, Coimbatore - S. Sankaran, R. Kulandaivelu, S. Subramanian.

Indian Agricultural Research Institute, New Delhi - S.K. Sinha, K.K. Nathan.

Haryana Agricultural University, Hissar - D.P. Singh, Phool Singh.

Punjab Agricultural University, Ludhiana - R.S. Narang, V.V.N. Murty, A.K. Tiwari.

Marathwada Agricultural University, Parbhani - G. Ramakrishna Rao, V.S. Pawar, D.G. Phulari.

International Crops Research Institute for the Semi-Arid Tropics, Patancheru - S.M. Virmani, A.K.S. Huda, M.V.K. Sivakumar, Sardar Singh, N. Seetharama, R.K. Maiti, J.M. Peacock, J.W. Estes, B. Gilliver, D.S. Murthy.

India Meteorological Department, Pune - R.P. Sarker, B.C. Biswas.

Mahatma Phule Krishi Vidyapeeth, Rahuri - R.P. Sandge, M.C. Varshneya, D.R. Bapat.

Mahatma Phule Krishi Vidyapeeth, Sholapur - S.Y. Daftardar, S.S. Salunke, N.D. Patil.

USA

Texas A&M University, Blackland Research Center, Temple - G.F. Arkin, W.A. Dugas, B. Jackson.

THAILAND

Khon Kaen University, Khon Kaen - V. Limpinuntana.

VALIDATION OF SORGHUM SIMULATION MODEL (SORGF) IN THE SEMI-ARID TROPICS

A previously developed grain sorghum simulation model (SORGF) reported by Arkin et al (1976) was selected for testing and validation to determine its potential for assessing sorghum production in the semi-arid tropics (SAT). The objective was to find whether SORGF could be adopted in the SAT to determine crop management strategies e.g., optimum date of planting, plant population and suitability of a given genotype for a given soil water and climatic conditions.

1. Description of SORGF

The SORGF model requires daily radiation, maximum and minimum temperature, and precipitation as input weather data. The initial plant and soil information needed includes date of sowing, depth of sowing, row spacing, plant density, potential number of leaves and their maximum size, maximum water holding capacity of the soil and available soil water at sowing. Different phenological stages including emergence, panicle initiation, anthesis and physiological maturity are simulated. The potential dry matter is computed from radiation intercepted and the net dry matter is estimated by accounting for temperature and moisture stress. The final grain yield per unit area is calculated by multiplying plant density with the grain weight per plant at maturity. A detailed description of SORGF model was given by Maas and Arkin (1978) and the utility was discussed by Huda and Virmani (1980).

2. Collaborative multilocation sorghum modeling experiment

To develop a data base to test and improve SORGF for its application in the semi-arid tropics (SAT), a collaborative multilocation sorghum modeling experiment was initiated in the 1979 rainy season by ICRISAT in cooperation with several research centers in India and abroad (Table 1). To ensure the uniformity in data collection across the locations, a manual describing the minimum data to be collected and the method of data collection was prepared and circulated to all cooperators. At a cooperators' meeting held from 2-4 April 1980 at the ICRISAT Center, initial evaluation of the model using the available data was discussed (Huda et al 1980).

3. Recommendation of the cooperators' meeting in 1980

- Several subroutines in SORGF which needed modification for adoption in the SAT regions were identified. These subroutines deal with phenology, light interception, dry matter accumulation and partitioning, soil water and leaf development.

- The collaborative experiments should be continued and efforts should be made to include additional locations for covering as much climatic variability as feasible.

- A treatment to ensure no moisture stress throughout the growing season of the crop should be included to obtain potential productivity.

Table 1. Summary of collaborative multilocation sorghum modeling field studies

Location	Year	Season	Genotypes	Treatment	Latitude (°N)
ICRISAT	1979	Rainy	CSH-1, CSH-6 SPV-351	Rainfed*	17° 27'
	1979	Postrainy	CSH-8, M-35-1	A and B**	
	1980	Rainy	CSH-1, CSH-6 SPV-351	Rainfed* and A	
	1980	Postrainy	CSH-6, CSH-8 M-35-1	A and B**	
	1981	Rainy	CSH-1, CSH-5, CSH-6, CSH-8, M-35-1	Rainfed* Adequate Management	
	1981	Rainy	-do-	Rainfed**, Medium fertility, and pesticide free	
	1981	Postrainy	-do-	Ratooning with* three N levels	
	1981	Postrainy	CSH-8, M-35-1	5 moisture** Treatments	
Coimbatore	1980	Postrainy	CSH-8	A	11° 00'
Delhi	1979	Rainy	CSH-1, CSH-6	Rainfed	28° 35'
	1980	Rainy	CSH-1, CSH-6	Rainfed and A	
	1981	Rainy	CSH-6	Rainfed & Irrigated	
Hissar	1979	Rainy	CSH-1 CSH-6	Rainfed	29° 10'
	1980	Rainy	CSH-6	Rainfed and A	
Khon Kaen (Thailand)	1979	Rainy	KU-300	Rainfed	16° 26'
	1980	Rainy	Hegari	Rainfed	
Ludhiana	1980	Rainy	CSH-1, CSH-6	Rainfed	30° 56'
	1981	Rainy	CSH-1, CSH-6	Rainfed	

Contd..../-

Table 1 contd..../-

Location	Year	Season	Genotypes	Treatment	Latitude (°N)
Parbhani	1979	Rainy	CSH-1, CSH-6	Rainfed	19° 08'
		Postrainy	CSH-8, M-35-1	Residual Moisture	
	1980	Rainy	CSH-1, CSH-6	Rainfed	
		Postrainy	CSH-8	A	
	1981	Rainy	CSH-1, CSH-6	Rainfed	
Pune	1979	Rainy	CSH-1, CSH-6	Rainfed	18° 32
		Postrainy	CSH-8, M-35-1	A	
	1980	Rainy	CSH-1, CSH-6	Rainfed	
		Postrainy	CSH-8	A	
Rahuri	1979	Rainy	CSH-1, CSH-6	Rainfed	19° 24'
		Postrainy	CSH-6, CSH-8 M-35-1	Residual moisture	
	1980	Rainy	CSH-1, CSH-6	Rainfed	
		Postrainy	CSH-8, M-35-1	A	
	1981	Postrainy	CSH-8, M-35-1	Residual moisture & Irrigated	
Sholapur	1979	Postrainy	CSH-8, M-35-1	Residual moisture	17° 40'

A = Adequately watered; B = Water stressed;

* = Both Vertisols and Alfisols; ** = Only Alfisols; + = Only Vertisols

- The experiments conducted under adequate plant protection and soil fertility management conditions should be continued over the next year. Literature search should be made to identify subroutines which can be adapted for quantifying the response to applied nitrogen.

- Written documentation on the model should be made available to each center so as to enhance the familiarity of the cooperators with the existing model.

- The cooperators agreed that every effort will be made to collect crop and soil data at five growth stages i.e. at panicle initiation, flag leaf, anthesis, soft dough, and physiological maturity.

- A note explaining the methods of data collection and identification of different growth stages should be made available to all cooperators. At centers where leaf area meters are not available constants for estimating leaf area from leaf width and length measurements for selected cultivars should be made available.

- A meeting of the cooperators should be held to discuss the improvements made in SORGF based on data collected from this cooperative experiment.

4. Progress made

a. Field studies

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 during 1979-1981 (Table 1). Sorghum is not grown during the postrainy season at Delhi, Hissar, and Ludhiana because of cold temperatures. Additional moisture treatments of adequate water and water stress at certain critical growth stages were included in the postrainy season experiments. Data on crop phenology, leaf growth and development, dry matter production and partitioning, soil water, weather and management factors were collected. Detailed progress reports of these experiments were prepared (Huda et al 1980, 1982a, 1982b).

b. Cooperative consultancy

A cooperative consultancy program was established between Texas A&M University where SORGF was initially developed and ICRISAT to exchange data and revise some of the subroutines. GF Arkin from Temple, Texas, visited ICRISAT Center in 1979 and 1980 to review the sorghum modeling research. Sivakumar (1981) reviewed subroutines on light interception, dry matter accumulation and soil water and suggested revisions. Subroutines on phenology, dry matter partitioning and leaf development were reviewed by Huda (1982) and improvement made in SORGF with recent revisions was assessed.

c. Subroutines revised

(i) Phenology

Accurate simulation of phenological development is important because the stage of development determines the daily dry matter partitioning to various plant parts. The phenological simulation was based on three stages of sorghum development as defined by Eastin (1971). The stages are:

Growth stage 1 (GS1) - The time from emergence to panicle initiation.

Growth stage 2 (GS2) - The time from panicle initiation to anthesis.

Growth stage 3 (GS3) - The time from anthesis to physiological maturity.

The time from emergence to panicle initiation is computed as the sum of heat units (base temperature = 7.0°C and the upper limit of mean temperature = 30.0°C) and is a function of the maximum number of leaves. The 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 panicle initiation to flag leaf appearance. The time from emergence to physiological maturity is calculated as 1.4 times the computed number of days from emergence to anthesis.

In SORGF, the grain filling period is dependent upon the time until anthesis. The period from anthesis to physiological maturity is underestimated in SORGF. The period from emergence to panicle initiation is overestimated by SORGF particularly in lower latitude (e.g. ICRISAT). This overestimation could have been a result of the narrow data bases used in the development of the subroutines e.g., only data from U.S., where the daylengths are relatively longer.

Crop phenological data for almost all the growth stages were available in 50 data sets. Of these, ten were randomly selected for independent tests. The remaining 40 data sets were used to study the phenological development in order to develop new algorithms.

Calendar days

The GS1 duration is highly variable (Table 2). The mean duration is 23 days. The minimum and maximum value for GS1 was obtained for the same genotype (CSH-6) grown during rainy season at different locations. The minimum duration was observed at ICRISAT and Parbhani (low latitude) while the maximum duration was observed at Delhi and Hissar (high latitudes). To account for this variability, the data were further analyzed to establish the effect of daylength and temperature on phenological development.

Growing degree days

The approach of Stapper and Arkin (1980) was used to calculate GDD for sorghum with various threshold temperatures. GDD = (CMIN + CMAX)/2 - BASET. The cutoff temperature was varied from 26, 30, 34, and 38°C. Base temperatures of 7, 9, 11, and 13°C were also used to evaluate GDD. A cutoff temperature of 38°C with a base of 7°C was used in further analyses. Mean GDD and standard deviation and coefficient of variation for each growth stage was given in table 3. To take into account the higher variability in GS1 and GS2, the effect of daylength was also analyzed.

Daylength

The daylength at emergence, panicle initiation, anthesis and physiological maturity was computed. Daylength at emergence and panicle initiation was plotted against the GDD values for GS1 for hybrids CSH-1 and CSH-6 (Figs. 1 and 2). A similar relationship was proposed by Major (1980) for short day plants and by Stapper and Arkin (1980) for corn. Daylength at emergence at panicle initiation are highly correlated ($r = 0.99$) and therefore daylength at emergence can be used in place of daylength at panicle initiation.

For the present study, threshold value of daylength was 13.6 hour at emergence for two hybrids (CSH-1 and CSH-6). Data for other genotypes were not available above this threshold daylength.

To study the daylength sensitivity among genotypes, four groups were identified. They are:

Group 1 (CSH-1, CSH-6 grown above 13.6 hour daylength)

Group 2 (CSH-1, CSH-6, CSH-8 grown below 13.6 hour daylength)

Group 3 (SPV-351 and Hegari)

Group 4 (M-35-1)

Duncan's multiple range test for three growth stages were computed (Table 4). There is a significant difference between group 1 and 2 for all three growth stages. Differences in GS1 can be accounted for by daylength effect as shown in Figs. 1 and 2 and a similar effect was found for GS2.

The algorithm for describing daylength (DAYEM) and GDD effects on GS1 derived from Figure 1 is:

GDD = 370 + 400 * (DAYEM - 13.6) if DAYEM > 13.6 hour
GDD = 370 if DAYEM < 13.6 hour

The algorithm for describing DAYEM and GDD effects on derived similar to that of GS1 is:

GDD = 650 + 120 * (DAYEM - 13.6) if DAYEM > 13.6 hour
GDD = 650 if DAYEM < 13.6 hour

Differences in GS3 for groups 1 and 2 can be accounted for as a rature effect as shown by Schaffer (1980). This effect is shown by plotting the inverse of duration $(\text{day})^{-1}$ of GS3 against the mean temperature ($\bar{T}$) of GS3 for hybrids CSH-1 and CSH-6 (Fig. 3). The duration decreases with an increase in $\bar{T}$ to 27°C and increases above 27°C. From figure 3 a base temperature of 7°C can be derived for GDD computation in GS3. A base temperature of 7°C was previously selected for all growth stages. Thus, for GS3 the following algorithms are used to account for temperature effects in GDD computation for GS3.

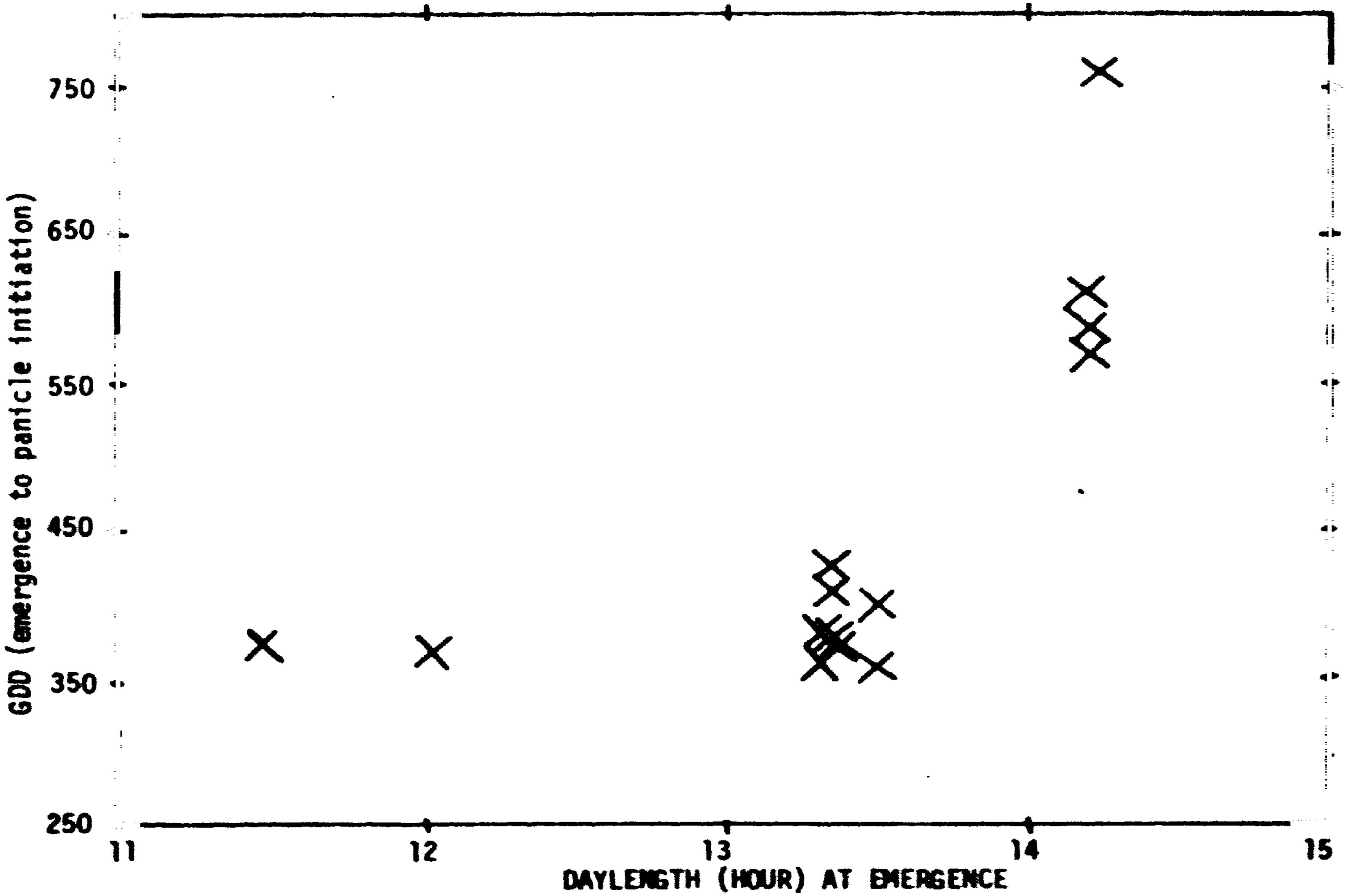

Fig. 1. Relationship between growing degree days for emergence to panicle initiation and daylength at emergence for sorghum hybrids CSH-1 and CSH-6.

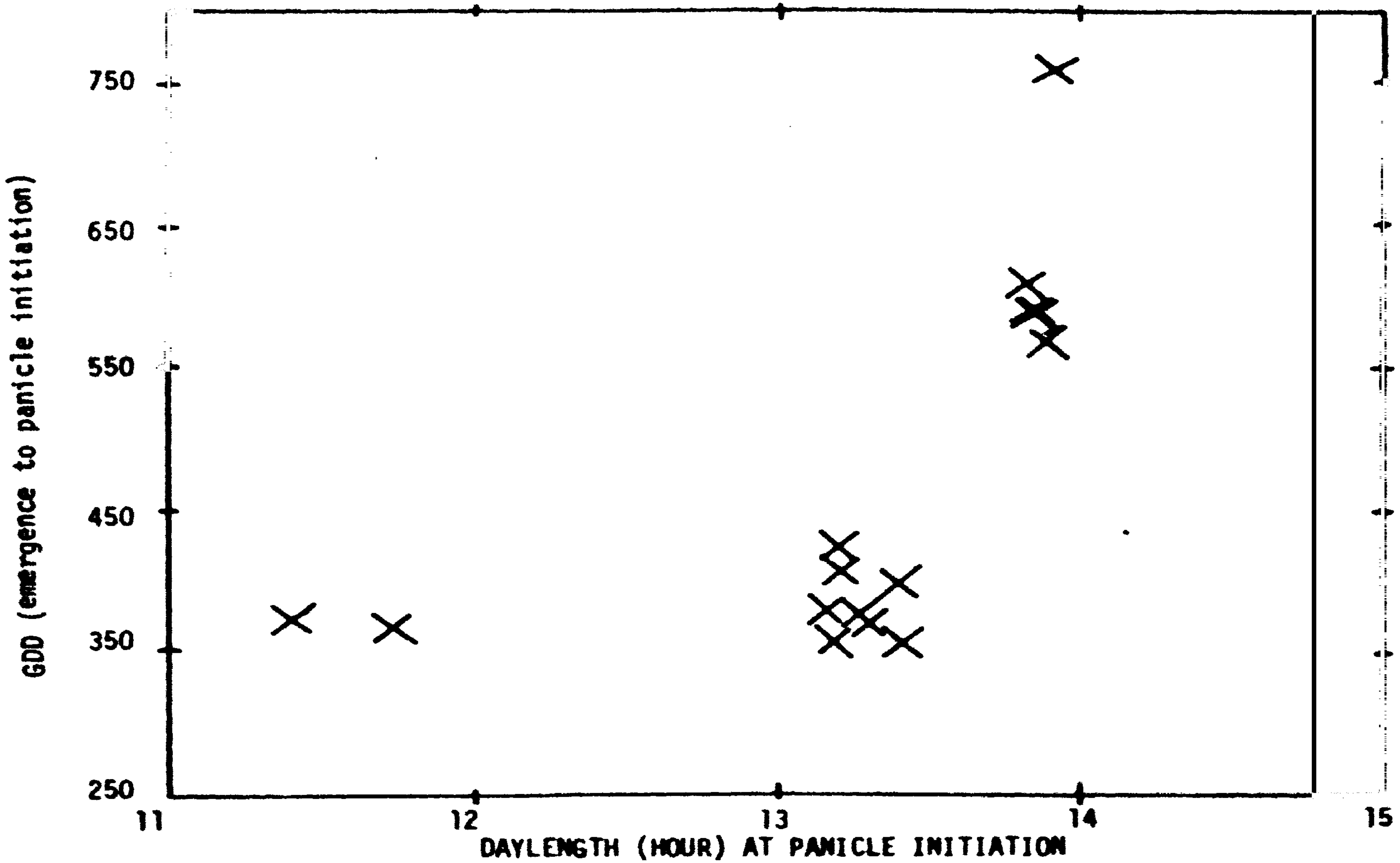

Fig. 2. Relationship between growing degree days for emergence to panicle initiation (PI) and daylength at PI for sorghum hybrids CSH-1 and CSH-6.

Table 2. Days required between different sorghum growth stages. (Data pooled over locations, seasons, and genotypes.)

Stage		Mean	Standard Deviation	Mini Value	Maxi Value	C.V.
GS 1	29	23	4	17	31	19
GS 2	29	37	6	30	50	10
GS 3	30	35	6	22	53	18
GS 1 + GS 2	39	60	7	50	80	11
GS 1 + GS 2 + GS 3	40	96	10	80	115	15

Table 3. Growing degree days between sorghum growth stages (Cutoff temperature = 38°C and base temperature = 7.0°C, n = 40)

Growth stage	Mean GDD	Standard Deviation	C.V.
GS 1	440	120	27
GS 2	670	60	11
GS 3	650	110	20

Table 4. Mean growing degree days for different growth stages for four groups of sorghum. (n = 40)

Group	Growth stage GS 1	Growth state GS 2	Growth stage GS 3
1	610 a	720 a	800 a
2	370 b	650 b	560 c
3	560 a	655 b	555 c
4	365 b	680 b	670 b

Means with the same letter are not significantly different.

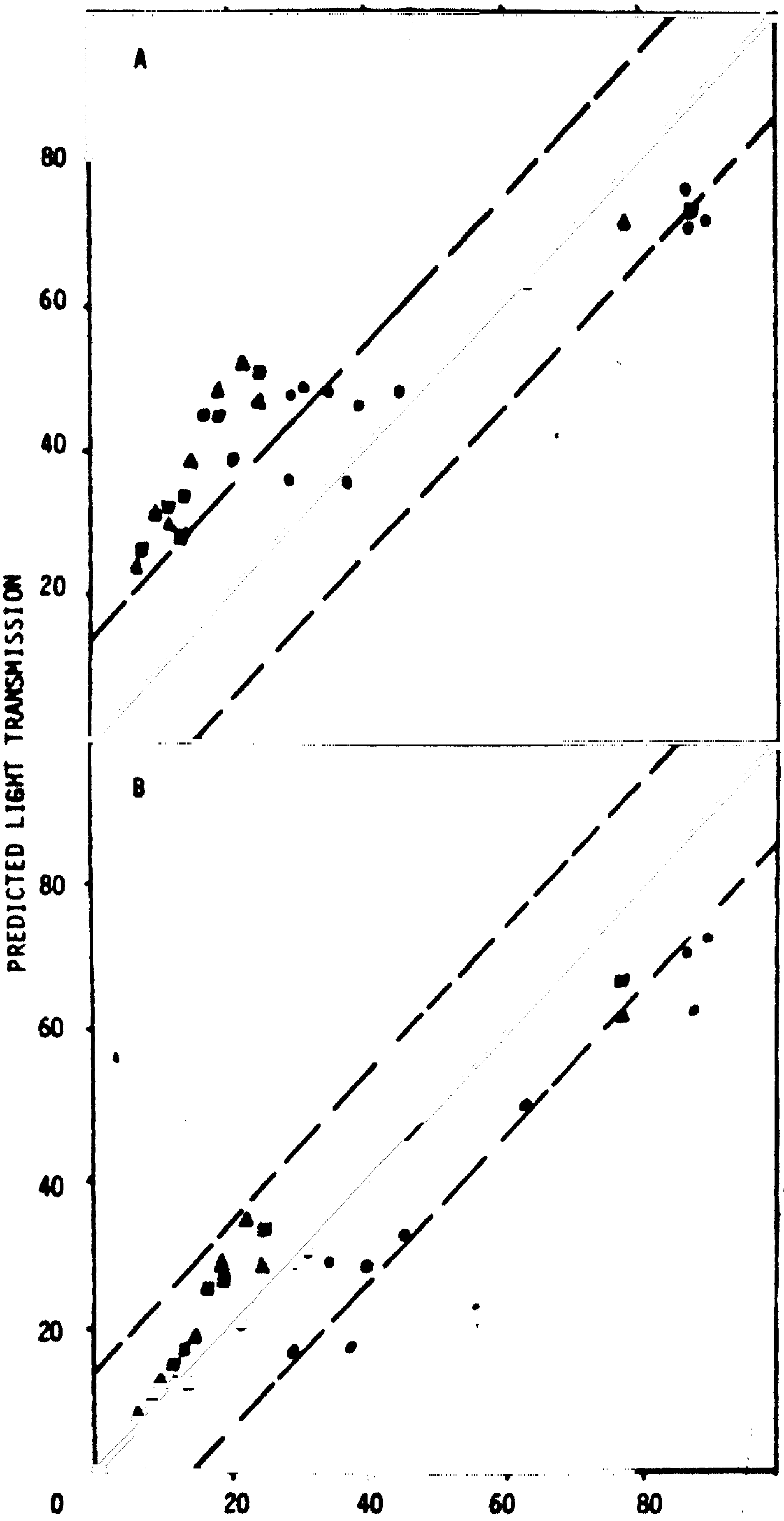

Fig. 3. Relationship between measured and predicted light transmission under 45 cm sorghum rows according to (A) SORGF and (B) Revised equations (symbols represent data from different growing seasons).

$GDD = \bar{T} - \underline{7}$, when $\bar{T}$ $27^{\circ}\underline{C}$
$GDD = (54-\bar{T}) - 7$, when $\underline{\bar{T}} = 27^{\circ}C$

These algorithms were used to compute GDD for the 40 field studies. The mean GDD computed using these algorithms are presented in Table 5. No significant difference in GDD among groups was found for all growth stages except in GS1 for rainy season variety (SPV-351 and Hegari). The weighted mean GDD for GS3 is 620.

These algorithms were used to compute GDD for all three growth stages for the 40 field studies from which data to derive these relations were collected. The root mean square error (RMSE) for the three growth stages were compared with SORGF and the revised algorithms (Table 6). The RMSE was considerably reduced for all three stages using the revised algorithms.

These revised algorithms were tested against 10 independent field study data sets. RMSE for SORGF and the revised algorithms are given in Table 7. The RMSE for all the three stages were considerably reduced using the revised algorithms.

(ii) Light interception

The light interception portion of the model simulates the relative quantum flux intercepted by a single plant. Intercepted Photosynthetically Active Radiation (PAR) is calculated on an hourly basis following a Beer's law relationship using solar radiation and light transmission values. Hourly solar radiation is computed from the input solar radiation and by accounting for the number of hours of sunlight for any day which is calculated as a sine function of the local solar time and daylength. Validations with data collected at ICRISAT Center showed that model computation of solar declination and daylength are accurate resulting in sufficiently accurate estimation of hourly solar radiation. The quantum flux density (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 using measured data on PAR and RS for extended periods of time indicated that the constant relating PAR to solar radiation (RS) should be altered. In the revised version, PAR is thus calculated as 0.09 times RS.

Light transmission in SORGF is calculated from the relationship of extinction coefficient and maximum light transmission for a given row spacing.

In order to validate the light transmission model, data sets from 13 different experiments conducted during 1977-1980 at the ICRISAT Research Center have been used. Canopy light transmission was measured using a frame that encloses four quantum sensors for the measurement of PAR in a 3 m^2 grid.

An examination of the computed and measured light transmission for different row spacings showed that the model was overestimating light transmission, especially at low levels of canopy light transmission and for row spacings greater than 137 cm, the SORGF model does not work because computed light transmission exceeds 100 percent.

Table 5. Mean growing degree days after daylength correction (GS1 and GS2) and temperature correction (GS3) for different growth stages.

Group	Growth stage GS 1	Growth stage GS 2	Growth stage GS 3
1	390 a	655 a	628 a
2	370 a	650 a	640 a
3	560 b	655 a	615 a
4	365 a	680 a	609 a

Means with the same letter are not significantly different.

Table 6. Root mean square error (days) for different growth stages for 40 field studies.

Stage	SORGF	Revision
GS 1	7	3
GS 1 + GS 2	7	5
GS 1 + GS 2 + GS 3	19	4

Table 7. Root mean square error (days) for different growth stages for 10 independent field study data sets.

Stages	SORGF	Revision
GS 1	7	4
GS 1 + GS 2	7	6
GS 1 + GS 2 + GS 3	18	3

In order to improve model estimation of light transmission, it was necessary to recompute extinction coefficient (X2) and maximum percent light transmission (X1) for each of the data sets used. The original equation relating row spacing to X2 in SORGF and the revised equation are as follows:

SORGF = X2 = 0.0026 * R - 0.322
REVISED = X2 = 0.0065 * R - 0.469

Similarly the relationship between row spacing and X1 was recomputed and these are as follows:

SORGF = X1 = 0.5946 * R + 67.9915
REVISED = X1 = 0.4711 * R + 67.2642

At leaf area index values less than the parameter X3 (generated from computed values of X1 and X2) the model uses the function given below to compute light transmission.

LITRAN = 100 * EXP (-0.7675 * DLAI (1))

Values of X3 for different row spacings are given in Table 8. Threshold values of leaf area index at which light transmission is computed range from 0.60 for 30 cm row spacings to -0.05 for the 150-cm rows. Even in the narrow rows, a LAI of this magnitude is reached fairly early in the growing season and since the time for emergence to a LAI of this size is generally less than 10 days, the magnitude of error involved in computing light transmission using only X1 and X2 will not be large. One reason for using the parameter X3 appears to be the low values of extinction coefficient (X2) generated by the SORGF model. Use of such extinction coefficients at a low leaf area index would give a higher light transmission than is observed in the field. Since the revised equation relating extinction coefficient to row spacing performs satisfactorily in this respect, there is no need for computing and using X3.

Considering the above, the revised algorithm for computation of light transmission is as follows:

X1 = 0.1855 * ROSPZ + 67.2642
X2 = 0.0026 * ROSPZ - 0.6469
LITRAN = X1 * EXP (X2 * DLAI (1))

Comparisons of predicted and measured light transmission for 45 cm and 75 cm rows using the data sets collected at ICRISAT are shown in Figures 3 and 4 respectively. Data points shown in 3(a) deviate from the 1:1 line beyond the 15 percent limits at low levels of light transmission and use of the revised quations substantially improves predictability of the light transmission. Data for the 75-cm row spacing show a similar trend (Fig. 4).

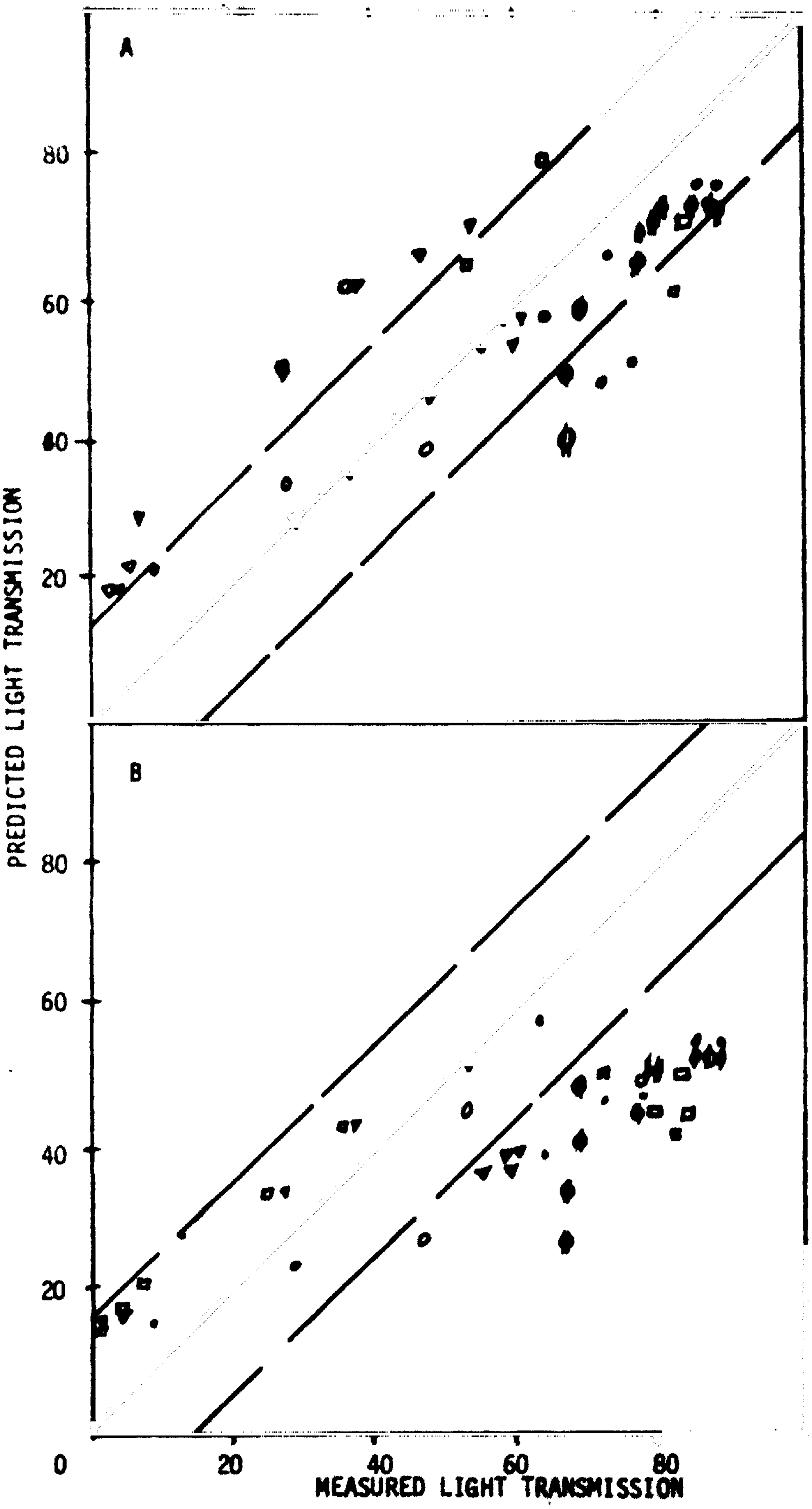

Fig. 4. Relationship between measured and predicted light transmission under 75 cm sorghum rows according to (A) SORGF and (B) Revised equations (symbols represent data from different growing seasons)

(iii) Dry matter accumulation

In SORGF daily potential photosynthesis (DAYPOPO) is calculated in the PHOTO subroutine from intercepted PAR. In the SYNTH subroutine, the potential net photosynthesis (TOPOTO) is calculated as a function of DAYPOPO and the coefficients TEMPCO and WATSCO as described by Arkin et al (1976). Net daily photosynthesis (TOPOTO) is then redefined by accounting for respiration. Daily increase in plant dry weight (DRIWT) is then determined in part from TOPTO and soil surface area allocated for each plant.

Biscoe and Gallagher (1977), Williams et al (1968) and Monteith (1977) showed that dry matter production early in the season is related to the amount of radiation intercepted by the crop. Gallagher and Biscoe (1978) then showed that for wheat and barley grown at Sutton Bonington and Rothamstead, about 3 gm of dry matter were produced for each MJ of PAR absorbed until ear emergence. For the whole crop about 2.2 gm of dry matter were produced per MJ absorbed.

Dry matter/intercepted PAR relationships were also examined at ICRISAT during 1978 and 1979 growing seasons for sorghum (Agroclimatology, 1979, 1980). For several crops of sorghum, dry matter produced per MJ absorbed PAR varied from 1.20 to 2.82, the lowest value corresponding to a nonirrigated crop during the postrainy season. The highest value was recorded for a sorghum crop which was irrigated at 10-day intervals in the postrainy season. From these observations, it seems reasonable to define a factor ALPHA which is gm of dry matter produced per MJ of PAR absorbed and assign a value of 3.0 of ALPHA. This value defines an upper limit for cases with no water or temperature stress. The TEMPCO and WATSCO functions as defined in the model are then used to calculate daily dry weight increase.

(iv) Dry matter partitioning

Partitioning of dry matter to plant parts varies according to the stage of development. Therefore, an accurate estimate of phenological development is important for simulating the partitioning process. Accurate simulations of grain yield, the component of yield generally of most interest, depends upon the ability to correctly partition dry matter to grain and other plant parts.

Leaf, culm, head + grain weights (g/plant) simulated with SORGF were compared with measured data collected from destructive weekly samples (27 field studies) throughout the growing season at the ICRISAT Center. The root mean square error (RMSE) was calculated for measured and simulated plant part weights for each field study. The highest RMSE was observed for the head + grain component within a range of 7 to 34 (g/plant). The lowest RMSE was observed for culm weight with a range of 2 to 12 (g/plant). The range in RMSE for leaf weight was 6 to 21 (g/plant). These RMSE values are indicative of the accuracy with which SORGF partitions dry matter to the plant organs.

Measured mean total dry matter (TDM) (g/plant) and percent partitioned to the plant parts at panicle initiation (PI), anthesis (AN) and physiological maturity (PM) are given in Table 9. The percent TDM partitioned to the leaf decreases from 64 to 11 percent from PI to PM and increases from 36 to 60 percent from PI to AN then decreases to 36 percent at PM for the culm. Fortyone percent of TDM was partitioned to grain at PM.

The percent of TDM partitioned to leaf was not significantly different between hybrids and varieties (Table 10). The percent of TDM partitioned to the culm was significantly higher in the varieties than in the hybrids at both anthesis and maturity. TDM (per plant) at AN and PM was also not significantly different between hybrids and varieties. The percent of TDM partitioned to grain was higher in hybrids (0.45) compared to varieties (0.32). TDM partitioning within a growth stage was not studied.

The significant difference in partitioning TDM to the grain component was due to moisture stress (Table 11) for the hybrids. For adequately watered treatments 50 percent of TDM was partitioned to grain while 43 percent was partitioned to grain for water stressed treatments for hybrids. Moisture treatments did not significantly influence partitioning to any plant part for varieties.

(v) Soil water

In SORGF 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 in the SORGF model was calculated using a site-specific sine function. This function was revised to enable the computation of Ro for any latitude. Open pan evaporation and Eo estimated are compared in Figure 5. This change resulted in improved estimates of Eo as can be seen in Figure 5.

Daily values of water stress coefficient (WATSCO) are computed in the SOLWAT subroutine using the current available soil water (SW) and the maximum amount of water (UL) in the profile. Values of UL are inputs of the model. Current available soil water (SW) is computed in the model after Ritchie (1972). Values of potential evaporation from bare soil (Eo) and below a plant canopy (Eos) used in computing SW are calculated in the subroutine EVAP. This approach could result in erroneous computation of a true water stress coefficient because the available soil water in the entire soil profile is not available to the plant in the early stages of crop growth.

A more representative coefficient could be obtained by considering an effective rooting depth function and computing available soil water for the portion of the profile where roots are present. In order to incorporate this aspect in the computation of water stress coefficient,

Table 8. Maximum percent light transmission (X1), extinction coefficient (X2) and leaf area index (X3) used in computing light transmission in SORGF for different row spacings.

Row spacing (cm)	X1	X2	X3	Light transmission at LAI [illegible] 3.0
30	75.01	-0.29	0.60	31.3
45	78.53	-0.28	0.49	34.3
60	82.04	-0.26	0.39	37.0
75	85.55	-0.25	0.30	40.9
90	89.06	-0.23	0.22	45.0
120	96.08	-0.20	0.07	53.0
150	103.11	-0.17	-0.05	62.0

Table 9. Total dry matter and percent partitioned to leaf, culm, head + grain and grain at three growth stages (Data pooled over all genotypes, seasons and moisture treatments, n = 27).

	Panicle initiation		Anthesis		Physiological maturity	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Leaf	0.64	0.04	0.24	0.04	0.11	0.02
Culm	0.36	0.04	0.60	0.06	0.36	0.07
Head	0.0	0.0	0.16	0.04	0.53	0.08
Grain	0.0	0.0	0.02	0 01	0.41	0.08
Total Dry Matter (g/plant)	1.6	1.2	35.2	15.0	67.4	23.3

Table 10. Total dry matter and percent partitioned to leaf, culm head + grain and grain at three growth stages for hybrid and variety (Data pooled over seasons and moisture treatments, n = 27).

	Panicle initiation		Anthesis		Physiologicle maturity	
	Hybrid	Variety	Hybrid	Variety	Hybrid	Variety
Leaf	0.64 a	0.64 a	0.25 a	0.22 a	0.11 a	0.12 a
Culm	0.36 a	0.36 a	0.57 b	0.66 a	0.32 b	0.45 a
Head + Grain			0.18 a	0.12 b	0.57 a	0.43 b
Grain					0.45 a	0.32 b
Total Dry Matter (g/plant)	1.3 b	2.5 a	32.0 a	43.0 a	65.0 a	73.0 a

Means with different letter are significantly different.

Table 11. Comparison of total dry matter and percent partitioned to leaf, culm, head + grain and grain for two moisture treatments during postrainy season for CSH-6, CSH-8, M-35-1.

	CSH-6 & CSH-8		M-35-1	
	Adequately Watered	Water Stressed	Adequatel Watered	Water Stressed
A) GS 1				
Leaf	0.64	0.63	0.64	0.63
Culm	0.36	0.37	0.36	0.37
Total Dry Matter (g/plant)	0.86	0.99	1.17	1.64
B) GS 2				
Leaf	0.22	0.24	0.20	0.21
Culm	0.60	0.57	0.68	0.65
Head + Grain	0.18	0.19	0.12	0.14
Grain			0.02	0.03
Total Dry Matter (g/plant)	31.7	20.8	42.8	30.6
C) GS 3				
Leaf	0.10	0.12	0.10	0.12
Culm	0.30	0.30	0.47	0.47
Head + Grain	0.60	0.58	0.43	0.41
Grain	0.50*	0.43*	0.32	0.30
Total Dry Matter (g/plant)	64.4*	38.9*	70.4	51.0

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*Significantly different

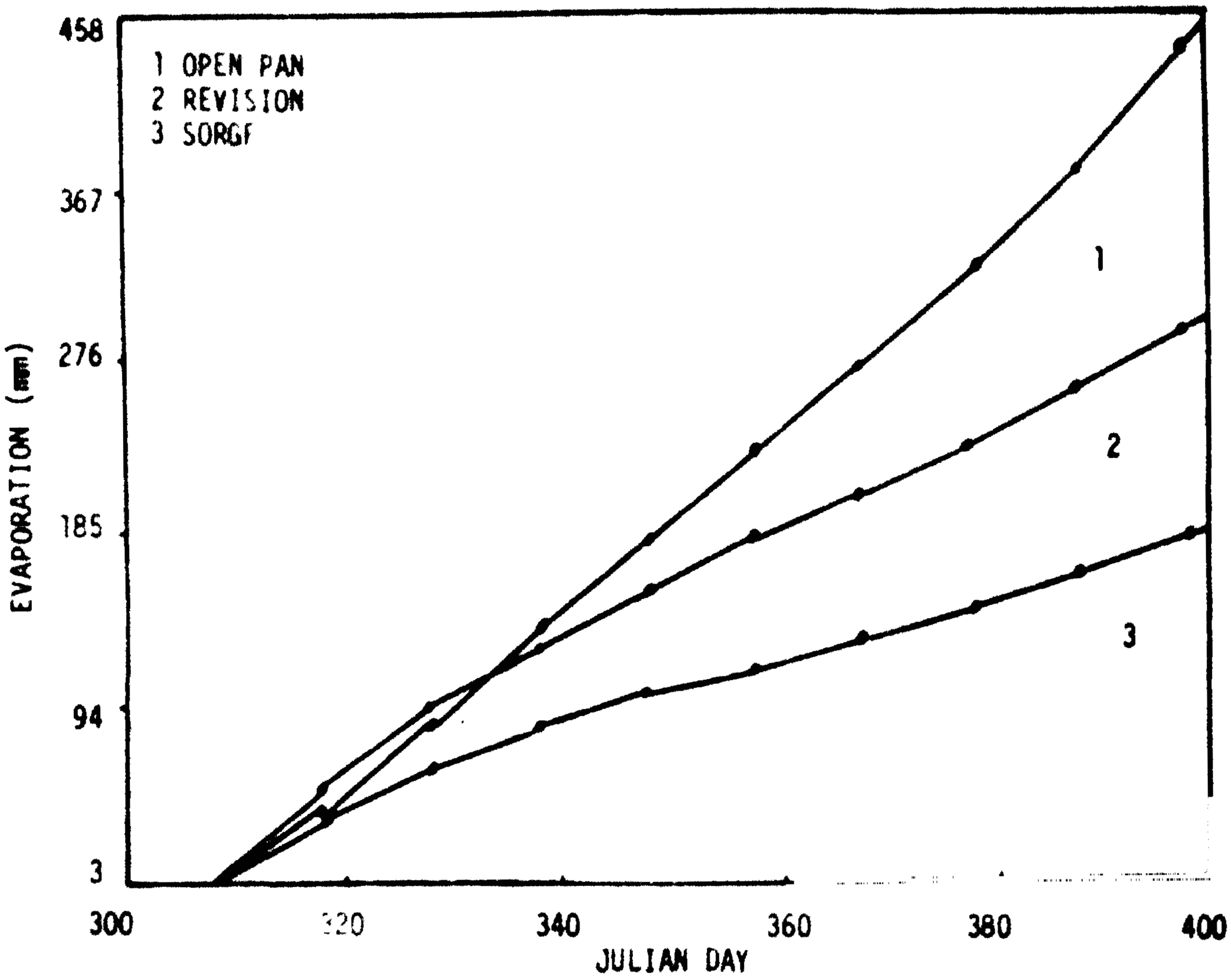

Fig. 5. Plot of cumulative evaporation from the bare soil (E_0) during 1978 at ICRISAT research center according to SORGF and the revised equation. Open pan evaporation is presented for comparison.

the extraction of drainage components developed by Williams and Hann (1978) was used. This approach consists of a routing technique to predict flow through root zones. For the ICRISAT data sets, the medium Alfisol soil was divided into nine storage layers: 0-10, 10-22, 22-30, 30-45, 45-60, 60-75, 75-90, 90-105, and 105-120 cm. The available water capacities for each of the nine layers were given by Russell (1980). When the total water in the first layer exceeds the capacity, drainage into the next layer can occur.

In order to check the validity of incorporating the effective rooting depth (ERD) and water extraction from the soil profile by layers, data collected by ICRISAT Research Center on supplemental irrigation responses of sorghum during the postrainy seasons of 1977 on a deep Vertisol and 1978 on a medium deep Alfisol have been used. Experimental details of these two trials have been described by Sivakumar et al (1978, 1980).

Deep Vertisols

The profile depth of the deep Vertisol is 187 cm and bulk density of the upper 20 cm layer averages 1.3 g/cm^3 (Russell 1980). Below this depth, the bulk density ranges between 1.35 and 1.45, with an average of 1.4 g/cm^3. Amounts of plant available water are 30, 50, 45, 40, 35 and 30 mm in the 0-22, 22-52, 52-82, 82-112, 112-142, and > 147 cm soil layers, respectively (Russell 1980).

Seasonal changes in modeled and measured available soil water for irrigated and nonirrigated sorghum on deep Vertisol are shown in Figures 6 and 7, respectively. Available soil water predicted by SORGF model (curve 1) is consistently higher than measured soil water. Available soil water summed over all the layers and using the new algorithm for calculation of EO is referred to as 'REVISION' here. Revision estimates of soil water are better than SORGF, but still higher than the measured soil water amounts. For the nonirrigated sorghum, the REVISION estimates are excellent.

Medium deep Alfisol

The profile depth of the medium deep Alfisol is 127 cm and the bulk densities range from 1.5 to 1.95 g/cm^3 (Russell 1980). Available soil water in the 0-22, 22-52, 52-82, 82-112, and 112-127 cm layers are 26, 33, 18, 12 and 6 mm respectively.

Seasonal changes in available soil water for the irrigated and nonirrigated sorghum in a medium Alfisol were also compared. As in the case of the Vertisols, SORGF model consistently overestimated measured values. REVISION provided slightly better estimates in the irrigated treatment and much better estimates in the nonirrigated sorghum (Figs. 8 and 9). Nonirrigated sorghum in the Vertisols received no irrigation at all, while it received three early irrigations in the Alfisols.

Thus, improvements in soil water estimates are resulting from improved estimates of evaporation from a bare soil surface (Eo). Incorporation of a layered soil water model seems to work reasonably well for the nonirrigated sorghum. Overestimates of computed soil water in the case of irrigated sorghum may be related to the inaccurate assumption in the SORGF model of no runoff.

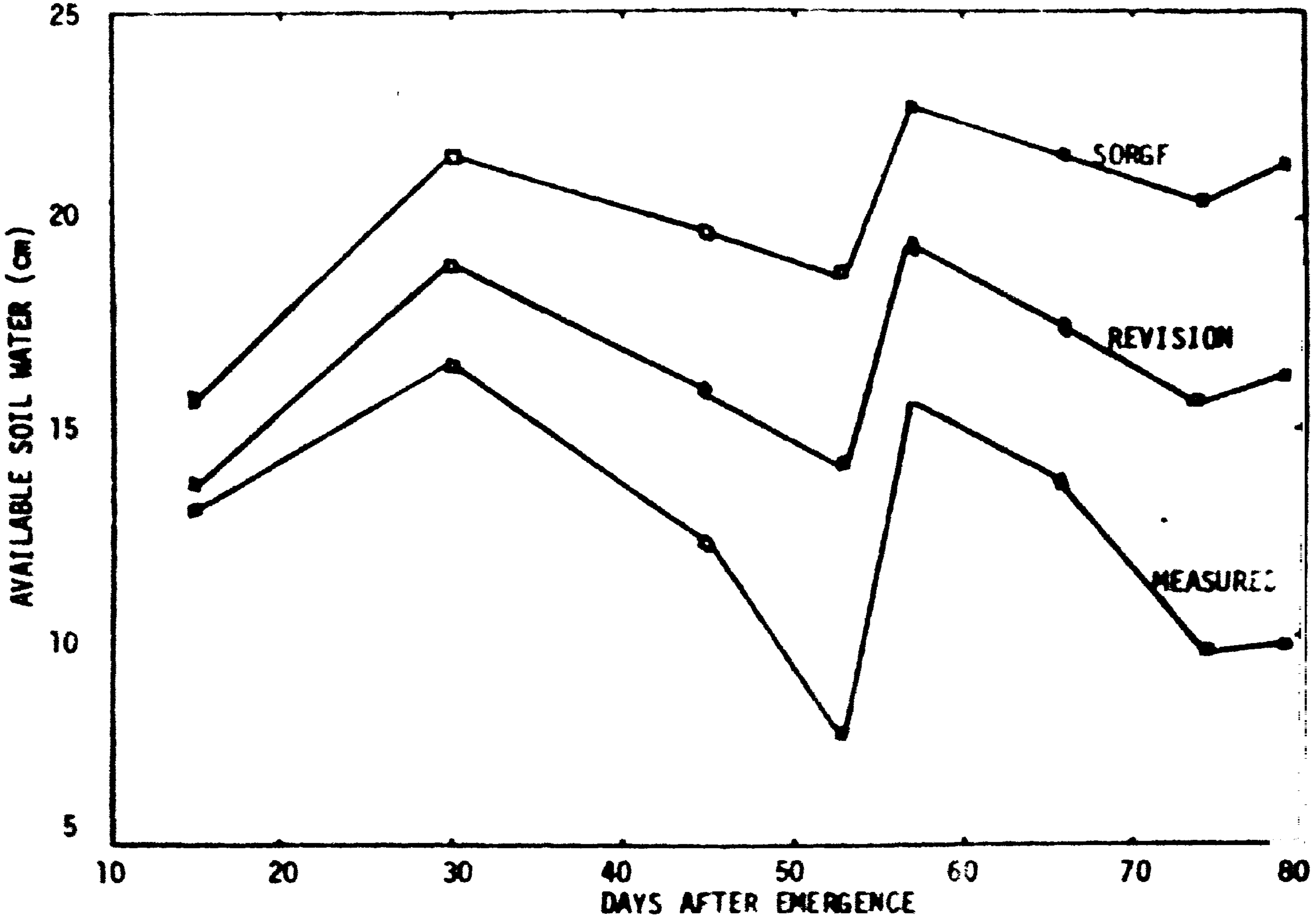

Fig. 6. Seasonal changes in the available soil water for irrigated sorghum in a deep Vertisol.

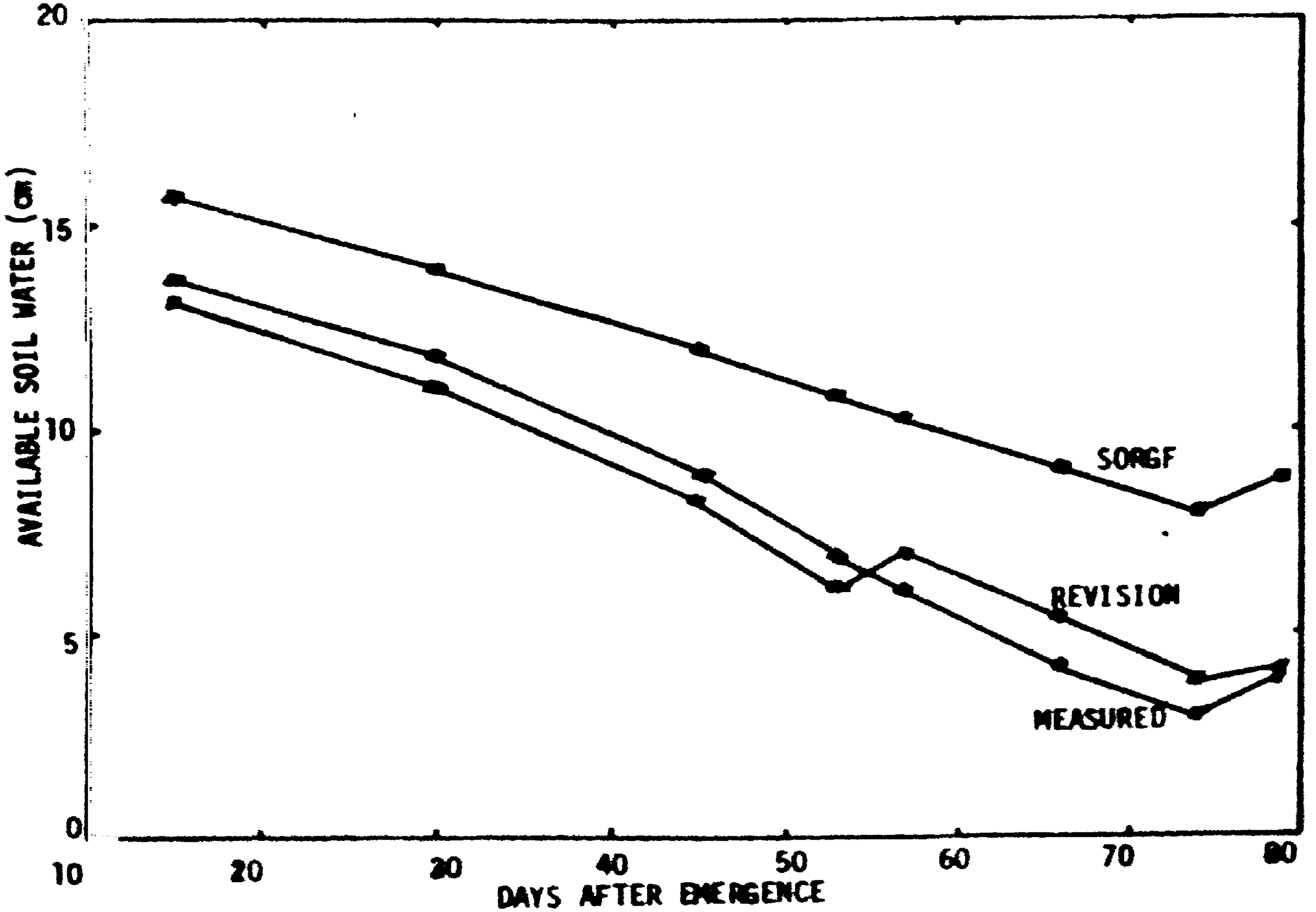

Fig. I. Seasonal changes in the available soil water for nonirrigated sorghum in a deep Vertisol.

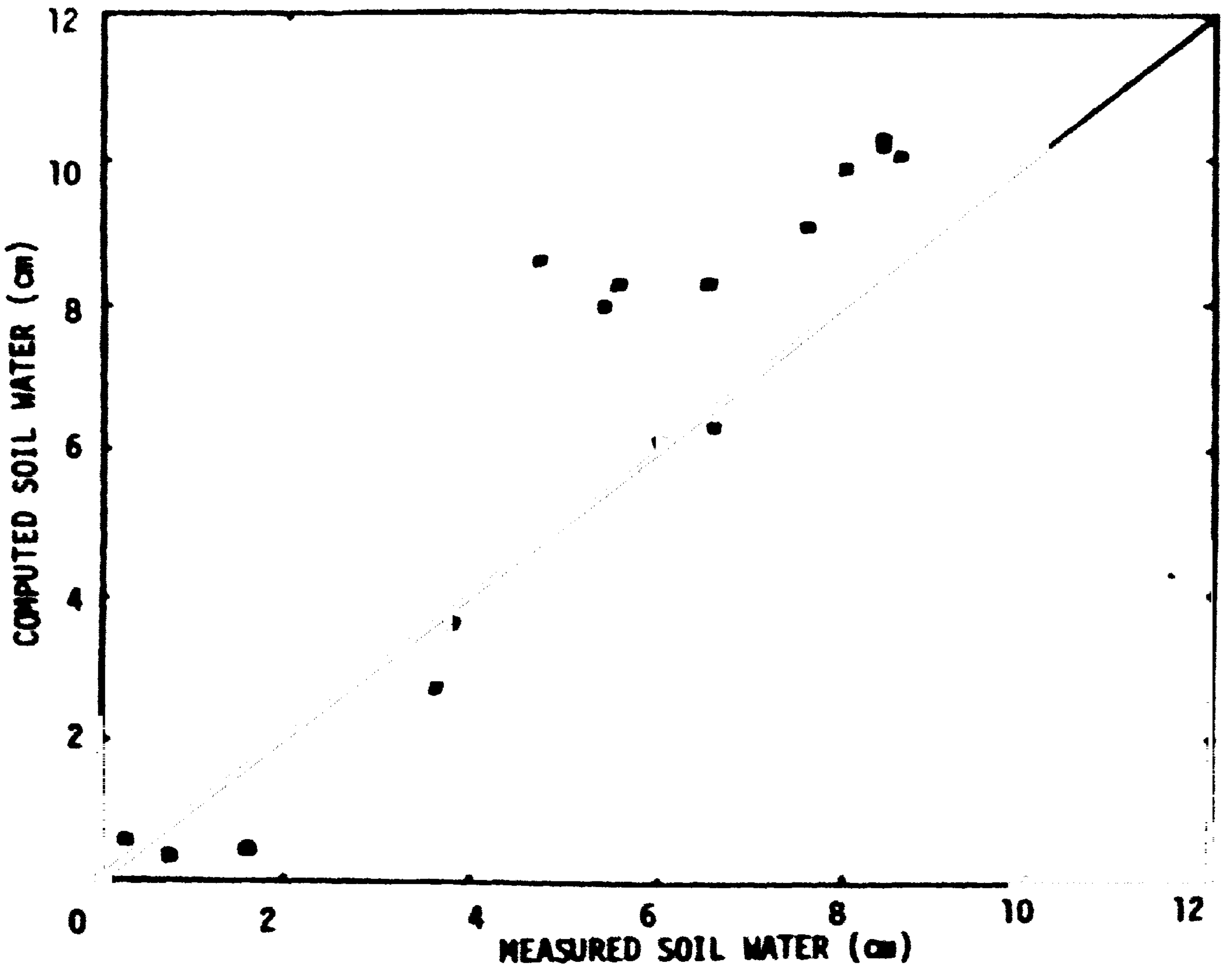

Fig. 8. Measured and computed available soil water according to layered model for irrigated sorghum on a medium Alfisol.

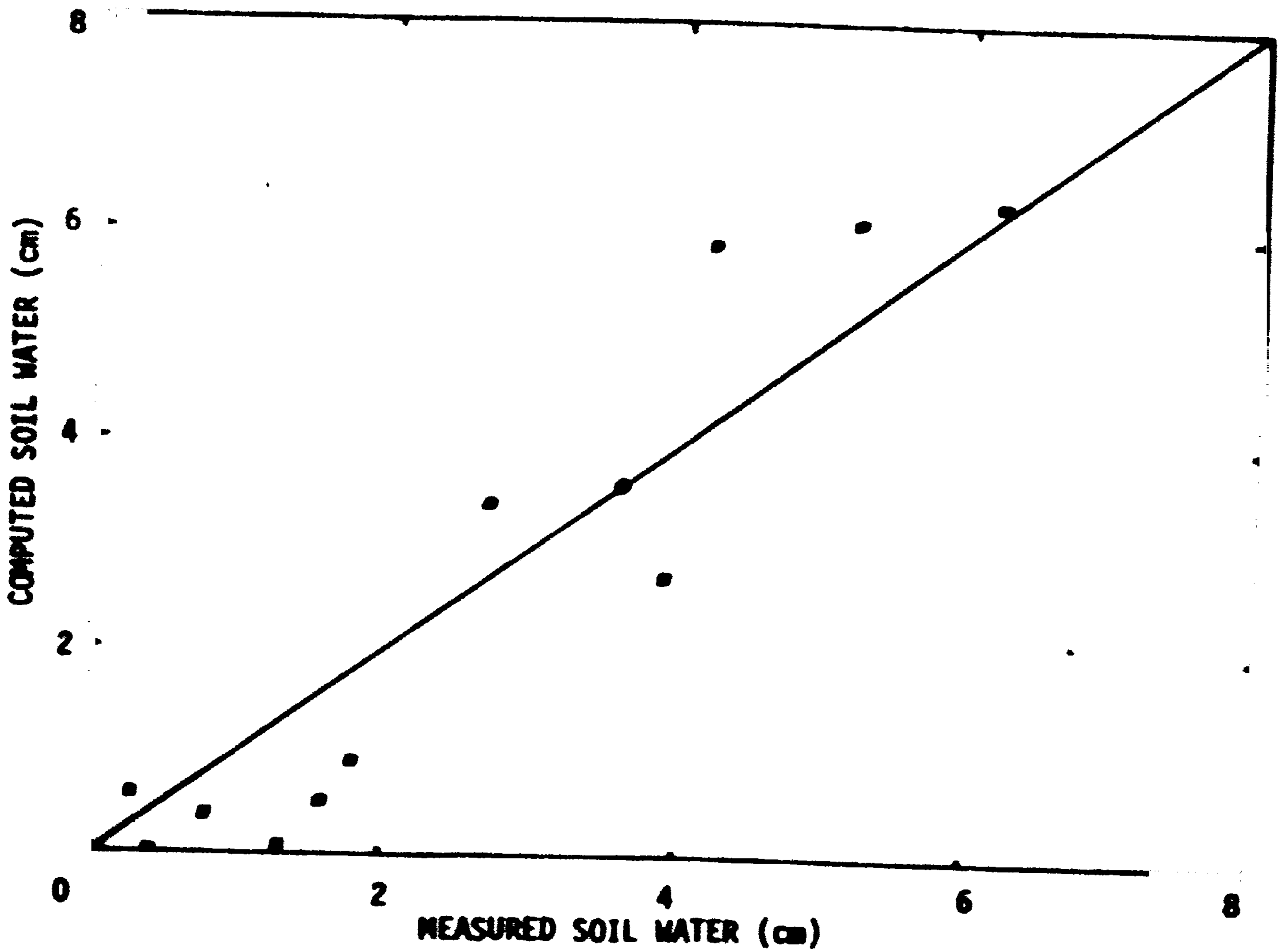

Fig. 9. Measured and computed available soil water according to the layered model for nonirrigated sorghum on a medium Alfisol.

Using SORGF and the layered model, WATSCO was computed for the treatments described above. Computation of WATSCO for the irrigated treatments showed little variability and, thus, data for the nonirrigated sorghum grown on the deep Vertisol were used to compare WATSCO predicted by SORGF, the layered model and field measurements. Use of a layered model provided consistently better estimates of WATSCO than SORGF when compared to field measurements (Table 12). For the nonirrigated sorghum, with progressive depletion of available soil water, the measured WATSCO decreased from 0.93 at 15 DAE to 0.73 by 79 DAE, and WATSCO computed by the layered model also decreased to 0.72 by 79 DAE while WATSCO predicted by SORGF stayed at 1.0 throughout the growing season. Use of layered model appears to provide improved estimates of WATSCO to account for the effect of water stress on sorghum growth.

(vi) Leaf development

Leaf area is overestimated by SORGF, particularly in the grain filling period. Total number of leaves and maximum area of each leaf are input data requirements for SORGF. In SORGF each leaf achieves its maximum area irrespective of moisture and temperature stress conditions. Leaf senescence is accounted for as follows: the first leaf senescences after the 11th leaf expands fully and as each successive leaf expands fully the next leaf senesces. No leaf senescence occurs after the last leaf is fully expanded. It was previously observed (Huda 1982) that when leaf 7 is fully expanded (leaf 8, 9, 10,....) consecutive leaves (leaf 2, 3, 4,.....) senesce and that leaf area at PM is 50 percent of leaf area at AN.

Leaf area data were collected at 7-10 days interval at 27 ICRISAT field studies and 16 cooperating field studies. The analyses however were made for only ICRISAT data. The maximum leaf area was achieved at AN (Table 13) with a mean of 1710 cm^2/plant and a standard deviation of 622 cm^2/plant. The leaf area variability is the result of pooling hybrids and varieties and moisture treatments. The highest leaf area at AN was obtained for variety SPV-351 (3227 cm^2/plant) and the lowest leaf area (761 cm^2/plant) was obtained for CSH-6 grown during the postrainy season in the water stressed treatment. Leaf area at PM was 50 percent of the maximum leaf area attained.

Leaf area was reduced by moisture stress during the postrainy season (Table 14). Leaf area was significantly different at PM for adequately watered and water stressed hybrids. From AN to PM leaf area decreased approximately 70 percent for hybrids and varieties experiencing water stress. For adequately watered treatments leaf area decreases 36 to 46 percent from AN to PM for hybrids and varieties, respectively.

Leaf area estimation

Several methods for the estimation of leaf area were studied to find out an easy method that has simple data requirement. This is particularly essential to use the crop data from other centers where it is difficult to measure leaf area directly. Based on the data collected from cooperative experiments, leaf area was estimated from leaf length and maximum width as well as only from leaf length. Area for individual leaves was also estimated to ascertain the variability in the coefficients for each leaf. The coefficients differed between genotypes, environments and individual leaves. Regression coefficients relating the product of leaf length (L)

Table 12 . Seasonal changes in WATSCO for a nonirrigated sorghum on a deep vertisol.

Days after emergence	SORGF	Layered model	Measured
15	1.0	0.58	0.93
30	1.0	0.99	0.98
45	1.0	0.98	0.97
53	1.0	0.95	0.90
57	1.0	0.92	0.94
66	1.0	0.76	0.85
74	0.9	0.56	0.67
79	1.0	0.72	0.73

Table 13. Leaf area (cm^2/plant) at three growth stages. Data pooled over all genotypes, seasons, and moisture treatments.

Stage	Mean	S.D.	Minimum	Maximum
Panicle initiation	369	268	145	1022
Anthesis	1710	622	761	3227
Physiological maturity	876	449	196	1848

Table 14. Mean leaf area (cm^2/plant) for adequately watered and water stressed treatments for both hybrid and variety grown during the postrainy season.

	Hybrid		Variety	
	Adequately Watered	Water Stressed	Adequately Watered	Water Stressed
Panicle initiation	218	216	319	304
Anthesis	1490	1113	1764	1273
Physiological Maturity	956*	360*	949	381

*Significantly different

and maximum width (W) to leaf area (Y) for four genotypes grown at ICRISAT Center are given in Table 15. The coefficients ranged from 0.67 to 0.71. For CSH-6 (n=4471) the coefficient was 0.696 while it was 0.641 for CSH-8 (n=[illegible]). The relationship between leaf area and leaf weight varied with genotypes,environment and growth stage. A manuscript is under preparation to discuss the detailed results on estimating leaf area.

Table 15. Regression coefficients relating the product of leaf length and maximum width to leaf area of sorghum.

Season	Genotype	No. of observations	Regression* coefficient	R^2
1979 rainy	CSH-1	512	.6973	.99
	CSH-6	447	.7111	.98
1979 postrainy	CSH-8	3135	.6829	.98
	M-35-1	3589	.6654	.92
1980 rainy	CSH-1	1728	.7017	.98
	CSH-6	2117	.7129	.98
1980 postrainy	CSH-8	2479	.6911	.97
	M-35-1	2101	.2101	.98

*Coefficient (b) in the functional relationship of Y (leaf area) b . L (leaf length) . W (maximum width).

3. Simulation comparison

The revised algorithms discussed earlier were incorporated in SORGF. Simulation results of several components of the model and the yield simulations were compared with observed data. Examples of testing some of the revised algorithms with the data obtained from 1981-82 experiments (which were not utilized for model revision) were given.

(i) Emergence

In SORGF, emergence is simulated when 70 heat units above 7°C base temperature accumulates after sowing provided the available soil water for the entire profile is above 10 percent.

The results of emergence computation were compared with the data obtained from 1981 rainy season experiments conducted at ICRISAT Center. Dry seeding of sorghum (a recommended practice for Vertisols) was done on a deep Vertisol (10 June) and on a medium deep Vertisol (12 June) ahead of monsoon. The available water holding capacity of these two soils are 200 and 165 mm respectively. At the time of sowing the available water in the entire profile for the two fields were 65 and 29 mm respectively (above 10% for the entire profile for both fields). Thus in SORGF, emergence was computed within 4 days after sowing.

However, in the top 30 cm layer for both the fields there was no available water. Thus emergence in both these fields actually occurred only on 22 June after 35 mm rainfall was received on 18 June. When the layered soil water model (top 0-30 cm; and beyond 30 cm) was used, the emergence data for both these fields was simulated as 21 June.

(ii) Phenology

The computation of phenological events such as PI, AM, and PM were compared with 19 observations obtained from 1981 experiments. The duration of emergence to PI was computed within [illegible] days due to revisions in phenology algorithms compared to ± 5 days as was done in SORGF. Similarly the root mean square error (RMSE) in simulating the duration of emergence to maturity was reduced from ± 15 days to ± 4 days.

(iii) Grain yield

The coefficient of determination (R^2) was improved from 50 percent to over 80 percent (due to revisions in the model) for grain yields obtained from 20 observations of 1981 experimental data conducted in ICRISAT Center.

(iv) Pooled data on grain yield and total dry matter

Simulation results of grain yield and total dry matter were compared with observed data pooled over seasons and genotypes from ICRISAT field studies and studies from other cooperating centers. The coefficient of determination for both grain yield (n = 59) and total dry matter (n = 54) was 76 percent according to revised model. The RMSE for grain yields and total dry matter for pooled data were 561 kg/ha and 1348 kg/ha respectively.

The relationship between observed and simulated grain yield and total dry matter are given in figures 10 and 11 respectively.

e. Model applications

First approximation answers to questions on sorghum yield potential can be generated by this model using climate and soil information. Answers to questions about the sorghum yield potential and to determine the optimum crop duration period matching with the water availability were sought by the Magarini Land Settlement Scheme in Kenya. May et al (1981) used this model to delineate the cumulative probability distribution of simulated grain yields in Kenya for optimum sowing dates chosen from the rainfall probability analysis. An example of such analysis was given in Figure 12 for two sowing dates at Marafa for the period 1937-80. The figure indicates that more than 5000 kg/ha sorghum yield can be obtained under adequate management practices in 50 percent of these years. Analysis of the soil and climatic data from different locations of the project area suggest that prospects for growing sorghum in both the long rains and short rains are fairly promising.

Arkin and Dugas (1981) used this model to determine the feasibility of sorghum ratooning in Texas. They constructed a 40-year (1939-78) cumulative probability distribution of simulated ratoon yields for 0, 5, 10, and 15 cm of ASW at the beginning of the ratoon crop, the probability of producing a 1500 kg/ha or more grain yield for a ratoon crop was about 80%. The profitability of ratoon cropping in Temple, Texas is dependent on soil moisture conditions at the start of the ratoon crop each,(Figure 13).

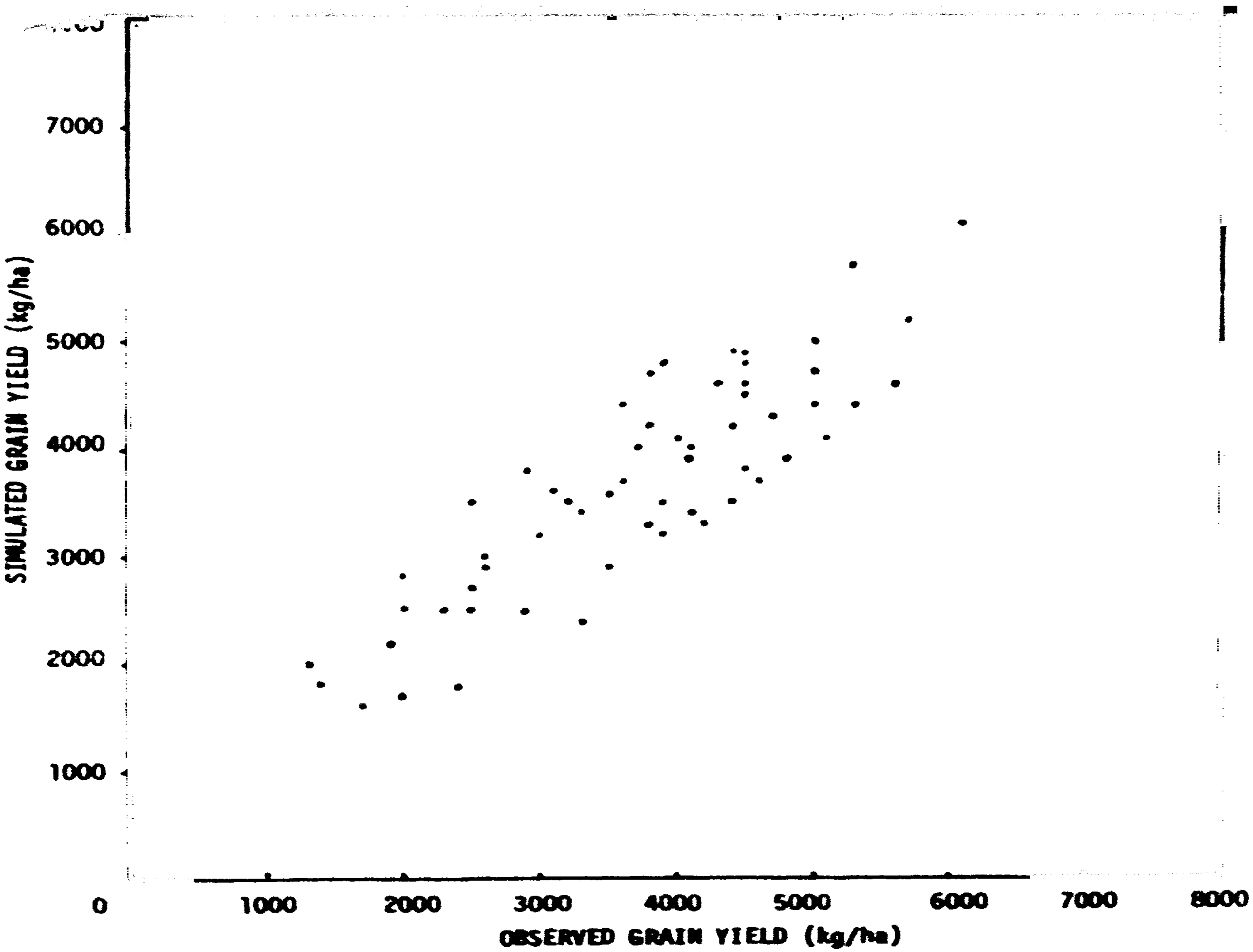

Fig. 10. Relationship between observed and simulated grain yield (kg/ha) of sorghum according to revised sorghum model for pooled data (n = 59).

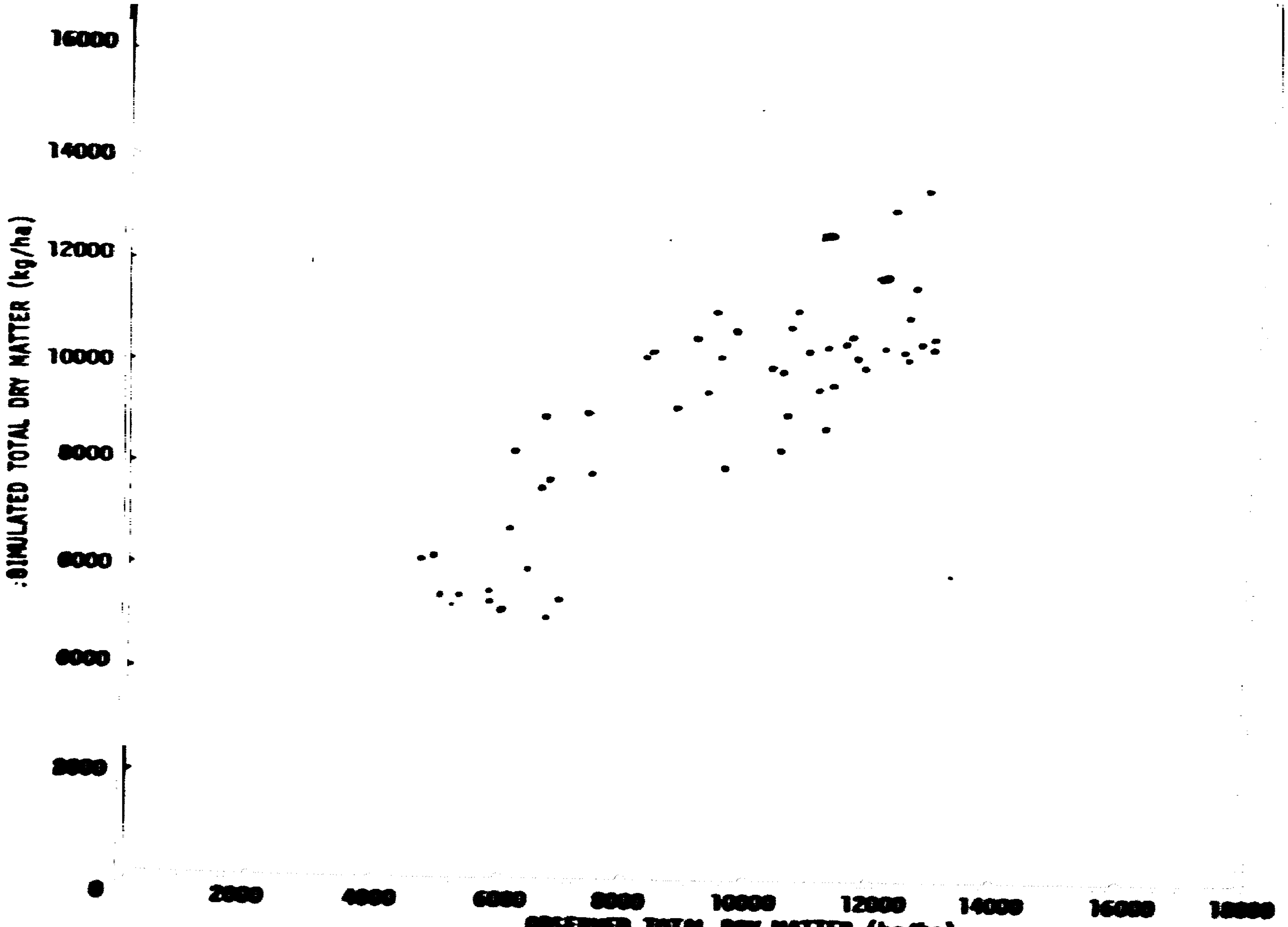

Fig. 11. Relationship between observed and simulated total dry matter (kg/ha) of sorghum according to revised SORGF model for pooled data (n = 54).

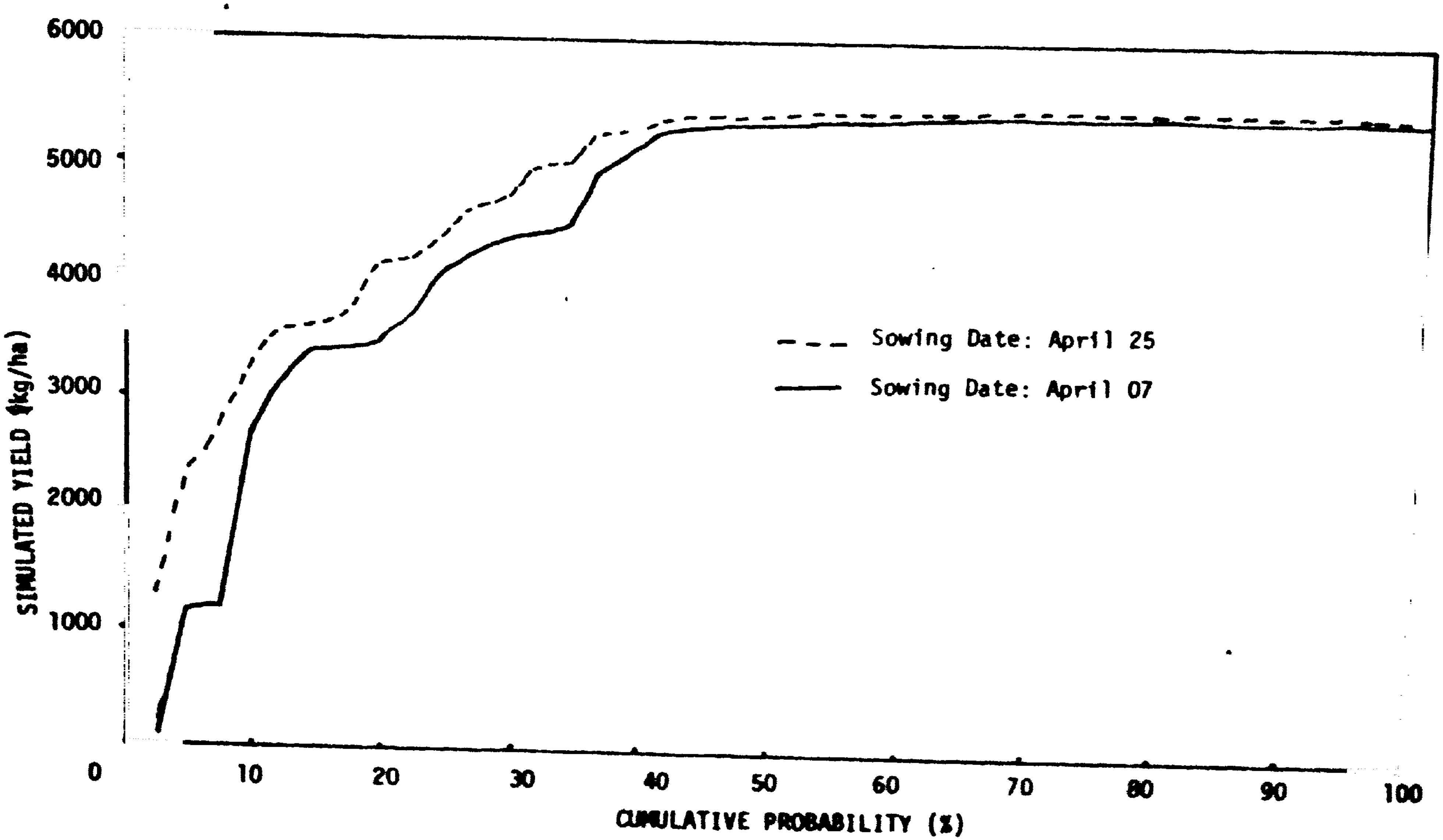

Fig. 12. Cumulative probability distribution of simulated grain yield (kg/ha) of soeghum according to revised SORGF model for two sowing dates at Marafa (Kenya) from 1937-1980.

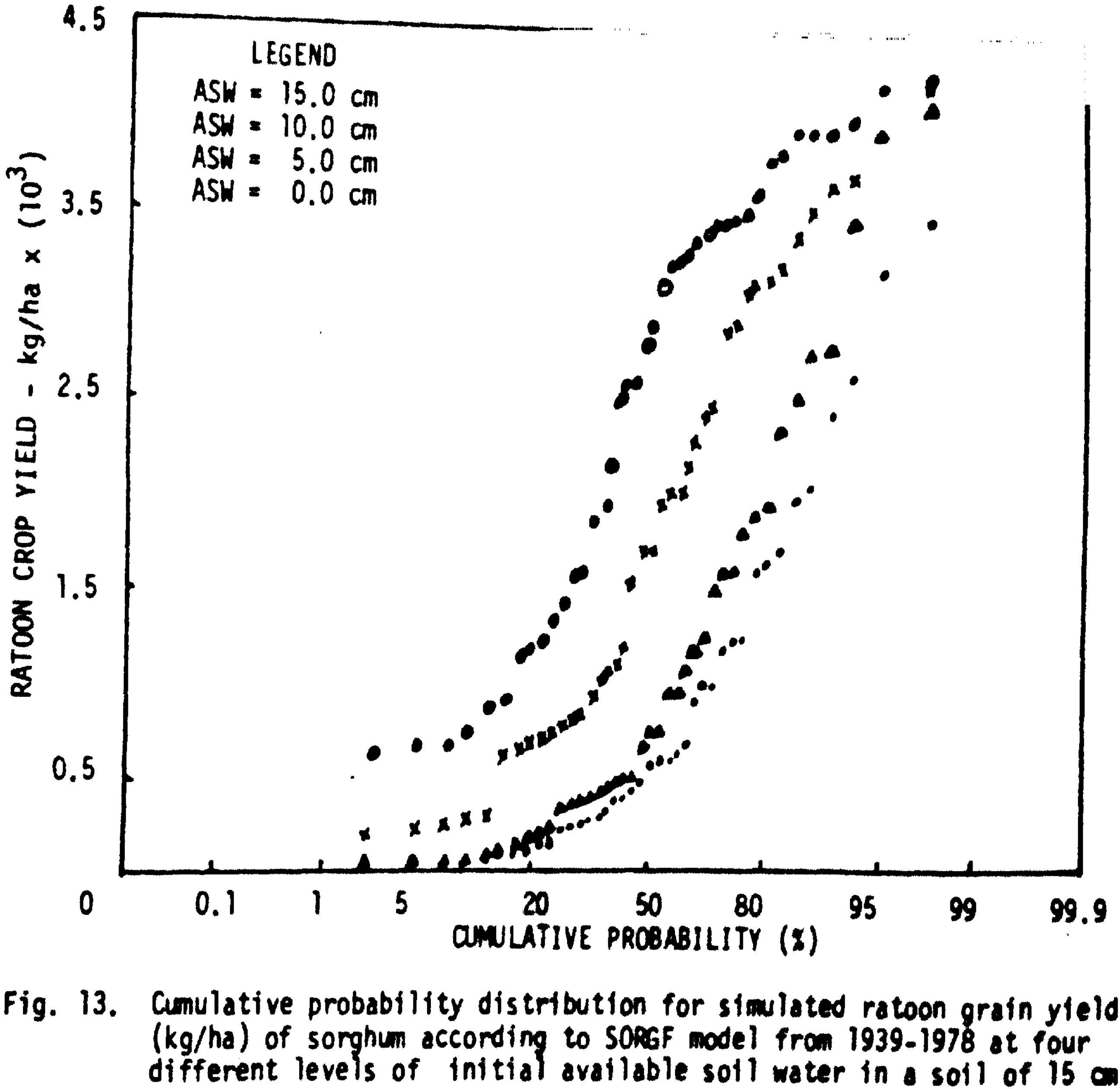

Fig. 13. Cumulative probability distribution for simulated ratoon grain yields (kg/ha) of sorghum according to SORGF model from 1939-1978 at four different levels of initial available soil water in a soil of 15 cm available water holding capacity in Temple, Texas.
(After Arkin and Dugas, 1981).

LOOKING AHEAD

Our experience with the sorghum simulation model over the past five years gave us useful leads to examine alternative management strategies and extend the knowledge to other crops. We will continue our efforts:

- To extend knowledge in developing growth models for other crops of ICRISAT mandate. Pearl millet which is the second cereal crop of our mandate was obviously the next choice. Efforts have been initiated by the Farming Systems Research Program in cooperation with the pearl millet improvement program at ICRISAT to develop a growth and development model for pearl millet. Experiments are being conducted from the 1981 rainy season to collect standard data sets on crop, soil and weather to achieve this objective.

  Collaborative experiments are being designed to study light interception, water use, phenology, tillering habit, dry matter accumulation, and partitioning of pearl millet under both Indian and West African conditions. Experiments are also planned to study the effects of method of planting e.g. row (practised in India) versus hill (practised in West Africa) on the growth and development of pearl millet.

- To use the revised sorghum model in developing a methodology for first order screening of different environments for their crop production potential.

- Sorghum yield simulations are presently made assuming that crops are raised under adequate nutrient supply, weed free, insects/disease free conditions. Algorithms addressing these questions should be developed and incorporated in the model for yield simulation under the real world situations. Thus collaborative experiments need to be planned for quantifying the stress factors (moisture, nutrient, biotic etc).

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