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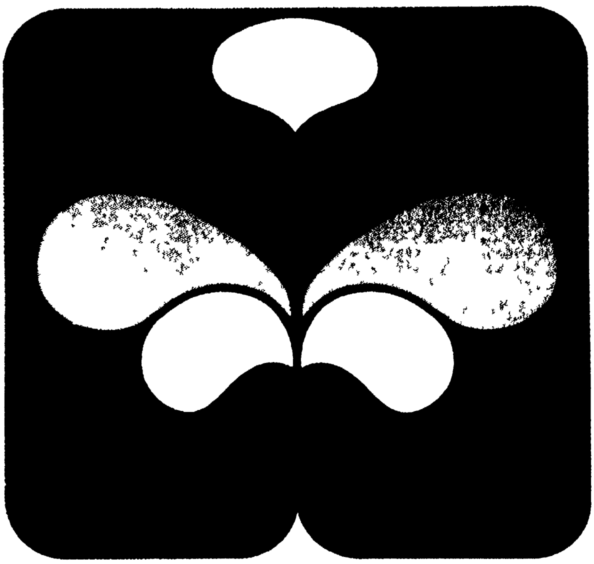

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Field Crops Research, 15 (1987) 309-325
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Simulating Yields of Sorghum and Pearl Millet in the Semi-Arid Tropics*

A.K.S. HUDA

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, AP (India)

(Accepted 22 May 1986)

ABSTRACT

Huda, A.K.S., 1987. Simulating yields of sorghum and pearl millet in the semi-arid tropics. *Field Crops Res.*, 15: 309-325.

A sorghum simulation model, SORGF, was revised for use in the semi-arid tropics. As a result of the revisions in the model, the correlation coefficient between observed and simulated grain yield of sorghum ($n=59$) increased from 0.52 to 0.86. Comparison between simulated and observed grain yields showed that the SORGF model can be used to estimate sorghum yields with reasonable accuracy before harvest. Responses of sorghum to drought-stress and to changes in plant density were simulated. The correlation coefficient between observed and simulated sorghum grain yield data pooled over five levels of plant density and two cultivars was 0.91. The correlation coefficient between observed and simulated sorghum grain yield data pooled over two water treatments, two cultivars, and two seasons was 0.92. The model was used to compute the probabilities of simulated sorghum grain yield and the requirements of N-fertilizers based on 30 years of climatic data for four locations in India.

A simulation model for pearl millet was developed following an approach similar to that of SORGF. The pearl millet model was tested against independent data; further testing of the pearl millet model is required before its application.

INTRODUCTION

Regression-type models using environmental factors as independent variables are widely used to predict crop yields (Fisher, 1924; Gangopadhyaya and Sarkar, 1964; Runge, 1968; Brown and Vanderlip, 1969; Thompson, 1969; Huda et al., 1975; Feyerherm and Paulsen, 1981; Huda et al., 1985b). Process-based crop simulation models based on soil, crop, and weather factors are effective research tools for planning alternative strategies for cropping, land use and water management (Jordan, 1983). These models also have potential for yield forecasting (Nix, 1976; Huda and Virmani, 1980; Arkin and Dugas, 1984). A grain sorghum growth simulation model, SORGF, developed by Arkin et al.

*Submitted as ICRISAT Journal Article No. 665.

0378-4290/87/$03.50

TABLE 1

Input data required for SORGF -- a sorghum simulation model

Plant data	
	Leaf number -- total number of leaves produced
	Leaf area -- maximum area of each leaf
Planting data	
	Sowing date
	Plant population
	Row width
	Depth of sowing
Climatic data (daily from sowing to maturity)	
	Maximum temperature
	Minimum temperature
	Solar radiation
	Rainfall
Soil data	
	Available water holding capacity
	Initial available water content
Location data	
	Latitude

(1976) using data from the U.S.A. is one of the examples of process-based models. The objectives of this paper are to briefly describe revisions made in the SORGF model and to illustrate the applications of the revised model in the semi-arid tropics.

The SORGF model calculates the daily growth and development of an average grain sorghum plant under adequate plant protection and nutrient supply. The input data required for this model are given in Table 1. The model accounts for the processes suh as phenology, leaf area development, light interception, and water use which are independently computed and used as sub-models. The potential dry matter accumulation is calculated from radiation intercepted and the net dry matter accumulation is calculated accounting for water and temperature stress. Partitioning of dry matter into different plant parts is based on the stage of development of the plant. The final grain yield per unit area is calculated by multiplying plant density with the grain weight per plant at physiological maturity.

MATERIALS AND METHODS

Multilocation experiments

A collaborative study was conducted at nine locations in India (11–31°N latitude), to evaluate the growth and development of selected *Sorghum bicolor*

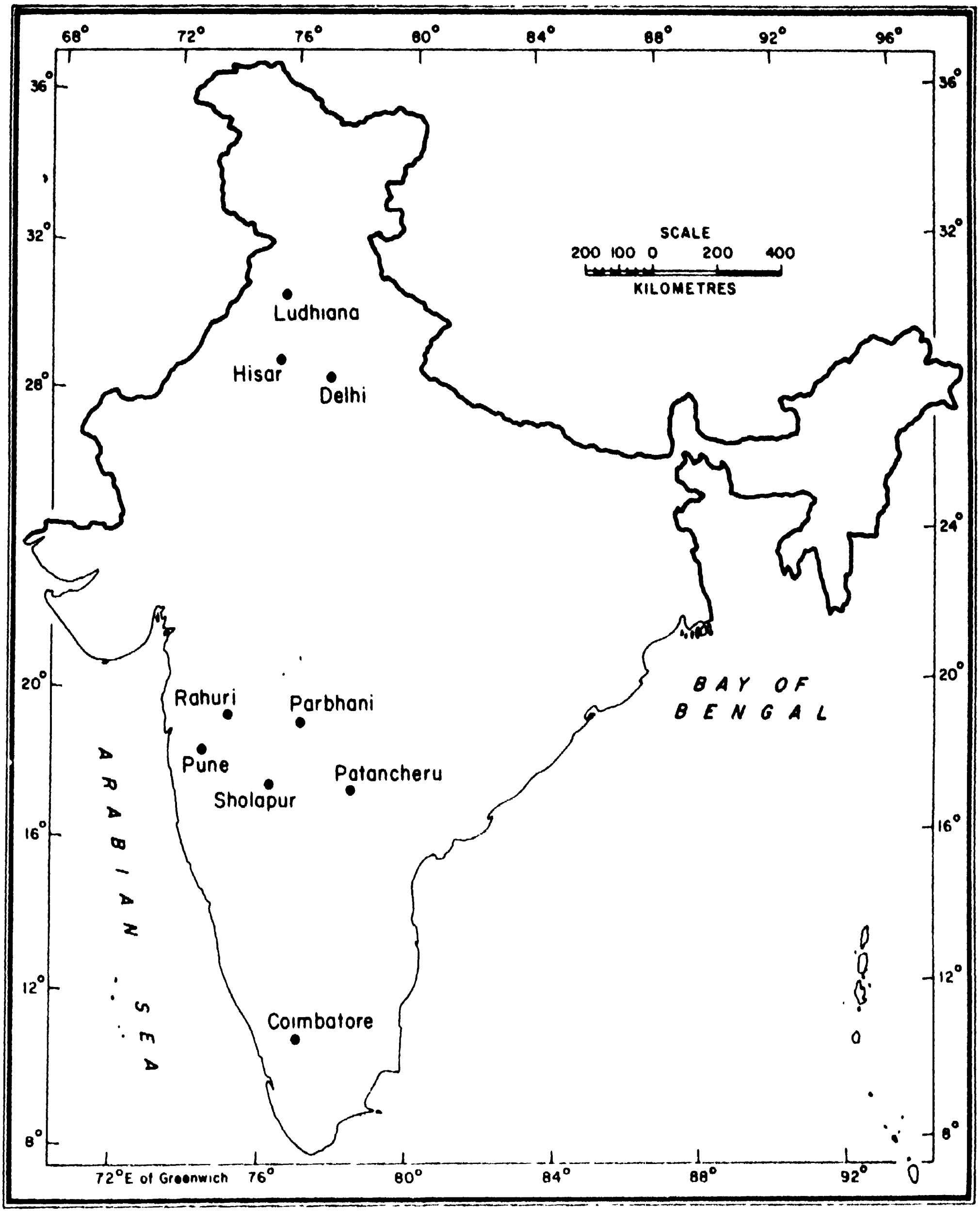

Fig. 1. Nine locations in India where sorghum modeling experiments were conducted.

[L.] Moench cultivars (CSH 1, CSH 6, CSH 8, SPV 351, M 35-1) of maturity durations ranging from 80 to 115 days after emergence (DAE), during the rainy and post-rainy seasons, over 4 years (1979–1982). Figure 1 shows the locations where the collaborative experiments were conducted. Mean annual rainfall for these locations is 446 mm in Hisar, 520 mm in Rahuri, 612 mm in Coimbatore, 704 mm in Ludhiana, 714 mm in Delhi and Pune, 742 mm in Sholapur, 792 mm in Patancheru, and 902 mm in Parbhani.

Standard data sets on crop, soil, and weather factors (Table 1) were collected from these experiments. Crop phenology, light interception, water use, and dry matter production and its partitioning were studied to evaluate the role of environmental factors in these proceses. The rate of crop growth and development was monitored to examine its role in crop water use and light interception. The effects of temperature and daylength on phenology were studied. The time from emergence to panicle initiation (GS1), from panicle initiation to flowering (GS2), and from flowering to physiological maturity (GS3) i.e., the time when black layer appears at the hyla region of grains, were monitored. A date for emergence was given when 50% of plants had emerged. Ten plants from each replication were observed for phenological development. A date for a particular phenological event was given when 50% of the plants sampled from three replications reached that event (i.e., panicle initiation, flowering, and physiological maturity).

Model revision

Since the SORGF model was developed in the Texas semi-steppe sub-tropical conditions, initial testing of the model showed that several subroutines of this model needed modification for its applications in the semi-arid tropics (Huda et al., 1980). Accordingly, these subroutines were revised using data from collaborative multilocation field experiments. A brief account of these revisions is given below.

RESULTS

Phenology

In SORGF, the time from seedling emergence to panicle initiation was simulated as the sum of heat units (base temperature = 7°C and the upper limit of mean temperature = 30°C) and was a function of the maximum number of simulated date the flag leaf was expanded plus 0.86 times the simulated number of days from panicle initiation to flag leaf appearance. The time from emergence to physiological maturity was calculated as 1.4 times the simulated number of days from emergence to flowering. The effects of daylength and temperature was not systematically studied for developing the original phenology subroutine. The length of the GS1 period was overestimated by SORGF, particularly at lower latitudes (e.g., ICRISAT Center, 17°N), probably as a result of the narrow data base used in the development of this subroutine (e.g., only data from the U.S.A. where daylengths are relatively longer). For the present study, crop phenological data for almost all the growth stages were collected in 50 data sets, of which 10 were randomly selected for independent tests. The remaining 40 data sets were used to study phenological development in order to develop new algorithms.

TABLE 2

Duration (days) of different growth stages in sorghum (data pooled over locations, seasons, and cultivars)

Growth stage	Number of observations	Duration (days)			CV (%)
		Mean	Minimum value	Maximum value	
GS1	29	23	17	31	19
GS2	29	37	30	50	10
GS3	39	35	22	53	18
GS1+GS2	39	60	50	80	11
GS1+GS2+GS3	40	96	80	115	15

The duration of GS1 was highly variable (Table 2), ranging from 17 to 31 days, with a mean of 23 days. The minimum and maximum length of GS1 was obtained for the same cultivar (CSH 6) grown during the rainy season at different locations. The minimum duration was observed at ICRISAT Center and Parbhani (17°N); the maximum at Ludhiana (31°N). To account for this variability the data were further analyzed to establish the effect of daylength and temperature. To revise the subroutine on phenology, the approach of Stapper and Arkin (1980) was used to calculate growing degree days (GDD) using a base temperature of 7°C. Daylength at emergence (DAYEM) and at panicle initiation were found to be highly correlated ($r=0.99$) and therefore, DAYEM was plotted against the GDD values for GS1 for cultivars CSH 1 and CSH 6 (Fig. 2). A similar relationship was proposed by Major (1980) for short-day plants and by Stapper and Arkin (1980) for corn. For the present study, the

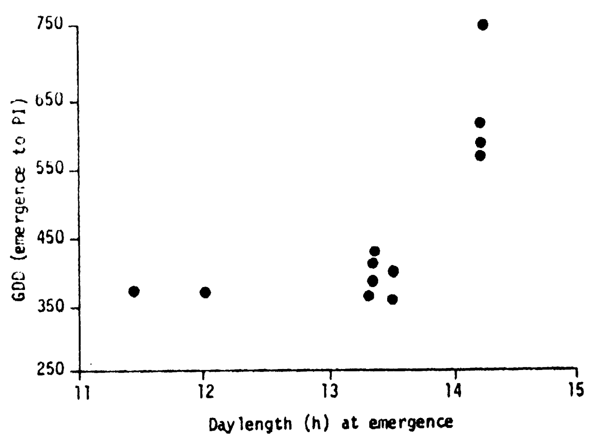

Fig. 2. Relationship between growing degree days (GDD) required from emergence to panicle initiation (PI) and daylengths at emergence of sorghum (cultivars CSH 1 and CSH 6) grown in different locations.

threshold value of daylength was 13.6 h at emergence. Differences in GS1 can be accounted for by daylength and temperature effects as shown in Fig. 2. A similar relationship was found for GS2, but no effect of daylength was observed for GS3.

The algorithm for describing DAYEM and GDD effects on the length of GS1 was:

$\mathrm{GDD} = 370 + 400\ (\mathrm{DAYEM} - 13.6)$ if $\mathrm{DAYEM} \geqslant 13.6$ h

$\mathrm{GDD} = 370$ if $\mathrm{DAYEM} < 13.6$ h

The algorithm for describing DAYEM and GDD effects on the length of the GS2 was:

$\mathrm{GDD} = 650 + 120\ (\mathrm{DAYEM} - 13.6)$ if $\mathrm{DAYEM} \geqslant 13.6$ h

$\mathrm{GDD} = 650$ if $\mathrm{DAYEM} < 13.6$ h

Differences in the length of GS3 can be accounted for as a temperature effect, as shown by Schaffer (1980). The duration of GS3 decreased with an increase in mean air temperature (T) of 27 °C and increased above 27 °C. This increase in duration of GS3 with increase in temperature above 27 °C needs further verificatioin under controlled conditions. A base temperature of 7 °C was derived from computing GDD in GS3. Thus for GS3 the following algorithms were used to account for temperature effects in GDD computation:

$\mathrm{GDD} = T - 7$, when $T \leqslant 27\,°\mathrm{C}$

$\mathrm{GDD} = (54 - T) - 7$, when $T > 27\,°\mathrm{C}$

These revised algorithms were tested with 10 independent field study data sets. As a result of these revisions, the root mean square error was reduced from 7 to 4 days for the length of the period from emergence to panicle initiation, and from 18 to 3 days for the total duration from emergence to physiological maturity.

Light interception

Light transmission in the original SORGF was calculated from the relationship of extinction coefficient and maximum light transmission, using information on row spacing and leaf area index (LAI). The model overestimated light transmission, especially at low levels of canopy light transmission, and it did not work for row spacings of more than 1.37 m.

The light interception portion of the SORGF model simulated the relative quantum flux intercepted by a single plant. Intercepted photosynthetically active radiation (PAR) was calculated on an hourly basis following a Beer's Law relationship using solar radiation and light transmission values. Hourly solar radiation was computed from the input daily solar radiation, and by accounting for hours of sunlight, which was calculated as a sine function of the local solar time and daylength.

Validations with data collected at ICRISAT Center showed that the model computations of solar declination and daylength were accurate, resulting in sufficiently accurate estimation of hourly solar radiation. The quantum flux density in Einsteins/m^2/day was estimated in SORGF from the energy flux density (RS) in cal/cm^2/day as

$$PAR = RS\ (0.121)$$

However, our results using measured data on PAR and RS indicated that the constant relating PAR to solar radiation (RS) should be altered as follows:

$$PAR = RS\ (0.09)$$

The functions for estimating maximum light transmission ($X1$) and extinction coefficient ($X2$) were revised. The revised algorithms are:

$$X1 = 0.1855\,R + 67.2642$$

$$X2 = 0.0026\,R - 0.6469$$

$$\text{Light transmission} = X1\ e^{X2(DLAI)}$$

where R = Row spacing (cm)

DLAI = Daily leaf area index

Comparison of simulated and measured light transmission data showed that data points (Fig. 3) deviated from the 1:1 line beyond the 15% limits at low levels of light transmission. The use of the revised equations substantially improved the simulation of light transmission.

Soil water

In SORGF daily available water for the entire soil profile (single layered) was calculated after Ritchie (1972), using information on initial available soil water, available water holding capacity, rainfall/irrigation, and evaporative demand. Potential evaporation below a plant canopy (EOS) was calculated after simulating the potential evaporation from bare soil (EO) and using LAI values. EO was calculated in the model using net radiation as input data. Net radiation was calculated from albedo, maximum solar radiation reaching the soil surface (RO), and sky emissivity. RO in the original SORGF model was calculated using a site-specific sine function. This function was revised to calculate RO for any latitude and resulted in improved estimates of EO.

The original SORGF model simulated soil water for the entire soil profile (single-layered) and thus, much of the simulated soil-water may not be available to the plants, particularly in the early stages of crop growth. Better estimates of soil water could be obtained by considering an effective rooting-depth function and calculating available soil water for the portion of the profile where roots are present. In order to incorporate this aspect in the model, daily evapotranspiration was simulated after Ritchie (1972) and was apportioned to the appropriate layers by using a root growth model by Stinson (1979). Daily potential root growth was calculated using the ratio of cumulative daily leaf area to the maximum leaf area for the whole plant. The extraction of drainage components developed by Williams and Hann (1978) was also used. This approach consists of a routing technique to predict flow through the root zone.

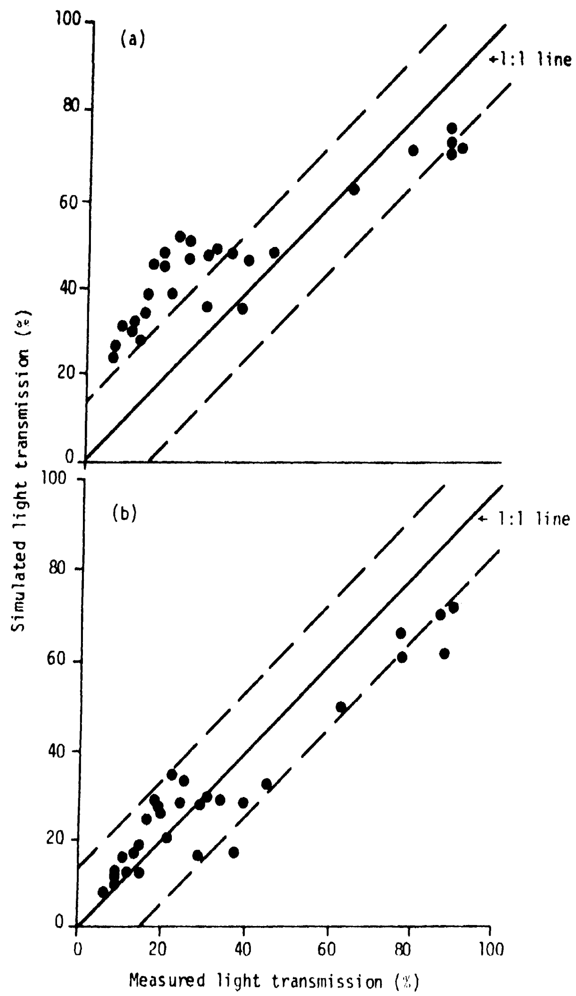

Fig. 3. Relationship between measured and simulated light transmission data pooled from different sorghum experiments according to (a) SORGF and (b) revised algorithms (dashed lines represent ±15% from 1:1 line).

Simulation of available soil water for various layers and using the new algorithm for calculation of RO is referred to as revision. Arkin et al. (1976) defined the water-stress coefficient as 1.0 (suggesting no water-stress) until available soil water in the entire profile was depleted up to 60%, and the coefficient decreased with the further depletion of soil water. The coefficient ranged between 0.0 and 1.0. The revised model provided better estimates of soil water and water-stress coefficients. For example, in a non-irrigated sorghum in the post-rainy season in a deep Vertisol (1.87 m) at ICRISAT Center, with progressive depletion of available soil water, the measured water-stress coefficients decreased from 0.93 at 15 DAE to 0.73 by 79 DAE; water-stress computed by the revised model also decreased to 0.72 at 79 DAE, while water-stress coefficients by the SORGF model stayed at 1.0 throughout the growing season.

Dry matter production and partitioning

In SORGF daily potential photosynthesis was calculated from intercepted photosynthetically active radiation (PAR). The potential net photosynthesis was calculated after accounting for the water and temperature stress, and respiration losses. A simpler relationship between total dry matter and intercepted radiation was developed using the approach of Gallagher and Biscoe (1978), and Stapper and Arkin (1980). For several crops of sorghum, dry matter produced per MJ of intercepted PAR varied from 1.20 to 2.82 g, the lowest value corresponding to a non-irrigated crop during the post-rainy season. The highest value was recorded for a sorghum crop that was irrigated at 10-day intervals in the post-rainy season. From these results, it seemed reasonable to use a value of 3 g dry matter produced for each MJ of PAR intercepted for irrigated sorghum. The temperature and water-stress coefficients were then used to calculate daily dry-weight increase.

Partitioning of total dry matter to different plant parts was observed to be different between hybrids (CSH 1, CSH 6, and CSH 8) and varieties (SPV 351, and M 35-1). For example, at flowering, percent of total dry matter partitioned to culm (stem + leafsheath) was 57% in hybrids and 66% in varieties. At physiological maturity, percent of total dry matter partitioned to grain was 45% in hybrids and 32% in varieties. Since the SORGF model did not account for these differences, suitable changes were made in the dry-matter partitioning subroutine.

Testing of revised SORGF

Figure 4 shows the relationship between observed and simulated grain yield of sorghum using independent data ($n = 59$) pooled from different cooperating centers. The correlation coefficient between observed and simulated grain yield increased from 0.52 to 0.86 due to revisions in the model.

Model applications

Using the following examples, applications of the revised SORGF model were illustrated to:

(i) Predict grain yield of sorghum;
(ii) Assess the impact of drought on sorghum grain yield;
(iii) Simulate the response of sorghum to plant density;
(iv) Screen environments for sorghum production and input responses;
(v) Develop models for other crops such as pearl millet (*Pennisetum americanum* [L.] Leeke) using an approach similar to that of SORGF.

Predicting grain yields of sorghum. Simulated yields were compared with inde-

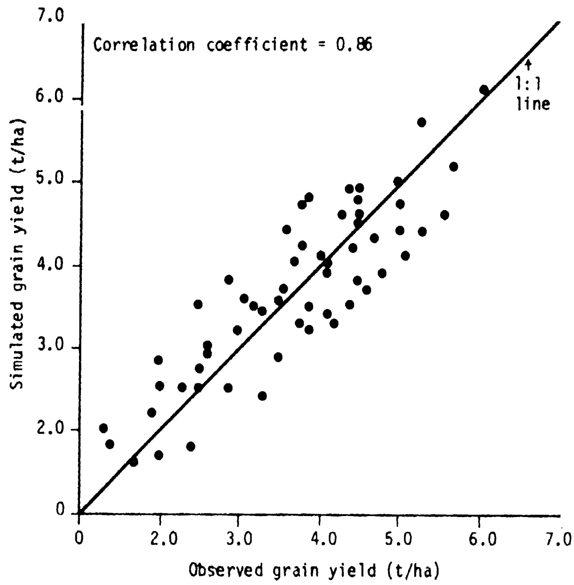

Fig. 4. Relationship between observed and simulated grain yield (t/ha) of sorghum according to revised sorghum model for pooled data ($n = 59$).

pendent data of observed sorghum grain yield (cv CSH 6) from the rainy seasons 1978–1984 at ICRISAT Center, Patancheru. Simulated yields were within the range 1–9% of the observed yields in 6 years, when observed yields ranged from 4.9 to 6.2 t/ha and within 16% for 1 year when the yield was 6.6 t/ha.

Grain yields were also simulated using actual weather data from sowing to flowering and assuming average weather data (based on 10 years' data from 1974 to 1983 at ICRISAT Center, Patancheru) from flowering to physiological maturity. Simulated yields using these data were within the range 2–13% of the observed grain yields. The purpose of this exercise was to illustrate that the model can be used to predict yields ahead of harvesting.

Assessing the impact of drought on sorghum grain yield. The revised SORGF model was tested by comparing the simulated and observed response of two sorghum cultivars (CSH 8 and M 35-1) to drought stress in two post-rainy seasons (1979/80 and 1980/81). The experiment was conducted in an Alfisol (85 mm available water holding capacity) at ICRISAT Center, Patancheru, with two water treatments (irrigated and drought-stressed) and two cultivars.

The environmental conditions of the 2 years (1979/80 and 1980/81) differed. The GS1 period in the first year (sown in late November) was characterized by lower temperatures, evaporative demands, and radiation compared to the experiment in the second year which was sown in early October. As the growing period advanced, however, the reverse occurred. For example, during the GS3 period of the experiment in the first year, temperatures, evaporative demands and radiation were higher. In both years, the number of irrigations

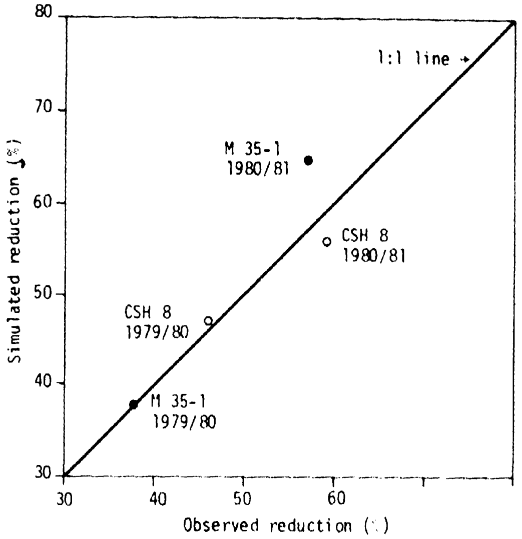

Fig. 5. Comparison between observed and simulated reduction in sorghum grain yield due to drought-stress for two sorghum cultivars in two post-rainy seasons at ICRISAT Center, Patancheru.

in the irrigated and drought-stressed treatments were five and three respectively, but the timings were different. In the first year sorghum was sown on 19 November 1979 and the field was irrigated to field capacity just after sowing; emergence occurred on 22 November. In the irrigated treatment four irrigations were given at 19, 39, 57, and 76 DAE. The drought-stressed treatment received two irrigations at 19 and 57 DAE. In the second year, sorghum was sown on 10 October 1980 followed by an irrigation on 11 October to charge the profile; emergence occurred on 13 October. In the irrigated treatment, four irrigations were given at 10, 28, 39, and 70 DAE. The drought-stressed treatment received two irrigations at 10, and 39 DAE. At each irrigation, in both experiments, the profile was fully charged.

Grain yields from the irrigated treatments were 3.8 t/ha for CSH 8 and 2.1 t/ha for M 35-1 in the first year, 6.1 t/ha for CSH 8 and 3.9 t/ha for M 35-1 in the second year. Grain yields from the drought-stressed treatment were 2.1 t/ha for CSH 8 and 1.3 t/ha for M 35-1 in the first year, 2.5 t/ha for CSH 8 and 1.7 t/ha for M 35-1 in the second year. Higher grain yields in the second year were due to changes in timing of sowing and irrigation schedule between two years. The correlation coefficient between observed and simulated grain yield data pooled over two water treatments, two cultivars, and 2 years was 0.92. A comparison between the observed and simulated percent reduction in grain yield due to drought-stress (Fig. 5) showed that the model was capable of simulating the impact of drought-stress on sorghum grain yield.

Simulating the response of sorghum to plant density. Observed and simulated grain yields of two sorghum cultivars (CSH 6 and SPV 351) are given as a

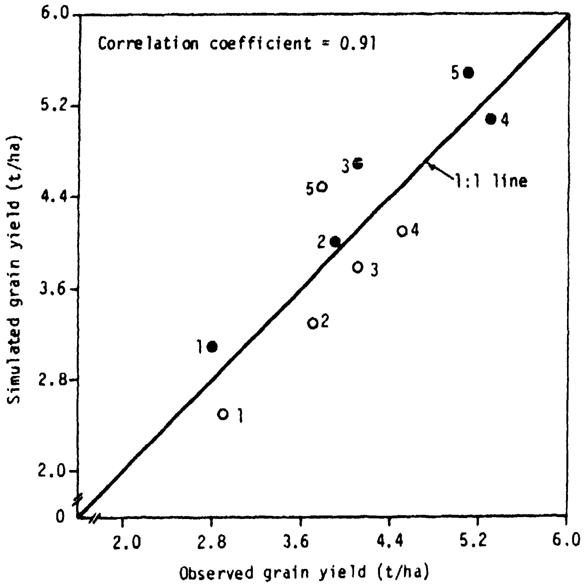

Fig. 6. Observed and simulated grain yield of two sorghum cultivars (● = CSH 6, ○ = SPV 351) under five levels of plant density (1 to 5 denotes lowest to highest plant density) in 1983 rainy season at ICRISAT Center, Patancheru.

function of plant density in Fig. 6. This experiment was conducted in a medium-deep Vertisol (150 mm available water holding capacity) at ICRISAT Center, Patancheru, with five levels of plant density ranging from 40 000 to 200 000 plants/ha. Sorghum was sown on 21 June 1983, and was grown rainfed (rainfall June to October, 1021 mm).

Both cultivars produced similar grain yields up to a density of 120 000 plants/ha, but above this CSH 6 gave higher grain yield than SPV 351. Simulated grain yields for CSH 6 were higher than SPV 351 at each plant density. Maximum grain yields were observed at 160 000 plants/ha for both cultivars (5.3 t/ha CSH 6, and 4.5 t/ha SPV 351). Further increase in plant density did not increase grain yield in CSH 6 but decreased grain yield in SPV 351. Simulated grain yields in both cultivars increased with increasing plant density and were between 3 and 15% of the observed data. The correlation coefficient between observed and simulated grain yield was 0.91 (Fig. 6).

Screening environments for sorghum production and input responses. The revised SORGF model was used to compute the probabilities of simulated sorghum grain yield for four locations in India using climatic data from 1941 to 1970. Mean annual rainfall for these locations is: 527 mm in Anantapur (14°41′N Lat., 77°37′E Long.); 792 mm in Patancheru (17°27′N Lat., 78°28′E Long.); 889 mm in Dharwar (15°27′N Lat., 75°00′E Long.); and 1001 mm in Indore (22°43′N Lat., 75°48′E Long.). Available water holding capacity of

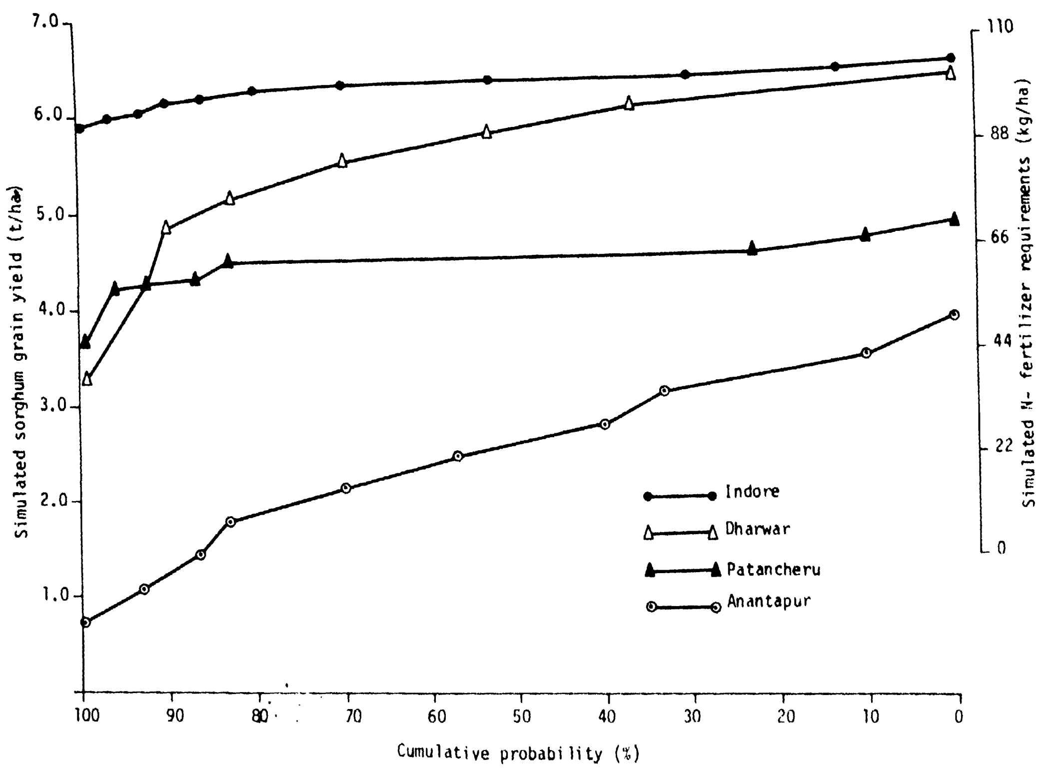

Fig. 7. Cumulative probability of simulated sorghum grain yield (more than a given amount) and simulated N-fertilizer requirements based on climatic data from 1941 to 1970 for four locations in India.

soils was 50 mm in Anantapur, and 150 mm in the other three locations. Simulated sorghum grain yields under adequate management (e.g., timely field operations, high yielding cultivar, recommended doses of nutrients and adequate plant protection measures) in 70% of the years were more than 2.2 t/ha for Anantapur, 4.5 t/ha for Patancheru, 5.5 t/ha for Dharwar, and 6.2 t/ha for Indore (Fig. 7). These results show that crops such as pearl millet would be better suited for Anantapur. Agroclimatic environments of Indore can be more profitably utilized by growing high value crops such as soybean and by adopting cropping systems (intercrop, sequential) capable of harnessing better soil water availability of this location (D. Sharma, Coordinator, On-Farm Research, ICRISAT, personal communication, 1986). Agroclimatic environments of Patancheru and Dharwar are suitable for sorghum-based cropping systems.

The probabilities of N-fertilizer requirements for these locations were simulted following the approach of Huda et al. (1985a) using the information given below:

(i) A total uptake of 20 kg N/ha was required to produce 1.0 t/ha sorghum grain yield (Kanwar and Rego, 1983);

(ii) N-uptake from unfertilized plot was 30 kg/ha (Singh and Das, 1984;

C.W. Hong, Soil Scientist, IFDC/ICRISAT Program, personal communication, 1985).

Based on the simulated sorghum yields, the N-fertilizer requirements in 70% of the years would have been at least 15 kg/ha in Anantapur, 60 kg/ha for Patancheru, 80 kg/ha for Dharwar, and 95 kg/ha for Indore (Fig. 7).

Developing a model for pearl millet. Because of the similarity in some of the growth and development processes of pearl millet and sorghum, a model for simulating growth and yield of pearl millet was developed following an appraoch similar to that of SORGF. In the SORGF model, sorghum was described as a single-culm plant and the leaf area was calculated from the input data on total number of leaves and maximum area for each leaf. Pearl millet generally produces tillers and this is a major difference between sorghum and pearl millet. Thus it would be very difficult to get input data of the total number of leaves and the maximum area for each leaf in pearl millet to calculate leaf area. The SORGF model simulates growth and yield of a single plant while, in the pearl millet model, an approach to simulate growth and yield over a unit area was used. The input data and the subroutines used in pearl millet model are briefly described.

— Input data: Climatic, soil, and location data requirements of the pearl millet model are similar to that of SORGF. For plant data, maximum leaf area index (LAI) is used instead of total number of leaves, and maximum area of each leaf.

— Phenology: Huda et al. (1984) studied the duration of three growth stages, emergence to panicle initiation (GS1), panicle initiation to flowering (GS2), and flowering to physiological maturity (GS3) for pearl millet cultivar BJ 104. Mean GDD values using a base temperature of 7 °C were 350 for GS1, 470 for GS2, and 570 for GS3. The coefficient of variation was 29% for GS1, 14% in GS2, and 9% for GS3. Since pearl millet has a quantitative short-day response, the duration of GS1 increased with increasing daylength. When daylength correction was introduced in the model, variability in GS1 was reduced to 10%.

— Leaf area development: An approach different from that of SORGF was used in the pearl millet model to simulate daily progression of leaf area. Potential maximum LAI (measured or assumed at flowering) was given as input data. Huda et al. (1984) reported that leaf area development in pearl millet (cv BJ 104) was slower than in sorghum (cv CSH 6) in GS1 and only 10% of the maximum LAI was achieved at panicle initiation. LAI increased linearly from 10 to 100% from panicle initiation to flowering, remained 100% for about a week after flowering, then dropped to 50% linearly at physiological maturity.

— Light interception: The subroutine on light interception from the revised SORGF model was used.

— Soil water: The subroutine on soil water from the revised SORGF model was used.
— Dry matter production and its partitioning: The relationship between intercepted PAR and dry matter of pearl millet (cv BJ 104) grown at ICRISAT was studied by Jarwal (1984), who reported that 2.2 g dry matter was produced for each MJ of radiation intercepted. Ong and Monteith (1985) reported the amount of dry matter produced per unit of intercepted radiation appeared to be conservative at about 2.4 g/MJ ($\pm 10\%$) for cultivar BK 560. These relationships were used in the pearl millet model to calculate potential dry matter accumulation. Net dry-matter accumulation was calculated using the water-stress coefficients calculated from the soil water availability. Partitioning of total dry matter among leaf, culm, head and grain at different growth stages was performed according to empirical data.
— Testing of pearl millet model: Simualted grain yields were compared with independent data of observed grain yields on pearl millet (cv BJ 104) from the rainy seasons of 1978 and 1980 to 1984. Simulated yields differed in the range of 2–12% of the observed yields in 5 years, when observed yields ranged from 2.2 to 2.9 t/ha, and was within 46% in 1 year when the yield was 1.7 t/ha. Observed grain yield in 1980 was very low because 190 mm rain fell in two days (19 and 20 August) which coincided with flowering. The pearl millet crop is sensitive to water logging as well as to water deficits.

CONCLUSIONS

The revised SORGF model can be used to screen environments for sorghum production and identify input- (e.g., fertilizer-) -responsive areas using the data on climate and soil. Responses of sorghum to drought stress and to changes in the plant density could be simulated using this model. Another important application of the SORGF model was its use as a framework to develop a pearl millet model. Further testing of the pearl millet model is required before it may be usefully applied.

ACKNOWLEDGEMENTS

This paper, earlier approved as ICRISAT Conference Paper No. 209, was presented in the symposium on Crop Yield Forecasting Methodology, 11–12 October 1984, organized by the Indian Agricultural Statistics Research Institute, New Delhi, India.

ICRISAT has published revisions made in the SORGF model under the citation: Huda, A.K.S., Sivakumar, M.V.K., Virmani, S.M., Seetharama, N., Singh, Sardar. and Sekaran, J.G., 1984. Modelling the effect of environmental factors on sorghum growth and development. In: Proceedings of the International Symposium on Agrometeorology of Sorghum and Millet in the Semi-Arid

Tropics, ICRISAT Center, India, 15–20 November 1982. ICRISAT, Patancheru, A.P. 502 324, India, pp. 277–287.

Data supplied by the cooperating scientists are gratefully acknowledged. The cooperators included Drs. R.S. Narang (Ludhiana), D.P. Singh (Hisar), S.K. Sinha (Delhi), G. Ramakrishna Rao (Parbhani), M.C. Varshneya (Rahuri), B.C. Biswas (Pune), S.S. Salunke (Sholapur), R. Kulandaivelu (Coimbatore), D.S. Murty and B.S. Talukdar (ICRISAT Center, Patancheru).

REFERENCES

Arkin, G.F. and Dugas, W.A., 1984. Evaluating sorghum production strategies using a crop model. In: Proc. Int. Symposium on Agrometeorology of Sorghum and Millet. ICRISAT, Patancheru, A.P., India, pp. 289-295.

Arkin, G.F., Vanderlip, R.L. and Ritchie, J.T., 1976. A dynamic grain sorghum growth model. Trans. ASAE., 19: 622-626, 630.

Brown, J.T. and Vanderlip, R.L., 1969. Relations of Palmer drought variable to yield of wheat. Agron. J., 61: 95-98.

Feyerherm, A.M. and Paulsen, G.M., 1981. Development of a wheat yield prediction model. Agron. J., 73: 277-282.

Fisher, R.A., 1924. The influence of rainfall on the yield of wheat at Rothamsted. Philos. Trans. R. Soc. London, Ser. B, 213: 89-142.

Gallagher, J.N. and Biscoe, P.V., 1978. Radiation absorption, growth and yield of cereals. J. Agric. Sci., Camb., 91: 47-60.

Gangopadhyaya, M. and Sarkar, R.P., 1964. Curvilinear study on the effect of weather on growth of sugarcane. Indian J. Meteorol. Geophys., 15: 215-226.

Huda, A.K.S. and Virmani, S.M., 1980. A systems analysis approach to developing cropping systems in the semi-arid tropics. In: D. Yaron and C. Tapiero (Editors), Operations Research in Agriculture and Water Resources. North-Holland, Amsterdam, The Netherlands, pp. 239-248.

Huda, A.K.S., Ghildyal, B.P., Tomar, V.S. and Jain, R.C., 1975. Contribution of climatic variables in predicting rice yield. Agric. Meteorol., 15: 71-86.

Huda, A.K.S., Virmani, S.M., Sivakumar, M.V.K. and Sekaran, J.G., 1980. Proceedings of a meeting on collaborative multilocation sorghum modeling experiment. Agroclimatol. Prog. Rep. 4, ICRISAT, Patancheru, A.P., India, 79 pp.

Huda, A.K.S., Sivakumar, M.V.K., Alagarswamy, G., Virmani, S.M. and Vanderlip, R.L., 1984. Problems and prospects in modeling pearl millet growth and development: A suggested framework for millet model. In: Proc. Int. Symposium on Agrometeorology of Sorghum and Millet. ICRISAT, Patancheru, A.P., India, pp. 297-306.

Huda, A.K.S., Sivakumar, M.V.K. and Rego, T.J., 1985a. An analysis of agroclimatic data in relation to fertilizer use in dryland farming areas of India. Fert. News, 30(2): 35-41.

Huda, A.K.S., Virmani, S.M. and Sekaran, J.G., 1985b. Simple models for predicting sorghum grain yield using environmental factors. J. Indian Soc. Agric. Stat., 37: 184-191.

Jarwal, S.D., 1984. Canopy architecture, light interception, water use, and dry matter production relationships in pearl millet (*Pennisetum americanum* [L.] Leeke). Ph. D. Thesis, Haryana Agricultural University, Hisar, Haryana, India, 203 pp.

Jordan, W.R., 1983. Whole plant responses to water deficits. An overview. In: H.M. Taylor, W.R. Jordan and T.R. Sinclair (Editors), Limitations to Efficient Water Use in Crop Production. American Society of Agronomy., Madison, WI, pp. 289-317.

Kanwar, J.S. and Rego, T.J., 1983. Fertilizer use and watershed management in rainfed areas for increasing crop production. Fert. News., 28(9): 33-43.

Major, D.J., 1980. Photoperiod response of characteristics controlling flowering of nine crop species. Can. J. Plant Sci., 60: 777-784.

Nix, H.A., 1976. Climate and crop productivity in Australia. In: Climate and Rice. International Rice Research Institute, Los Banos, The Philippines, pp. 495-508.

Ong, C.K. and Monteith, J.L., 1985. Response of pearl millet to light and temperature. Field Crops Res., 11: 141-160.

Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res., 8: 1204-1213.

Runge, E.C.A., 1968. Effects of rainfall and temperature interactions during the growing season on corn yield. Agron. J., 60: 503-507.

Schaffer, J.A., 1980. The effect of planting date and environment on the phenology and modeling of grain sorghum, (*Sorghum bicolor* [L.] Moench). Ph.D. thesis, Kansas State University, Manhattan, KS.

Singh, R.P. and Das, S.K., 1984. Nutrient management in drylands with special reference to cropping systems and semi-arid red soils. Proj. Bull. 8, All India Coordinated Research Project for Dryland Agriculture, Hyderabad, India, 56 pp.

Stapper, M. and Arkin, G.F., 1980. CORNF: A dynamic growth and development model for maize (*Zea mays* [L.]). Program and model documentation No. 80-2, Texas Agricultural Experiment Station, Temple, TX, 91 pp.

Stinson, D.L., 1979. A simulation-based soil and water resource evaluation for ratoon cropping grain sorghum in the central blacklands of Texas. M.S. Thesis, Texas A&M University, College Station, TX.

Thompson, L.M., 1969. Weather and technology in the production of corn in the U.S. corn belt. Agron. J., 61: 453-456.

Williams, J.R. and Hann, R.W. Jr., 1978. Optimal operation of large agricultural watersheds with water quality constraints. TR-96, Texas Water Resources Institute, Texas A&M University, College Station, TX.

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