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Observed and Simulated Responses of Two Sorghum Cultivars to Different Water Regimes

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ABSTRACT

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The responses to different water treatments of two sorghum (*Sorghum bicolor* (L.) Moench) cultivars, a hybrid (CSH 8) and a local variety (M 35-1), were studied on an Alfisol (Udic Rhodustalfs) at ICRISAT Centre, Patancheru during the post-rainy seasons of 1979/80 and 1980/81. Two water treatments, irrigated and drought-stress, were created by applying water five or three times during each of the growing seasons. Observed responses were compared with the simulated data using the sorghum simulation model SORGF. Neither observed nor simulated durations of growth stages were affected by drought-stress. Comparisons between observed and simulated duration of growth stages showed that the model simulated phenological development with good accuracy. Drought-stress coefficient calculations were based on the availability of water in the soil profile; simulated drought-stress coefficients agreed well with observed values. Observed and simulated grain yields of CSH 8 were higher than those of M 35-1 under both the irrigated and drought-stressed conditions. The correlation coefficients between observed and simulated total dry matter and grain yield data pooled over two water treatments, two cultivars, and two seasons were respectively 0.80 and 0.92. Comparisons between observed and simulated reductions in TDM and grain yield showed that the model is sufficiently sensitive to simulate the response of sorghum to drought-stress.

INTRODUCTION

Droughts of variable duration and intensity are common in the arid and semi-arid tropics where most of the world's grain sorghum (*Sorghum bicolor* (L.) Moench) production occurs (Jordan and Sullivan, 1982). Thus, the response of sorghum to drought-stress has received wide attention. The effects of water deficits on growth and development of sorghum were described by

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Garrity et al. (1982a, b). Howell and Hiler (1975) observed that the yield response of grain sorghum was not strongly related to total seasonal evapotranspiration (ET) but was highly dependent on the timing of ET deficit, which is regulated by environmental conditions.

A key factor in rational water use and irrigation scheduling in the semi-arid tropics would be development of the capability to predict the quantitative effects of drought stress. The relationship between ET and yield as developed for a number of crops (De Wit, 1958; Arkley, 1963; Stewart et al., 1975, 1977) could be used to develop models for predicting optimal water allocation. Crop simulation models driven by soil, climate and management factors could be effectively used as management tools to predict the effect of drought-stress on crop yield over a range of environmental conditions (Jordan and Sullivan, 1982).

Dugas et al. (1983) and the United States Department of Interior (USDI, 1983) using the sorghum simulation model SORGF developed by Arkin et al. (1976), attempted to assess agricultural drought (in terms of sorghum yield) and to ascertain how early in the season such assessments could be made. They compared modelled grain yield with the county and crop-reporting district yields for 30 years (1950–79) at four locations, Temple, Amarillo, and Lubbock in Texas, and Manhattan in Kansas. Some of the difficulties in this yield comparison study were as follows: i) observed yields were the average of several cultivars grown over a county and a crop-reporting district while the model needs cultivar-specific input data; ii) in the absence of information on actual plant density and planting date, only one plant density (148 200 plants ha^{-1}) across all locations and years, and one planting date (separate for each location) over all years were used as input data; and iii) the model simulates grain yield under adequate nutrient supply and plant protection measures, whereas these assumptions are difficult to meet when data from counties and crop-reporting districts are used. These difficulties partially explain why it was found that the correlation coefficients between modelled grain yield and county and crop-reporting district yields ranged from 0.2 to 0.5. It was also concluded that some 30 days or more before the end of the grain filling period the model's yield-predictive capability is weak.

The objective of this paper is to use the modified SORGF model (Huda et al., 1984) to compare experimental and simulated data on phenology, drought-stress coefficients, total dry matter, and grain yield of two sorghum cultivars (CSH 8, a high-yielding hybrid, and M 35-1, a medium-yielding local variety) under different water regimes in a semi-arid tropical environment.

MATERIALS AND METHODS

Experimental details

The experiments were conducted at ICRISAT Center, Patancheru, India (17°32′N Lat., 78°16′E Long.) during the post-rainy seasons of 1979/80

(November to March) and 1980/81 (October to February), on an Alfisol classified as a fine, clayey, mixed, hyperthermic Udic Rhodustalf (USDA Soil Taxonomy). The available water-holding capacity (between −0.03 and −1.5 MPa) of the 0.9-m soil profile was 85 mm. The experiment was laid out in a split-plot design with three replications. The main plots were the water treatments and the sub-plots were the cultivars. Adequate management practices (i.e. timely field operations, recommended fertilizer application, and plant protection measures) were used throughout the growing season.

In the first year, sorghum was sown at 0.05-m depth on 19 November 1979 and the field was irrigated to capacity just after sowing. Emergence occurred on 22 November. Two water regimes were generated by applying irrigations at 19, 39, 57, and 76 days after emergence (DAE) for the irrigated treatment and at 19 and 57 DAE for the drought-stressed treatment. The soil profile was fully recharged with water at each irrigation.

In the second year, sorghum was sown at 0.05-m depth on 10 October 1980 and irrigation was applied on 11 October to fully charge the profile; crops emerged on 13 October. For the irrigated treatment, additional irrigations were applied at 10, 28, 39, and 70 DAE. The drought-stressed treatment received irrigations at 10 and 39 DAE.

In both years, crops were sown on ridges at 0.75-m row spacing. At maturity, plant population was measured in a 50-m^2 area which was harvested for grain yield and for above-ground total dry matter (individual plants were cut at ground level). Though the initial plant population was 150 000 plants ha^{-1}, final plant density at harvest ranged between 120 000 and 150 000 plants ha^{-1}, except in the drought-stressed treatment of M 35-1 in the second year (85 000 plants ha^{-1}). Plant samples (from a 1.5-m^2 area) in each plot were taken at 8- to 10-day intervals for growth analysis and leaf area measurements. Area of individual leaves of all plants in a given plot was measured by using a leaf area meter (LI-3100 area meter, Lambda Instruments Corporation, Lincoln, Nebraska)*. Measurement of leaf area for individual leaves in the drought-stressed treatment commenced after the differential irrigations were imposed, i.e., 39 and 28 DAE during the 1979/80 and 1980/81 growing seasons, respectively. In order to determine the partitioning of dry matter in different treatments, each plant was separated into leaf, culm (stem + leaf sheath), panicle, and grain. Plant parts were dried to constant weight in a forced-draft oven at 65 °C then weighed. Ten plants were tagged at random in each replication at the beginning of each growing season to monitor the total number of leaves. Also, ten plants from each replication were observed for phenological development. A date for a particular phenological event (i.e. panicle initiation, anthesis, and physiological maturity) was given when 50% of the plants reached

*Mention of commercial products or companies does not imply endorsement or recommendation by ICRISAT, nor prejudice against any other manufacturer.

that stage of development. Gravimetric soil water measurements to the 0.9-m soil depth were taken (0.0–0.1, 0.1–0.3, 0.3–0.6, and 0.6–0.9 m) before and after each irrigation.

Model Description

The SORGF model, developed by Arkin et al. (1976) and modified by Huda et al. (1984) calculates growth and development of an average grain sorghum plant in daily increments under adequate plant protection and nutrient supply. Huda et al. (1984) revised and validated several subroutines of the SORGF model using data collected from multilocation field experiments. Revisions included incorporation of a multi-layered soil water balance sub-model, cultivar-specific information on daylength and temperature relationships for determining phenology, radiation interception and dry matter accumulation relationship, and cultivar-specific information on dry matter distribution patterns. The input data required by the model are described in Table 1.

Daily soil water is simulated in the model using the data on rainfall/irrigation, initial water content in the soil profile, and the available water-holding capacity of the soil, following the approach of Ritchie (1972). Evapotranspiration is determined from evaporation and transpiration, calculated separately. Evaporation is primarily dependent upon potential evapotranspiration (PET) and the number of days since the last significant rainfall/irrigation event. Ritchie (1973) reported that transpiration is dependent upon PET and the relative soil water level, RSW, defined as the ratio of available water on any day to the maximum available water-holding capacity of the rooted profile.

In the SORGF model, effects of daylength and temperature are taken into account for simulating durations from emergence to panicle initiation (GP1), and from panicle initiation to anthesis (GP2), while for duration from anthesis to physiological maturity (GP3), only the effects of temperature are considered. Huda et al. (1986) found that CSH 8 and M 35-1 had similar growing degree days (GDD) requirements (base temperature, 7°C); these were 370 for GP1, 650 for GP2 when daylength at panicle initiation was <13.6 h, and 620 for GP3.

Leaf area is simulated by the SORGF model from the input of total number of leaves produced by a cultivar and the maximum leaf area for an individual leaf. Potential dry matter accumulation is calculated from intercepted radiation, and net dry matter accumulation is calculated taking into account water and temperature stress. Partitioning of dry matter to different plant parts is based on the stage of development of the plant. Final grain yield per unit area is calculated by multiplying plant density with the grain weight per plant at physiological maturity (PM).

TABLE 1

Input data required for sorghum simulation model SORGF

Cultivar data	
	Leaf number - total number of leaves produced
	Leaf area - maximum area of each leaf
	Daylength and temperature relationship for phenology
	Dry-matter distribution pattern
Agronomic data	
	Sowing date
	Final plant population
	Row width
	Depth of sowing
Weather 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

RESULTS AND DISCUSSION

Growing season weather conditions

The environmental conditions of the two years (1979/80 and 1980/81) differed (Table 2). The GP1 period in the first year (sown in late November) was characterized by lower temperatures, lower radiation, and consequently lower evaporative demand than that in the second year, when sowing took place in early October. As the growing period advanced, however, the reverse occurred. For example, the grain-filling period (GP3) of the experiment in the first year was exposed to higher temperatures, higher radiation, and consequently higher evaporative demands.

The number of irrigations in the irrigated and drought-stressed treatments

TABLE 2

Summary of phenological-period weather data during the crop-growing seasons of 1979/80 and 1980/81

Parameter*	Emergence to panicle initiation		Panicle initiation to anthesis		Anthesis to physiological maturity	
	1979/80	1980/81	1979/80	1980/81	1979/80	1980/81
Total rainfall (mm)	8	6	0	0	4	18
Maximum temperature (°C)	28.3	31.3	28.3	29.2	32.2	27.0
Minimum temperature (°C)	17.0	17.0	14.9	14.8	17.4	14.7
Pan evaporation (mm)	4.0	6.0	4.9	5.5	7.1	4.9
Solar radiation ($MJ\ m^{-2}$)	16.6	20.0	17.1	18.1	20.0	16.7

*Except for rainfall, all values are daily averages.

was five and three, respectively, in both years but the timing of the irrigations was different. Because of lower evaporative demand during the early growing season in the first year (Table 2), the second irrigation was applied at 19 DAE (almost at the end of GP1). In 1980/81 the second irrigation was applied at 10 DAE (middle of GP1).

Drought-stress coefficients

Arkin et al. (1976) defined the drought-stress coefficient as 1.0 (suggesting no drought stress) if RSW is above 0.4, the coefficient decreasing linearly from there to 0.0 when RSW is 0.0. Since both sorghum cultivars showed similar observed water-depletion patterns, observed and simulated drought-stress coefficients for only CSH 8 are shown in Table 3. Results showed that even in the irrigated treatment both observed and simulated drought-stress coefficients were below 1.0 for some time, indicating the occurrence of mild drought stress. Simulated drought-stress coefficients agreed well with the observed values.

Phenology

In this experiment, it was found that the duration of growth periods for both cultivars was similar except for GP2 in the first year and GP1 in the second year. In both situations, M 35-1 had six days' longer duration (Table 4). No

TABLE 3

Observed and simulated drought-stress coefficients for two water treatments in 1979/80 and 1980/81 for sorghum cultivar CSH 8 at ICRISAT Center, Patancheru (see text for explanation)

Year	Days after emergence	Drought-stress coefficients			
		Irrigated		Drought-stressed	
		Observed	Simulated	Observed	Simulated
1979/80	17	1.0	1.0	1.0	1.0
	19	1.0	1.0	1.0	1.0
	37	1.0	1.0	1.0	1.0
	39	1.0	1.0	-*	1.0
	55	0.8	1.0	0.0	0.2
	57	1.0	1.0	1.0	1.0
	74	0.6	0.9	0.6	0.9
	76	1.0	1.0	-	0.7
	98	0.5	0.3	0.2	0.0
1980/81	8	1.0	1.0	1.0	1.0
	10	1.0	1.0	1.0	1.0
	26	1.0	1.0	1.0	1.0
	28	1.0	1.0	-	1.0
	37	1.0	1.0	0.5	0.7
	39	1.0	1.0	1.0	1.0
	68	0.6	0.5	0.7	0.5
	70	1.0	1.0	-	0.4
	106	0.7	0.7	0.3	0.0

*-Not measured

marked effect of drought-stress on the duration of phenological periods was observed in this experiment. The data in Table 4 show that the model simulated phenological development fairly well. For example, the root mean square error for the durations of GP1 and GP3 was ±4 days and for GP2 ±3 days.

Leaf number and leaf area

The number of leaves (the first emerging leaf labelled as leaf number 1) produced by CSH 8 and M 35-1 in the irrigated treatment in both years was 16 and 17, respectively; the drought-stressed treatment produced one leaf fewer in both cultivars (Fig. 1). A similar response was reported by Kannangara et al. (1983). The SORGF model does not account for changes in total leaf number due to drought stress.

The measured maximum area of each leaf for both irrigated and drought-stressed treatments is shown in Fig. 1. As differential irrigation treatment

TABLE 4

Comparsions between observed (O) and simulated (S) durations of growth stages of two sorghum cultivars for irrigated (I) and drought-stressed (D) treatments

Year	Cultivar	Water treatment	Duration (days)					
			Emergence to panicle initiation		Panicle initiation to anthesis		Anthesis to physiological maturity	
			O	S-O	O	S-O	O	S-O
1979/80	CSH 8	I	19	+4	41	+4	38	−4
		D	19	+4	43	+2	35	−1
	M 35-1	I	21	+2	46	−1	38	−4
		D	19	+4	50	−5	36	−2
1980/81	CSH 8	I	22	0	44	−1	40	+4
		D	22	0	42	+1	38	+6
	M 35-1	I	28	−6	43	0	42	+2
		D	28	−6	42	+1	41	+3
	Root mean square error			±4		±3		±4

started only after panicle initiation, data for the first six leaves for both water treatments refer to plots designated as the irrigated treatment. A reduction in leaf size due to drought stress was observed from the seventh leaf onwards in

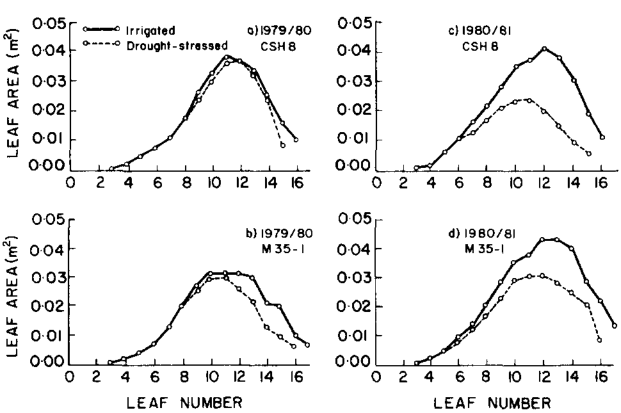

Fig. 1. The maximum area of each leaf (m^2) for two sorghum cultivars (CSH 8 and M 35-1) for irrigated and drought-stressed treatments in 1979/80 and 1980/81 at ICRISAT Center, Patancheru.

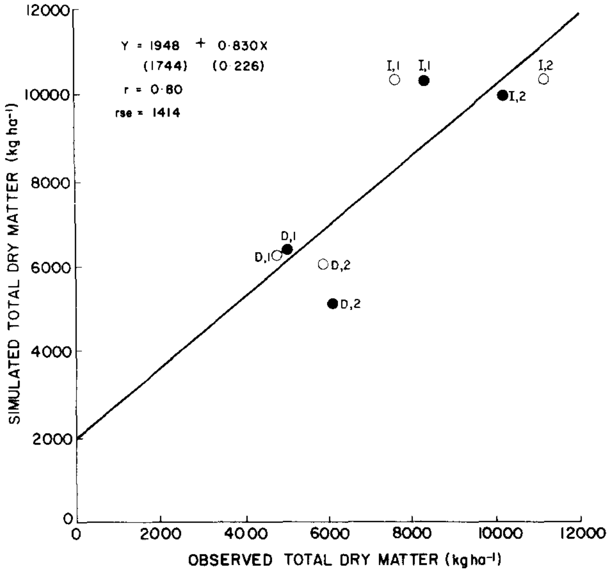

Fig. 2. Relationship between observed and simulated total dry matter of two sorghum cultivars (o = CSH 8, ● = M 35-1) in the irrigated (I) and drought-stressed (D) treatments in two seasons (1 = 1979/80, 2 = 1980/81) at ICRISAT Center, Patancheru.

1980/81, and from the ninth in 1979/80. The maximum area for comparable leaves in the irrigated treatments was generally greater in 1980/81. Differences in maximum leaf area between irrigated and drought-stressed treatments were also greater in 1980/81. This phenomenon may be associated with differences in timing of irrigations between two years.

Total dry matter

Observed total dry matter (TDM) for both cultivars was greater in 1980/81 than in 1979/80 in both the irrigated and drought-stressed treatments (Fig. 2). Simulated TDM was higher than the observed values in 1979/80, while the model underestimated TDM in 1980/81. The differences in observed TDM between years may have been due to changes in timing of sowing and irrigation scheduling. The higher TDM in 1980/81 was related to the higher rate of dry matter accumulation during the grain-filling period (GP3); the values in the irrigated treatments were 7 and 15 g m^{-2} d^{-1} for CSH 8, and 5 and 13 g m^{-2} d^{-1} for M 35-1, in 1979/80 and 1980/81, respectively. The rate of dry matter accumulation in GP3 was considerably reduced in both cultivars due to drought stress, more so in 1980/81 than in 1979/80.

The correlation coefficient between observed and simulated TDM pooled over two water treatments, two cultivars, and two seasons was 0.80 (Fig. 2).

The intercept was not significantly different from 0.0 and the slope was not significantly different from 1.0. Reductions in observed TDM due to drought stress were respectively 37 and 47% for CSH 8 in 1979/80 and 1980/81, and 40% for M 35-1 in both years. Reductions in simulated TDM due to drought stress were respectively 40 and 42% for CSH 8, and 39 and 49% for M 35-1, in 1979/80 and 1980/81.

Grain yield

Observed grain yield of CSH 8 was considerably higher than that of M 35-1 in both irrigated and drought-stress treatments (Fig. 3). This was because of greater grain numbers (Table 5), and higher rates of dry matter accumulation in the grain filling period, and consequently a higher percentage of TDM partitioned to grain (harvest index) at PM in CSH 8 than in M 35-1. Individual grain weight was the same for the two cultivars except in the drought-stressed treatment in 1979/80, when CSH 8 had higher grain weight. Harvest indexes (HI) in the irrigated treatments were 0.50 and 0.55 for CSH 8, and 0.26 and 0.39 for M 35-1, in 1979/80 and 1980/81, respectively. In the drought-stressed treatments these values were 0.43 and 0.42 for CSH 8, and 0.26 and 0.27 for M 35-1, in 1979/80 and 1980/81, respectively. Reductions in observed grain yield due to drought stress were 46 and 59% for CSH 8, and 38 and 58% for M 35-1, in 1979/80 and 1980/81, respectively.

Belum V.S. Reddy (Sorghum breeder, ICRISAT, personal communication, 1985) suggested, based on data from several field experiments, that average HI was 0.50 and 0.27 for CSH 8 and M 35-1, respectively; these values were input into the simulation of grain yield (Fig. 3A). The correlation coefficient between observed and simulated grain-yield data, pooled over two water treatments, two cultivars, and two years, was 0.77. The intercept was not significantly different from 0.0, and the slope was not significantly different from 1.0. Reductions in simulated grain yield due to drought stress were 40 and 42% for CSH 8, and 39 and 49% for M 35-1, in 1979/80 and 1980/81, respectively.

Grain yields were also simulated using the HI data observed in these experiments (Fig. 3B); the correlation coefficient between observed and simulated grain yield was 0.92. The intercept was not significantly different from 0.0, and the slope was not significantly different from 1.0. Reductions in simulated grain yield due to drought stress were 47 and 56% for CSH 8, and 38 and 65% for M 35-1, in 1979/80 and 1980/81, respectively.

CONCLUSIONS

Results of this study showed that grain yields of sorghum hybrid CSH 8 were higher than those of local sorghum variety M 35-1 in both irrigated and drought-stressed treatments. This was because of higher rates of dry matter accumu-

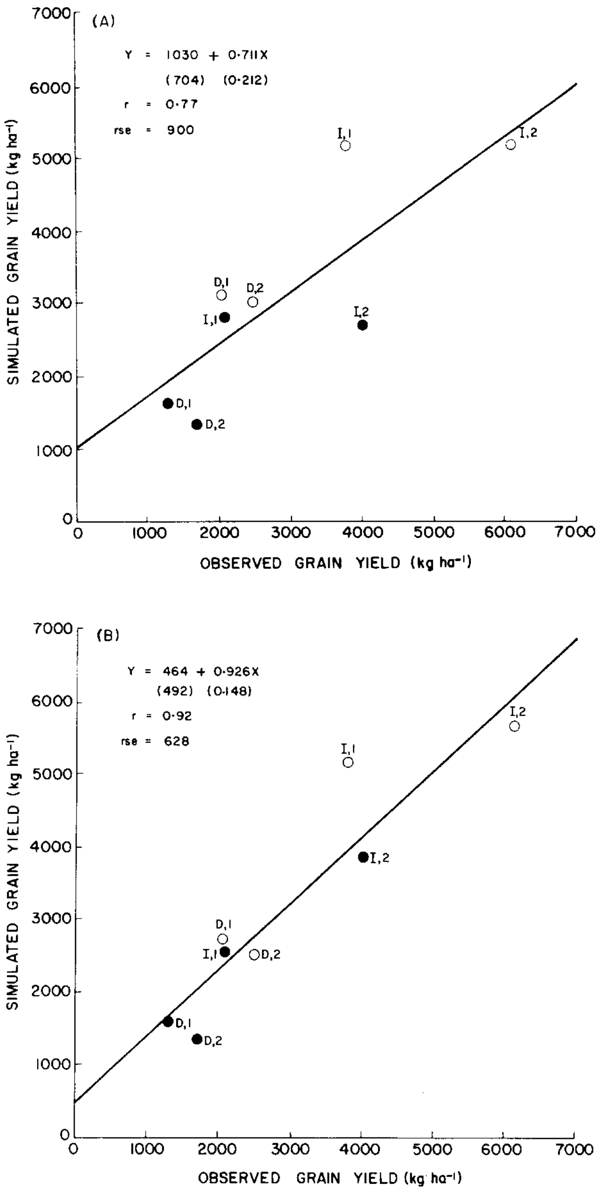

Fig. 3.Relationship between observed and simulated* grain yield of two sorghum cultivars (o = CSH 8,● = M35-1) in irrigated (I) and drought-stressed (D) treatments in two seasons (1 = 1979/80, 2 = 1980/81) at ICRISAT Center, Patancheru.
*A: Using harvest indexes of 0.50 for CSH 8 and 0.27 for M 35-1 as given by Belum V.S. Reddy, Sorghum breeder, ICRISAT, personal communication, 1985.
B: Using harvest indexes as observed in the present experiments.

TABLE 5

Plant population at harvest, grain number, and grain weight of two sorghum cultivars for irrigated (I) and drought-stressed (D) treatments

Year	Cultivar	Water treatment	Plant population (plants/ha)	Grain number per plant	Grain weight (mg)
1979/80	CSH 8	I	143 000	735	35.28
		D	125 000	496	34.21
	M 35-1	I	150 000	403	34.82
		D	150 000	287	30.21
	SE 1*			±55.7	±2.567
	SE 2			±46.1	±1.078
1980/81	CSH 8	I	132 000	1198	39.26
		D	129 000	614	31.58
	M 35-1	I	120 000	885	39.94
		D	85 000	661	31.39
	SE1			±88.3	±2.607
	SE 2			±77.0	±2.368

*SE1 = Standard error for comparing two water treatment means for the same cultivar.
SE2 = Standard error for comparingtwo cultivar means for the same water treatment.

lation in the grain-filling period, greater grain numbers, and higher harvest index in CSH 8 than in M 35-1. Comparisons between observed and simulated data on phenology, drought-stress coefficients, TDM, and grain yield showed that the model is capable of accurately simulating the response of sorghum to drought stress. However, more quantitative information, particularly on the effects of drought-stress imposed at specific growth periods, is necessary in order to develop strategies for water management practices and to make further improvements in the SORGF model.

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