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Modeling the Effect of Environmental Factors on Sorghum Growth and Development

1707

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Abstract

The yields of rainfed sorghum in the semi-arid regions in general are low and vary from year to year. An understanding of the interactions between the physical environment and the genotype is important to increase and stabilize production of sorghum. This information, through the systems-simulation approach, could be used to model sorghum growth and development. The grain sorghum growth simulation model—SORGF—was used as the basis to evaluate crop-weather interactions. A multilocation study was conducted in India over a period of 4 years to evaluate the growth and development of selected sorghum genotypes of varying maturity durations. Preliminary results suggested that several subroutines of the SORGF model needed modifications to simulate accurately the effect of environmental factors. Algorithms of the SORGF model dealing with light interception, phenology, leaf senescence, soil water, and total dry-matter accumulation and its partitioning to grain have been revised. The improvements resulting from the revisions made in each of the above subroutines are compared with the field data and the simulation results of the original SORGF model. The use of the SORGF model for irrigation scheduling and first-order screening of environments for sorghum production are illustrated.

Résumé

Facteurs environnementaux et la modélisation de la croissance et du développement du sorgho : En général, les rendements des cultures pluviales de sorgho dans les régions semi-arides sont faibles et varient d'une année à l'autre. Une compréhension des interactions entre le milieu physique et le génotype est importante pour augmenter et stabiliser la production de sorgho. Cette information sera utile à l'élaboration de modèles de croissance et de développement par l'approche de la simulation. Le modèle SORGF de simulation de la croissance du sorgho grain a servi de base pour l'évaluation des interactions entre le climat et la culture. Une étude multilocale fut menée en Inde pendant trois ans, afin d'évaluer la croissance et le développement de certains génotypes de sorgho à cycle variable. Les premiers résultats indiquent la nécessité de modifier plusieurs composantes du modèle SORGF, ce qui permettra de simuler avec précision l'effet des facteurs environnementaux. Les algorithmes du modèle SORGF portant sur l'interception de la lumière, la phénologie, la sénescence des feuilles, l'eau dans le sol, l'accumulation totale de matière sèche et sa répartition dans le grain ont été révisés. Le modèle perfectionné fut confronté avec les données réelles et les résultats de simulation du modèle SORGF de départ. L'emploi du modèle SORGF pour programmer les irrigations et l'évaluation préliminaire des milieux de culture du sorgho sont décrits.

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Sorghum (*Sorghum bicolor* [L.] Moench) is an important cereal with potential grain yields similar to other cereals. Sorghum grain yields of 16500 and 14250 kg/ha have been reported by Pickett and Fredericks (1959) and Fischer and Wilson (1975). However, at the farm level in the semi-arid tropics, the yields normally range from 300 to 1000 kg/ha under rainfed conditions. An understanding of the interactions between the physical environment and the genotype is essential to identifying the important factors for increased and stabilized production of sorghum. For example, most sorghum genotypes take 85 to 140 days to mature; hence the matching of the genotype with the soil-moisture availability period would be crucial to achieving higher biomass and grain yield. This would depend, however, on the maturity duration and the variability in environmental factors during the vegetative and reproductive growth stages.

A systems-simulation approach could be used to integrate the knowledge of crop growth and development and interaction with the environment. The grain sorghum growth simulation model SORGF (Arkin et al. 1976) was used as a basic model to evaluate crop-weather interactions. Many of the initial users suggested that several subroutines of the model needed to be modified to provide accurate simulation of sorghum growth and development in relation to environmental factors (Huda et al. 1980). Accordingly, these subroutines were revised, using detailed field measurements of interception of photosynthetically active radiation (PAR), leaf number and leaf area, soil water content, dry-matter production and distribution in different components, and phenology for different genotypes. Improvements made by these revisions in different subroutines and the overall model evaluation by using independent data sets are presented in this paper. The revisions made in the model were discussed in detail by Huda et al. (1983).

Experiments

A study was conducted at eight locations in India over a period of 4 years to evaluate the growth and development of selected sorghum genotypes of various maturity durations during the rainy and postrainy seasons with and without supplementary water given at different growth stages. Standard data sets on crop, soil, weather, and management factors were collected (Table 1). Crop phenology, light interception, water use, leaf initiation and expansion, and dry-matter accumulation and partitioning were studied in detail to evaluate the role of environmental factors in these processes. The effects of temperature and daylength on the panicle initiation, flowering, and maturity of these genotypes were studied. The rate of canopy development was monitored to examine its role in crop water use and light interception.

Table 1. Input data required for SORGF—a sorghum simulation model.

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

Source: Arkin et al. (1976).

Subroutines Revised

Phenology

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

Growth stage 1 (GS1)—Seedling emergence to panicle initiation.

Growth stage 2 (GS2)—Panicle initiation to anthesis.

Growth stage 3 (GS3)—Anthesis to physiological maturity.

In SORGF, the time from seedling emergence to panicle initiation is simulated as the sum of heat units (base temperature = 7°C and the upper limit of mean temperature = 30°C) and is a function of the maximum number of leaves. The time from emergence to anthesis is calculated as the simulated date the flag leaf was expanded plus 0.86 times the simulated number of days from panicle initiation to flag leaf appearance. The time from emergence to physiological maturity is calculated as 1.4 times the simulated number of days from emergence to anthesis. The effect of daylength and temperature was not systematically studied for developing the original SORGF model. The GS1 period is overestimated by SORGF, particularly at lower latitudes (e.g. ICRISAT Center, 17°N), probably as a result of the narrow data bases used in the development of the subroutines (e.g., only data from the USA, where daylengths are relatively longer).

Crop phenological data for almost all the growth stages were collected in 50 data sets, of which 10 were randomly selected for independent tests. The remaining 40 data sets were used to study phenological development in order to develop new algorithms.

The duration of GS1 was highly variable (Table 2), ranging from 17 to 31 days, with a mean of 23 days. The minimum and maximum length of GS1 was obtained for the same genotype (CSH-6) grown during the rainy season at different locations. The minimum duration was observed at ICRISAT Center and Parbhani (17°N); the maximum, at Ludhiana (31°N). To account for this variability, the data were further analyzed to establish the effect of daylength and temperature on phenological development.

The approach of Stapper and Arkin (1980) was used to calculate growing degree days (GDD) for sorghum with various threshold temperatures:

$$GDD = \Sigma \text{ (Mean temperature - base temperature)}$$

A cutoff temperature of 38°C, with a base of 7°C, was used. To take into account the higher variability in growth stages, the effect of daylength was also analyzed. Daylength at emergence was plotted against the GDD values for GS1 for hybrids CSH-1 and CSH-6 (Fig. 1). A similar relationship was proposed by Major (1980) for short-day plants and by Stapper and Arkin (1980) for corn.

For the present study, the threshold value of daylength was 13.6 h at emergence for two hybrids, CSH-1 and CSH-6.

Duncan's multiple range test values were computed for three growth stages. Differences in GS1 can be accounted for by daylength effect as shown in Figure 1. A similar effect was found for GS2, but no effect of daylength was observed for GS3.

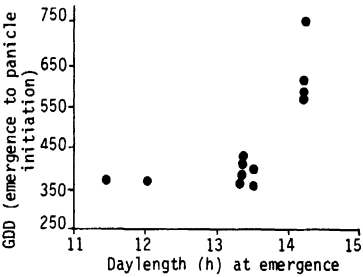

Figure 1. Relationship between growing degree days (GDD) from emergence to panicle initiation and daylength at emergence for sorghum hybrids CSH-1 and CSH-6.

Table 2. Duration (days) of different sorghum growth stages (data pooled over locations, seasons, and genotypes).

Growth stage	N[1]	Duration (days) Mean	SD	Minimum value	Maximum value	CV (%)
GS1	29	23	4	17	31	19
GS2	29	37	6	30	50	10
GS3	30	35	6	22	53	18
GS1+GS2	39	60	7	50	80	11
GS1+GS2+GS3	40	96	10	80	115	15

1. N = No. of observations.

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

$$GDD = 370 + 400^{*} (DAYEM - 13.6) \quad \text{if } DAYEM \geqslant 13.6 \text{ h}$$

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

The algorithm for describing DAYEM and GDD effects on GS2, derived in the same way as that for GS1, was:

$$GDD = 650 + 120^{*} (DAYEM - 13.6) \quad \text{if } DAYEM \geqslant 13.6 \text{ h}$$

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

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

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

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

These revised algorithms were tested against 10 independent field study data sets. The root mean square error (RMSE) for SORGF and the revised algorithms are given in Table 3. The RMSE for all three growth stages was considerably reduced by using the revised algorithms, compared with the original SORGF model; thus the simulated phenological events were close to the actual values.

Table 3. Root mean square error (days) for different growth stages of sorghum for 10 independent field-study data sets, using SORGF model and revised algorithms.

Growth stage	SORGF	REVISION
GS1	7	4
GS1 + GS2	7	6
GS1 + GS2 + GS3	18	3

Light Interception

The light interception portion of the model simulates the relative quantum flux intercepted by a single plant. Intercepted photosynthetically active radiation (PAR) is calculated on an hourly basis following a Beer's law relationship using solar radiation and light transmission values. Hourly solar radiation is computed from the input solar radiation, and by accounting for the number of hours of sunlight for any day, which is calculated as a sine function of the local solar time and daylength. Validations with data collected at ICRISAT Center showed that model computation of solar declination and daylength are accurate, resulting in sufficiently accurate estimation of hourly solar radiation. The quantum flux density in Einsteins/m² per day is estimated in SORGF from the energy flux density (RS) in cal/cm² per day as

$$PAR = RS(0.121)$$

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

$$PAR = RS\ (0.09)$$

Light transmission in SORGF is calculated from the relationship of extinction coefficient and maximum light transmission, using information on row spacings and leaf area index (LAI).

An examination of the computed and measured light transmission for different row spacings showed that the model was overestimating light transmission, especially at low levels of canopy light transmission, and that for row spacings of more than 137 cm, the SORGF model (Arkin et al. 1976) does not work, because computed light transmission exceeds 100%.

Comparison of predicted and measured light transmission for 45-cm rows, using the data sets collected at ICRISAT Center, are shown in Figure 2. Data points shown in Figure 2 deviate from the 1:1 line beyond the 15% limits at low levels of light transmission, and use of the revised equations substantially improves the predictability of light transmission.

Dry-matter Accumulation

In SORGF daily potential photosynthesis (DAYPOFO) is calculated in the PHOTO subroutine from intercepted PAR. In the SYNTH subroutine, the potential net photosynthesis (TOFOTO) is calculated as a function of DAYPOFO and the coeffi-

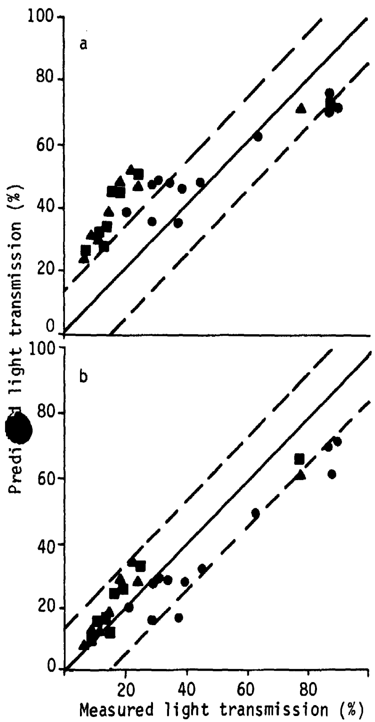

Figure 2. Relationship between measured and predicted light transmission in 45-cm sorghum rows according to (a) SORGF and (b) Revised algorithms (symbols represent data from different growing seasons).

cients of temperature stress (TEMPCO) and water stress (WATSCO) as described by Arkin et al. (1976). Net daily photosynthesis (TOFOTO) is then redefined by accounting for respiration. Daily increase in plant dry weight (DRIWT) is then determined in part from TOFOTO and soil surface area allocated for each plant.

Biscoe and Gallagher (1977) and Williams et al. (1965) showed that dry-matter production early in the season is related to the amount of radiation intercepted by the crop. Gallagher and Biscoe (1978) then showed that for wheat and barley grown at Sutton Bonington and Rothamsted, about 3 g of dry matter was produced for each MJ of PAR absorbed until ear emergence; for the whole crop, about 2.2 g of dry matter per MJ absorbed.

Dry-matter/intercepted PAR relationships were also examined at ICRISAT during the 1978 and 1979 growing seasons for sorghum (ICRISAT 1979, 1980). For several crops of sorghum, dry matter produced per MJ of absorbed PAR varied from 1.20 to 2.82 g, the lowest value corresponding to a nonirrigated crop during the postrainy season. The highest value was recorded for a sorghum crop that was irrigated at 10-day intervals in the postrainy season. From these observations, it seems reasonable to define a factor ALPHA (g of dry matter produced/MJ of PAR absorbed) and assign to it a value of 3.0 (Sivakumar 1981). This value defines an upper limit for cases with no water or temperature stress. The TEMPCO and WATSCO functions as defined in the model are then used to calculate daily dry-weight increase.

Dry-matter Partitioning

Partitioning of dry matter to plant parts varies according to the stage of development. Accurate simulation of grain yield depends upon the ability to correctly partition dry matter to grain and other plant parts.

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

Measured mean total dry matter (TDM) (g/plant) and percentage partitioned to the plant parts at panicle initiation (PI), anthesis (AN), and physiological maturity (PM) are given in Table 4. The TDM partitioned to the leaf decreases from 64 to 11% from PI to PM; that partitioned to the culm increases from 36 to 60% from PI to AN, then decreases to 36% again at PM. The TDM partitioned to grain at PM is 41%.

Table 4. Total dry-matter (TDM) and percent partitioned to leaf, culm, head + grain, and grain at three growth stages (data pooled over all genotypes, seasons, and moisture treatments; n=27).

	Panicle initiation		Anthesis		Physiological maturity	
	Mean	SD	Mean	SD	Mean	SD
Dry matter (%) partitioned to						
Leaf	0.64	0.04	0.24	0.04	0.11	0.02
Culm	0.36	0.04	0.60	0.06	0.36	0.07
Head+grain	0.00	0.00	0.16	0.04	0.53	0.08
Grain	0.00	0.00	0.02	0.01	0.41	0.08
TDM (g/plant)	1.60	1.20	35.20	15.00	67.40	23.30

Soil Water

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

Daily values of the water-stress coefficient (WATSCO) are simulated in the SOLWAT subroutine, using the current available soil water (SW) and the maximum amount of water (UL) in the profile. Values of UL are inputs of the model. Current available soil water (SW) is calculated in the model after Ritchie (1972). Values of potential evaporation from bare soil (E_o) and below a plant canopy (E_{os}) used in simulating SW are calculated in the subroutine EVAP. This approach could result in erroneous simulation of a true water-stress coefficient because the available soil water in the entire soil profile is not available to the plant in the early stages of crop growth.

A more representative coefficient could be obtained by considering an effective rooting depth function and calculating available soil water for the portion of the profile where roots are present. In order to incorporate this aspect in the computation of the water-stress coefficient, the extraction of drainage components developed by Williams and Hann (1978) was used. This approach consists a routing technique to predict flow through the root zone.

Amounts of plant-available water and their upper and lower limits for different layers of a 187-cm deep Vertisol were given by Russell (1980). Seasonal changes in modeled and measured available soil water for irrigated and nonirrigated sorghum on a deep Vertisol are shown in Figures 3 and 4, respectively. Available soil water predicted by the SORGF model is consistently higher than measured soil water. Available soil water summed over all the layers and using the new algorithm for calculation of R_o is referred to as "REVISION" here. REVISION estimates of soil water for irrigated sorghum are better than SORGF estimates, but still higher than the measured soil water amounts. For the nonirrigated sorghum, the REVISION estimates are excellent.

Use of a layered model provided consistently better estimates of WATSCO than SORGF when compared with field measurements (Table 5). For the nonirrigated sorghum, with progressive depletion of available soil water, the measured WATSCO decreased from 0.93 at 15 days after emergence (DAE) to 0.73 by 79 DAE, and WATSCO computed by the layered model also decreased to 0.72 by 79 DAE, while WATSCO predicted by SORGF stayed at 1.0 throughout the growing season. The use of the layered model appears to provide improved estimates of water-stress coefficients (WATSCO) to account for the effect of water stress on sorghum growth.

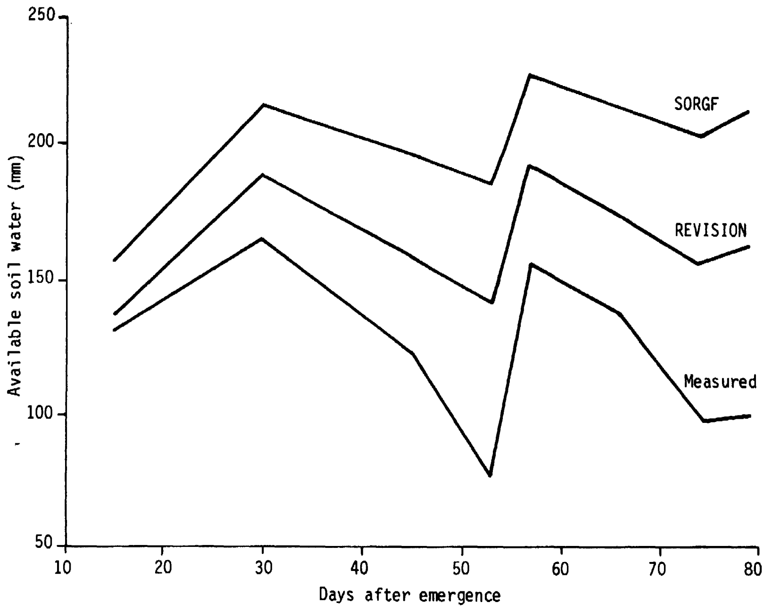

Figure 3. Seasonal changes in the available soil water for irrigated sorghum in a deep Vertisol, as shown by simulated (SORGF and REVISION) and measured values.

Leaf Development

Leaf area is overestimated by SORGF, particularly in the grain-filling period. Total number of leaves and maximum area of each leaf are input data requirements for SORGF. In SORGF, each leaf achieves its maximum area irrespective of moisture and temperature stress conditions. Leaf senescence is accounted for as follows: the first leaf senesces after the 11th leaf expands fully, and as each successive leaf expands fully, the next leaf senesces. No leaf senescence occurs after the last leaf is fully expanded. It was previously observed (Huda 1982) that when leaf 7 is fully expanded (leaf 8, 9, 10, ...), consecutive leaves from the bottom (leaf 2, 3, 4, ...) senesce. The maximum leaf area per plant was achieved at anthesis (Table 6) with a mean of 1710 cm^2 and a standard deviation of 622 cm^2. Leaf area at physiological maturity was 50% of that at anthesis. These results were included in the revised SORGF model.

Simulation Comparison

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

Emergence

The results of the emergence simulation were compared with the data obtained from 1981 rainy-season experiments conducted at ICRISAT Center. Dry seeding of sorghum (a practice recommended by ICRISAT for Vertisols) was done on a deep Vertisol (10 June) and on a medium-deep Vertisol (12 June), ahead of the monsoon. The available water-holding capacity of the deep Vertisol is 200 mm; that of the medium-deep, 165 mm. At the time of sowing the available water in the

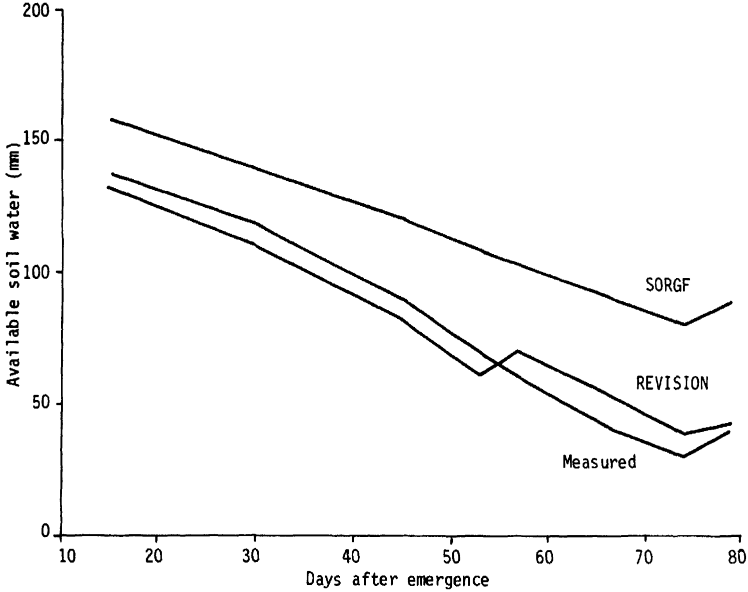

Figure 4. Seasonal changes in the available soil water for nonirrigated sorghum in a deep Vertisol, as shown by simulated (SORGF and REVISION) and measured values.

Table 5. Seasonal changes in water-stress coefficient (WATSCO) for a nonirrigated sorghum on a deep Vertisol, as simulated by two models and measured in the field.

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

Table 6. Leaf area (cm^2/plant) at three growth stages of sorghum (data pooled over all genotypes, seasons, and moisture treatments).

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

entire profile for the two fields was 65 and 29 mm respectively (above 10% of the entire profile for both fields). In SORGF, emergence is simulated when 70 heat units above 7°C base temperature accumulate after sowing, provided the available soil water for the entire profile is above 10%. Thus SORGF simulated emergence within 4 days after sowing, while actual emergence in the field occurred much later.

There was no available water in the top 30-cm layer in either field, and emergence in both these fields actually occurred only on 22 June after 35 mm rainfall was received on 18 June. The revised SORGF model with a layered soil water subroutine (top 0-30 cm and beyond 30 cm) simulated emergence date for both these fields as 21 June.

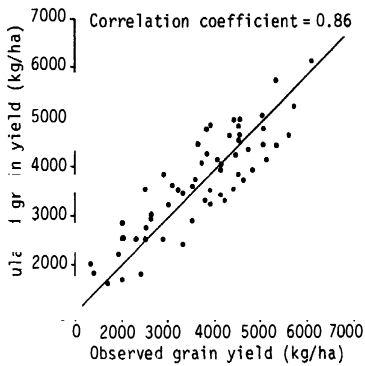

Figure 5. Relationship between observed and simulated grain yield (kg/ha) of sorghum according to revised sorghum model for pooled data (n = 59).

Phenology

The simulation of the course of phenological events, such as panicle initiation, anthesis, and physiological maturity, was compared with 19 observations obtained from 1981 experiments. The revised algorithms simulated the duration of GS1 (seedling emergence to panicle initiation) to within ±2 days of actual values in the field, whereas the SORGF simulated value was ±5 days. Similarly, revisions reduced the root mean square error (RMSE) in simulating the duration of the period from emergence to maturity from ±15 days to ±4 days.

Grain Yield

Improvements made in the model were tested with data sets obtained during 1981 at ICRISAT Center. Revisions in the model improved the coefficient of determination (R^2) by 35% (SORGF = 0.48, REVISION = 0.83) for grain yields. The root mean square error (RMSE) was reduced by the revision from 1423 kg/ha to 592 kg/ha.

We used pooled data (n=59) over different seasons and genotypes from ICRISAT Center and other cooperating centers to simulate the grain yield. The R^2 improved from 0.27 for SORGF to 0.74 for the revised model. The RMSE was reduced from 1479 kg/ha for SORGF to 591 kg/ha for the revised model. The relationship between observed and simulated grain yield for the pooled data is given in Figure 5.

Conclusions

The studies reveal that the effect of environmental factors on sorghum growth and development can be better understood from a standard set of crop, soil, and weather data. Such information would be useful in devising management practices to optimize yields in different environments.

First-approximation answers to questions on sorghum yield potential can be generated by this model, using climate and soil information. Answers to questions about the sorghum yield potential and the optimum crop-duration period to match the

Table 7. Simulated response of grain yield to supplemental irrigation at different growth stages of sorghum at Tombouctou, Mali (Simulation base: 43 years).

Supplemental irrigation at			Grain yield (kg/ha)		
Sowing	Panicle initiation	Anthesis	Mean	Maximum	Minimum
-	-	-	191	1798	0
X[1]	-	-	1725	2879	1586
X	X	-	2028	3174	1888
X	X	X	4249	4899	4094
X	-	X	4010	4657	3844

1. X = Irrigation of 100 mm.

water availability were sought by the Magarini Land Settlement Scheme in Kenya. May et al. (1981) used this model to delineate the cumulative probability distribution of simulated grain yields in Kenya for optimum sowing dates chosen from the rainfall probability analysis.

The model was used to construct cumulative probability distribution of sorghum grain yields for two locations (Bamako and Tombouctou) in Mali. Historical weather data (rainfall and temperature) for 49 years for Bamako and 43 for Tombouctou were used. Analysis showed that under adequate management conditions sorghum can be grown rainfed in Bamako, but in Tombouctou sorghum cultivation without irrigation could involve a high element of risk.

The mean annual rainfall for Tombouctou is only 195 mm; thus the model was also utilized to simulate the response of sorghum grain yield to supplemental irrigation (Table 7). Results showed that the model is sensitive enough to determine when and how much water should be applied to achieve optimum yield. For example, if only 200 mm irrigation water is available, it would be economical to use 100 mm at sowing for crop establishment and another 100 mm at anthesis for grain filling.

Some interagency projects would be required to evaluate the suitability of climatic environment for sorghum. Studies of the effect of environmental factors on growth and development of sorghum under controlled conditions would help supplement the information obtained from field studies.

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