589

Reprinted from *Agronomy Journal*
Vol. 80, No. 3

Simulating Growth and Yield Responses of Sorghum to Changes in Plant Density

A. K. S. Huda*

ABSTRACT

Though numerous field experiments have been conducted on the effects of plant density on growth and yield of sorghum [*Sorghum bicolor* (L.) Moench], tests showing the ability and validity of a sorghum simulation model to respond to changes in plant density have not been reported previously. Thus, a field experiment was conducted at ICRISAT Center, Patancheru, India, in the 1983 rainy season on a Vertisol (fine, clayey, montmorillonitic, isohyperthermic Typic Pellustert) to test the validity of the sorghum simulation model, SORGF, for simulating the effect of plant density on growth and development of sorghum. Simulations were compared to data collected on phenology, leaf area indices (LAI), total dry matter (TDM), and grain yield for five plant densities (4, 8, 12, 16, and 20 plants m^{-2}) of two sorghum cultivars (CSH 6 and SPV 351). Observed TDM and grain yield increased up to 16 plants m^{-2}, while simulated TDM and grain yield increased up to 20 plants m^{-2}. The model, on average, underestimated TDM by 8% and overestimated grain yield by 2%. Good agreement between observed and simulated LAI, TDM, and grain yield across five plant densities and two cultivars was supported by the insignificant differences of observed and simulated values from a one-to-one line. The model was further validated using climatic data from the ICRISAT Center between 1976 and 1984. Simulated grain yield using plant densities of 12 plants m^{-2} were within 3% in 6 yr and between 11 and 20% in the other 3 yr of observed data using plant densities of 13 plants m^{-2}. Results from this study suggest that the SORGF model appears useful for simulating the effect of plant density on the growth and yield of well-managed sorghum when input data on cultivar, climate, soil, and agronomic management are available.

***Additional Index Words:* *Sorghum bicolor* (L.) Moench, Phenology, Leaf area index, Dry-matter accumulation, Dry-matter distribution, Simulation model.**

THE EFFECT of plant density on grain yield of sorghum has been extensively studied (Stickler and Younis, 1966; Blum, 1967, 1970; Natarajan and Willey, 1980; Myers and Foale, 1981). Fischer and Wilson (1975) at Redland Bay, Queensland, Australia, reported that maximum grain yield (14 t ha^{-1}) of sorghum (cv. RS 610) was obtained at the highest plant density of 64.5 plants m^{-2}. Freyman and Venkateswarlu (1977) found that under rainfed conditions in Alfisols of the Deccan plateau in India, maximum (11 t ha^{-1}) sorghum (cv. CSH 5) grain yields were obtained at the highest plant density (22 plants m^{-2}). On the other hand, Balasubramanian et al. (1982) observed from their study under dryland management conditions at Hyderabad, India, that sorghum grain yields increased from 3.9 to 4.2 t ha^{-1} with an increase in plant density from 7.5 to 12.5 plants m^{-2}, but decreased at still higher plant densities (3.8 t ha^{-1} at 17.5 plants m^{-2} and 3.5 t ha^{-1} at 22.5 plants m^{-2}).

The results obtained from field experiments tend to be location-specific. Hence, crop simulation models based on crop, soil, weather, and management data may be used as research tools for generalization of research findings and to generate recommendations for specific locations (Jordan and Sullivan, 1982). Though numerous field experiments have been conducted to study the effect of plant density on the growth and yield of sorghum, tests showing the ability and validity of a sorghum simulation model to respond to changes in plant density have not been reported. An experiment was conducted to test whether the sorghum simulation model, SORGF, developed by Arkin et al. (1976) and modified by Huda et al. (1984), can be used to simulate growth and yield responses of sorghum due to changes in plant density. The SORGF model calculates daily growth and development of an average grain sorghum plant under adequate management (sufficient plant protection and recommended doses of nutrients) in a field stand. It accounts for phenology, leaf area development, light interception, and water use. Daily potential dry-matter production is calculated from radiation intercepted per day, and the net dry-matter gain per day is calculated by accounting for temperature and drought stress. Distribution of dry matter into different plant parts is based on the plant developmental stage and on cultivar characteristics. The final total dry matter (TDM) and grain yield per unit land area are determined by multiplying the TDM and grain yield of a single plant at physiological maturity (PM) by the plant density, respectively.

The objectives of this study were (i) to test the validity of the SORGF model compared to observed data on phenology, leaf area index (LAI), TDM, and grain yield for five plant densities of two sorghum cultivars, CSH 6 and SPV 351, and (ii) to simulate grain yield of sorghum for five plant densities using climatic data from the ICRISAT Center between 1976 and 1984, comparing observed grain yields for a plant density of 13 plants m^{-2} in those years, to the simulated grain yields.

MATERIALS AND METHODS

Field Experiments

The plant density experiment was conducted at the ICRISAT Center, Patancheru, near Hyderabad, India (17°32′ N Lat., 78°16′ E Long.) during the 1983 rainy season on a Vertisol. Plant extractable water in the top 1.27 m of the profile is 0.15 m; the upper and lower limits of plant extractable water in the profile are 0.55 and 0.40 m, respectively. The upper limit is defined (Russell, 1980) as the amount of water retained by an uncropped profile following cessation of drainage after infiltration of water in excess of that required to fully recharge it. The lower limit is defined (Russell, 1980) as the minimum water content remaining throughout the profile as measured in the field after growth of a well-managed, deep-rooted, long-season crop grown in the postrainy season with no irrigation.

The experiment was conducted using a split-plot design with three replications. Five plant densities ranging from 4 to 20 plants m^{-2} formed the main plots (30 by 12 m), and

Resource Management Program, ICRISAT, Patancheru, Andhra Pradesh 502 324, India. Submitted as Journal Article no. 624 by ICRISAT. Received 6 May 1986. *Corresponding author.

Published in Agron. J. 80:541-547 (1988).

two sorghum cultivars (CSH 6 and SPV 351) formed the subplots (15 by 12 m). CSH 6 is an early maturing, high-yielding hybrid. SPV 351 is a medium maturing variety that has a lower harvest index than CSH 6 and thus usually yields less than CSH 6. Planting was done at the 0.05-m depth on 0.75-m ridges on 21 June 1983, and seedling emergence occurred on 25 June. A basal dose (pre-planting) of 2.5 g N m^{-2} and 3.0 g P m^{-2}, and top dressings of 7.5 g N m^{-2} at 22 d after emergence (DAE) and 4.0 g N m^{-2} each at 39 and 55 DAE were applied. Adequate plant protection measures were undertaken to minimize the effects of diseases and insects.

Plant samples were harvested from 1-m lengths of two rows (1.5-m^{-2} area) in each replication at 8- to 10-d intervals. After plant numbers from the samples of three replications were recorded, green leaf area was measured for individual plants from only one replication (using an LI-3100[1] leaf area meter; LI-COR, Lincoln, NE). At anthesis and PM, green leaf area was measured for individual plants sampled from three replications. To determine the distribution of dry matter in different treatments, all harvested plants from each replication were separated into leaf, culm (stem plus leaf sheath), head (includes grain), and grain. Plant parts were dried to constant weight in a forced-draft oven at 65°C and weighed.

Crop phenology, i.e., panicle initiation (PI), anthesis, and PM, was monitored using 10 plants randomly selected from each subplot at regular intervals. A date for phenological events was established when 50% of the plants in each replication had reached that stage of development.

SORGF Simulation

Climatic input data needed (daily rainfall, maximum and minimum air temperatures, and solar radiation) to operate the model were recorded at the ICRISAT Meteorological Observatory located about 300 m south of the experimental plot. Other input data such as latitude, planting date and depth, row spacing, plant density, and available water holding capacity of soils have already been described. The amount of available soil water present at planting was 0.05 m. Crop input data (total number of leaves and maximum area for each leaf) used for the simulations are given in Table 1.

Table 1. Input data on number of leaves and maximum area for each successive leaf for sorghum cultivars CSH 6 and SPV 351. These data were common for all plant densities and came from previous studies at the ICRISAT Center.

	Sorghum cultivar	
Leaf number	CSH 6	SPV 351
	$m^2 \times 10^{-4}$	
1	0.9	0.8
2	2.3	1.7
3	6.0	4.9
4	11.4	11.0
5	24.3	22.2
6	45.4	45.4
7	69.9	93.4
8	123.5	148.8
9	172.0	202.2
10	271.8	326.2
11	335.9	406.6
12	387.0	490.9
13	429.9	492.3
14	398.6	417.4
15	342.8	326.0
16	226.6	243.2
17	144.6	147.1

[1] Mention of commercial products or companies does not imply endorsement or recommendation by ICRISAT.

These data were determined from previous (1981 rainy season) experiments at the ICRISAT Center (Huda et al., 1982), and were used as common input data within a cultivar for all plant densities in this simulation study. Though there was no difference between the two cultivars in total number of leaves, maximum areas of leaves (particularly from the seventh to the fourteenth) were greater in SPV 351 than CSH 6.

Based on data collected from field trials at nine locations in India (11–31°N) during 1979 to 1982, Huda et al. (1984) revised and validated the following relationships in SORGF. These revisions included incorporation of cultivar-specific relationships of the effect of daylength and temperature to determine durations of growth periods, relationship between dry-matter accumulation and radiation interception, a layered soil-water model, and cultivar-specific coefficients to distribute total dry matter among plant parts. The effects of daylength were not considered by Arkin et al. (1976) in developing the original phenology subroutine. Thus, data from multilocation trials were analyzed by Huda et al. (1984) to establish the combined effect of daylength and temperature on the duration of three growth stages as defined by Eastin (1972), i.e., emergence to PI (GS1), PI to anthesis (GS2), and anthesis to PM (GS3). Previous studies (Huda et al., 1982) have shown CSH 6 and SPV 351 to have significant differences only for GS1. The approach of Stapper and Arkin (1980) was used to calculate growing degree days (GDD) as follows:

$$\mathrm{GDD} = \frac{\text{daily (minimum + maximum) air temperature}}{2} - \text{base temperature}.$$

A base temperature of 7°C and a cutoff temperature (upper limit of maximum temperature) of 38°C were used in GDD calculations. Algorithms for relating the effect of daylength at emergence (DAYEM) and GDD for GS1 are as follows:

For CSH 6,

$$\mathrm{GDD} = 370 + 400 \times (\mathrm{DAYEM} - 13.6), \text{ if DAYEM} \geq 13.6 \text{ h};$$
$$\mathrm{GDD} = 370, \text{ if DAYEM} < 13.6 \text{ h}.$$

For SPV 351,

$$\mathrm{GDD} = 560, \text{ if DAYEM} < 13.6 \text{ h};$$

Data for this cultivar above a 13.6-h daylength were not available.

Algorithms for relating DAYEM effects to GDD for GS2 are as follows:

$$\mathrm{GDD} = 650 + 120 \times (\mathrm{DAYEM} - 13.6), \text{ if DAYEM} \geq 13.6 \text{ h};$$
$$\mathrm{GDD} = 650, \text{ if DAYEM} < 13.6 \text{ h}.$$

The duration of GS3 was determined only by temperature, and the GDD requirement for GS3 was 620.

For this study, a simple relationship of 3.75 g of potential dry matter accumulated for each megajoule of radiation intercepted was used. Separate coefficients for dry-matter accumulation efficiency are used in the model for the rainy season (3.75 g MJ^{-1}), postrainy season (3.0 g MJ^{-1}), and dry season (2.25 g MJ^{-1}), to account for the saturation vapor pressure deficit of the environment (Huda and Ong, 1988). The saturation deficit is usually less than 1 kPa in the rainy season, between 1 and 2 kPa in the postrainy season, and greater than 2 kPa in the dry season in the semi-arid environment of Hyderabad, India (Monteith, 1986a). Daily net

Table 2. Summary of sorghum phenological and weather data during the 1983 rainy season at the ICRISAT Center, Patancheru, A.P., India.†

Phenology/weather parameters‡	Emergence to panicle initiation (GS1)		Panicle initiation to anthesis (GS2)		Anthesis to physiological maturity (GS3)	
	CSH 6	SPV 351	CSH 6	SPV 351	CSH 6	SPV 351
Observed						
Duration (days)	19	27	34	40	33	35
LSD (0.05) to compare cultivars	1		1		1	
Simulated						
Duration (days)	17	26	34	34	34	34
Total rainfall (mm)	93	125	351	426	297	315
Maximum temperature (°C)	32.8	32.4	29.6	29.2	29.0	28.7
Minimum temperature (°C)	23.6	23.6	22.7	22.6	22.4	22.1
Open pan evaporation (mm)	8	7	5	4	4	4
Solar radiation (MJ m^{-2})	15.7	15.4	14.1	14.6	14.9	14.1

† All values except rainfall are daily averages. ‡ Data on observed phenology are averaged over five plant densities and three replications.

dry-matter gain is calculated by accounting for temperature and drought stress per the original SORGF model.

Previous studies (Huda et al., 1980 and 1982) have shown that the percentage of TDM present in culm, head (includes grain), and grain is different between CSH 6 and SPV 351 at both anthesis and PM. The original SORGF does not allow for cultivar differences in distribution of dry matter among plant parts. To account for the cultivar differences, the distribution coefficients for leaf, culm, head (includes grain), and grain as observed at PI, anthesis, and PM by Huda et al. (1982), were given as input data to the model. Simulated dry matter in any given plant part is obtained by multiplying TDM by the fraction of TDM found in that plant part on any given day. The fraction of dry matter in each plant part for any given day is a linear look-up function (based on GDD) between the distribution coefficients for any two successive growth stages (e.g., from emergence to PI, from PI to anthesis, and from anthesis to PM) for each cultivar.

Grain yields of CSH 6 were simulated for five plant densities ranging from 4 to 20 plants m^{-2} using climatic data from the ICRISAT Center between 1976 and 1984. Except for the present experiment in 1983, observed data for various plant densities were not available from 1976 to 1984 for comparing the simulated data. However, grain yield data under adequate management (12 g N m^{-2} and sufficient plant protection against diseases and insects) were supplied for CSH 6 (1976–1984) at one plant density (13 plants m^{-2}) grown on 0.75-m ridges (D.S. Murty, 1985, personal communication).

RESULTS AND DISCUSSION

Weather

Weather data for the different growth periods (GS1, GS2, GS3) during the experiment are summarized in Table 2. Total rainfall from June to October was 1021 mm, which was 52% above average. The distribution of rainfall between June and October indicates sufficient water for crop growth at all times (Fig. 1). Average air temperature in GS1, GS2, and GS3 was 28.1, 26.0, and 25.5°C, respectively.

Phenology

The SORGF model does not consider the effects of plant density on simulated durations of growth periods. In agreement with SORGF coding, observed phenology in this experiment was not affected by changes in plant density. Simulated durations of GS1, GS2, and GS3 were within 1 to 2 d of the observed durations except for GS2 in SPV 351 (Table 2). Based on cultivar coefficients developed from earlier studies, the model was coded to predict differences between CSH 6 and SPV 351 for the duration of GS1. The predicted duration of GS2 and GS3 was 34 d for both cultivars. The predictions were close for CSH 6, but the observed duration of GS2 in SPV 351 was 6 d longer than that predicted (Table 2). Apparently, GS2 in SPV 351 has higher GDD requirements than those reported by Huda et al. (1982). The GDD requirements reported in that study for GS2 in SPV 351 were higher than those for CSH 6, but both the cultivars had been grouped together for GS2 because the difference was not statistically significant. The effects of daylength on the duration of growth stages in SPV 351 need to be investigated.

Leaf Area Index

The leaf area of an average plant is simulated on a daily basis from the cultivar input data on the total number of leaves and the maximum area of each leaf. The simulated LAI accounts for plant density and leaf area for each plant. Comparisons between observed and simulated LAI of CSH 6 and SPV 351 achieved at anthesis and at PM are shown in Fig. 2.

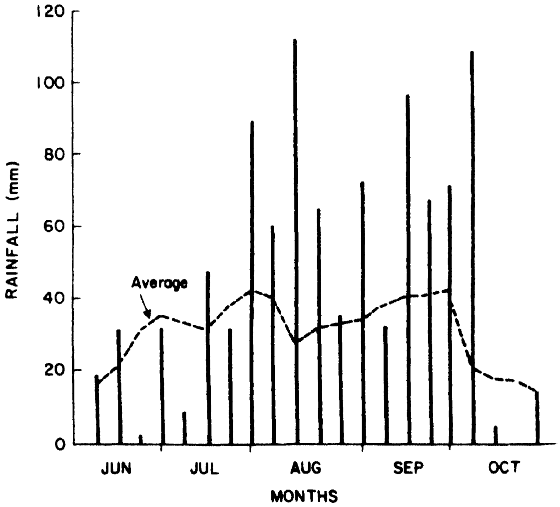

Fig. 1. Weekly total rainfall distribution at the ICRISAT Center, Patancheru, for the 1983 rainy season, and an average for 1901 to 1984.

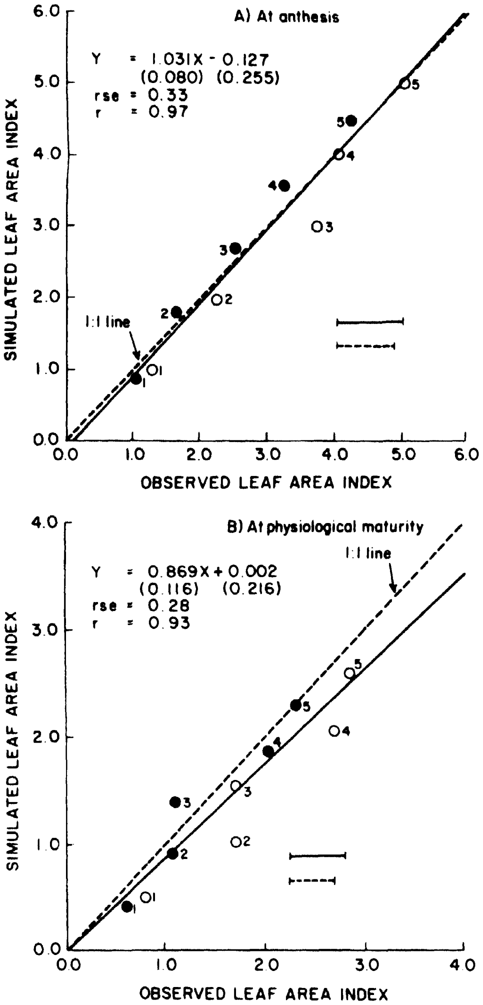

Fig. 2. Relationship between observed and simulated leaf area indices at (A) anthesis and (B) physiological maturity of two sorghum cultivars (● = CSH 6, ○ = SPV 351) for five plant densities (1–5 denotes lowest to highest density) in the 1983 rainy season at the ICRISAT Center, Patancheru. Values of the regression equation in parentheses refer to standard errors of the estimate. Solid horizontal bars represent the LSD (0.05) of the observed means to compare cultivars at the same plant density. Dashed horizontal bars represent the LSD (0.05) of the observed means to compare plant densities at the same cultivar.

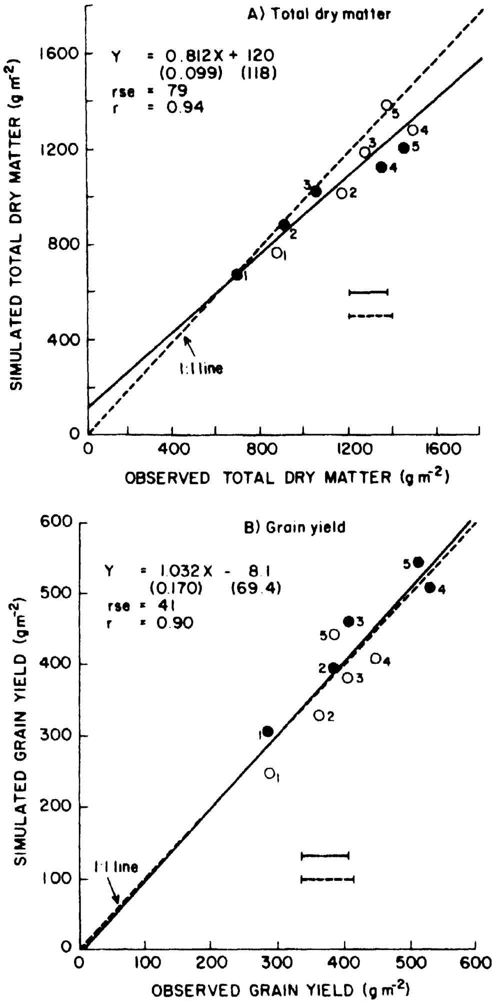

Fig. 3. Relationship between observed and simulated (A) total dry matter and (B) grain yield of two sorghum cultivars (● = CSH 6, ○ = SPV 351) for five plant densities (1–5 denotes lowest to highest density) in the 1983 rainy season at the ICRISAT Center, Patancheru. Values of the regression equation in parentheses refer to standard errors of the estimate. Solid horizontal bars represent the LSD (0.05) of the observed means to compare cultivars at the same plant density. Dashed horizontal bars represent the LSD (0.05) of the observed means to compare plant densities at the same cultivar.

LAI at Anthesis

Both observed and simulated LAI increased with plant density (Fig. 2A). Observed LAI was consistently greater for SPV 351 than CSH 6 at each plant density, but a significant difference between the two cultivars was found only at 12 plants m^{-2}. The correlation coefficient between observed and simulated LAI pooled over two cultivars and five plant densities, was 0.97. The residual standard error (*rse*) was 11% of the mean observed LAI (2.91). The difference between observed and simulated values shows that on average, simulated LAI was 3% lower than that observed (i.e., a bias of −3%). Insignificant differences between observed and simulated values were supported by the tests of significance for intercept and slope of the regression line. The intercept and the slope were not significantly different from 0.0 and 1.0, respectively, based on the *t* test.

LAI at Physiological Maturity

Simulated LAI increased with plant density (Fig. 2B). Observed LAI also increased with plant density, but the difference in LAI between 16 and 20 plants m^{-2} was not significant. Observed LAI was consistently greater for SPV 351 than CSH 6 at each plant density, but significant differences between the two cultivars were found at 8, 12, and 16 plants m^{-2}. Averaged over five plant densities, observed LAI at PM

Table 3. Dry-matter distribution coefficients used as model input and observed percentage of total dry matter present in leaf, culm, head (includes grain), and grain at anthesis and physiological maturity for two sorghum cultivars at five plant densities in the 1983 rainy season at the ICRISAT Center, Patancheru, A.P., India.

	Percentage of total dry matter present in:							
	Leaf		Culm		Head (includes grain)		Grain	
Plant density	CSH 6	SPV 351	CSH 6	SPV 351	CSH 6	SPV 351	CSH 6	SPV 351
	%							
	A. At anthesis							
Model input (all densities)	25	22	57	66	18	12		
Observed plants m^{-2}								
4	22	26	56	58	22	16		
8	24	24	57	61	19	15		
12	24	26	59	60	17	14		
16	25	26	58	61	17	13		
20	26	25	58	60	16	15		
LSD_c†	3		3		2			
LSD_p	4		3		3			
	B. At physiological maturity							
Model input (all densities)	11	12	32	45	57	43	45	32
Observed plants m^{-2}								
4	9	6	36	47	55	47	41	33
8	11	7	37	53	52	40	42	31
12	12	9	38	51	50	40	39	32
16	10	9	40	53	50	38	39	30
20	10	9	43	52	47	39	35	28
LSD_c	2		11		8		7	
LSD_p	2		9		6		6	

† LSD_c = LSD (0.05) of observed values to compare cultivars at the same plant density.
LSD_p = LSD (0.05) of observed values to compare plant densities for the same cultivar.

was 56% of the LAI at anthesis in CSH 6, and 60% of the LAI at anthesis in SPV 351. Simulated LAI at PM was nearly 50% of the LAI at anthesis in both CSH 6 and SPV 351. Consequently, the model simulated daily leaf growth and senescence well. The correlation coefficient, between observed and simulated LAI values at PM pooled over two cultivars and five plant densities, was 0.93. The *rse* was 16% of the mean observed LAI (1.70). The difference between observed and simulated values shows that on average, simulated LAI was 13% lower than that observed (i.e., a bias of −13%). Insignificant differences between observed and simulated values were supported by the tests of significance for the intercept and slope of the regression line. The intercept and the slope were not significantly different from 0.0 and 1.0, respectively, based on the *t* test.

Although not always statistically different, the greater LAI at each plant density for SPV 351 compared to CSH 6 at anthesis or PM is consistent with its longer GS2 duration. The poorer fit of observed and simulated LAI for SPV 351 is because of poorer prediction of GS2 duration.

Total Dry Matter

Simulated TDM increased with plant density in both cultivars. In CSH 6, though observed TDM increased up to 20 plants m^{-2}, there was no significant difference in TDM between 16 and 20 plants m^{-2}. In SPV 351, observed TDM increased up to 16 plants m^{-2} (Fig. 3A). Observed TDM was greater in SPV 351 than in CSH 6 except at 16 and 20 plants m^{-2}, where TDM of both cultivars was similar. The correlation coefficient, between observed and simulated TDM data pooled over two cultivars and five plant densities, was 0.94. The *rse* was 7% of the mean observed TDM (1164 g m^{-2}). The difference between simulated and observed TDM shows that on average, simulated TDM was 8% lower than that observed (i.e., a bias of −8%). Insignificant differences between observed and simulated values were supported by the tests of significance for the intercept and slope of the regression line. The intercept and the slope were not significantly different from 0.0 and 1.0, respectively, based on the *t* test.

Dry-Matter Distribution

In the revised SORGF model, simulated dry matter in any given plant part is obtained by multiplying TDM by the fraction of TDM found in that plant part on any given day. The fraction of dry matter in each plant part is a linear look-up function (based on GDD) within each growth phase where cultivar-specific values for fraction leaf, culm, head (includes grain), and grain at PI, anthesis, and PM are inputs into the model. Huda et al. (1982) reported that dry-matter distribution coefficients were similar for CSH 6 and SPV 351 at emergence (100% to leaf) and PI (64% to leaf, 36% to culm), but varied between cultivars at anthesis and PM. To account for cultivar differences in the distribution of TDM, dry-matter distribution coefficients obtained from previous studies (Huda et al., 1982) were used as the model input (see model input, Table 3). In agreement with the model input, the observed percentage of TDM present in different plant parts at anthesis and PM varied in the 1983 experiment between CSH 6 and SPV 351 (Table 3), and did not vary between cultivars at PI (results not shown). The model does not allow for the effects of plant density on the distribution of dry matter to different plant parts, although the minor effects of plant densities are evident.

The model results agreed well with the observations from the 1983 experiment except at 20 plants m^{-2}, where the percentage of TDM in head (includes grain) and grain at both anthesis and PM was slightly reduced (Table 3). The use of the same harvest index (percent of TDM present in grain at PM) in the model for all plant densities caused the model to overestimate grain yield in CSH 6, particularly at lower plant densities where simulated TDM was very close (between 2 and 4%) to the observed TDM. On the other hand, the underestimation of grain yield in SPV 351 was primarily due to an underestimation of TDM. Both the original and the revised subroutines on dry-matter distribution are based on empirical data. A better understanding of the dynamic (daily) dry-matter partitioning under a wide range of environmental conditions is needed if the model is required to simulate accurately the mass of different plant parts on a daily basis. This could improve the simulated yield response at high plant densities. However, for simulating final grain yield, harvest index (usually a cultivar characteristic as reported by Fischer and Wilson [1975] and Monteith [1986b]) can more easily be used to convert simulated TDM. Data on harvest index are frequently available, whereas the calculation of dynamic partitioning requires intensive in-season growth sampling.

Grain Yield

Simulated grain yield increased with plant density in both CSH 6 and SPV 351 (Fig. 3B). Observed grain yield did not increase for densities greater than 16 plants m^{-2} in either cultivar. Because the SORGF model assumes well-fertilized conditions, the model response of higher yields at 20 plants m^{-2} may indicate possible nutrient deficiences at high populations in the 1983 field experiment. Though 18 g N m^{-2} was applied during the growing season, some N had probably been leached from the root zone, as there was 1021 mm rain (52% above average) during June to October. This N stress may have limited grain yields for the 20 plants m^{-2} treatment to a level not significantly different from yields for densities of 16 plants m^{-2}. Additional applications of N might have increased the yields for plants grown at 20 plants m^{-2} so that yields would have continued to increase for higher plant densities as indicated by the model simulations and as reported by Fischer and Wilson (1975) and Freyman and Venkateswarlu (1977).

Table 4. Observed grain yield of sorghum (cv. CSH 6) at 13 plants m^{-2} and simulated grain yield of sorghum (cv. CSH 6) for five plant densities from 1976 to 1984 in a Vertisol at the ICRISAT Center, Patancheru, A.P., India.

Dates of planting	Observed grain yield at 13 plants m^{-2}	Simulated grain yield at five plant densities, plants m^{-2}				
		4	8	12	16	20
	g m^{-2}					
7 June 1976	514†	349	449	522	576	615
26 June 1977	534	364	465	542	598	639
1 July 1978	623	362	464	540	596	636
23 June 1979	559	382	489	569	628	671
11 June 1980	488	318	410	478	528	564
24 June 1981	521	363	464	539	594	634
18 June 1982	663	335	453	528	582	622
28 june 1983	528	313	403	470	518	553
18 June 1984	500	335	431	501	552	590

† Observed grain yield data obtained from D.S. Murty, 1985, personal communication.

Both observed and simulated grain yield were greater for CSH 6 than for SPV 351, particularly at 16 and 20 plants m^{-2}. This was due to a greater rate of dry-matter accumulation during grain filling (GS3) in CSH 6, particularly at 16 and 20 plants m^{-2}. For example, the observed rates during GS3 were 14, 19, 20, 26, and 27 g m^{-2} d^{-1} in CSH 6, and 15, 21, 21, 22, and 19 g m^{-2} d^{-1} in SPV 351 at 4, 8, 12, 16, and 20 plants m^{-2}, respectively. Simulated dry-matter accumulation rates during GS3 were similar for the two cultivars, and the values were 12, 17, 19, 21, and 22 g m^{-2} d^{-1} at 4, 8, 12, 16, and 20 plants m^{-2}. Because the duration of grain filling was similar in the two cultivars, greater observed rates of dry-matter accumulation in CSH 6 during GS3 at 16 and 20 plants m^{-2} resulted in greater grain yield. The correlation coefficient, between observed and simulated grain yield data pooled over both cultivars and all plant densities, was 0.90. The *rse* was 10% of the mean observed grain yield data (400 g m^{-2}). The difference between observed and simulated values shows that on average, simulated grain yield was 2% greater than that observed (i.e., a bias of 2%). Insignificant differences between observed and simulated values were supported by the tests of significance for intercept and slope of the regression line. The intercept and the slope were not significantly different from 0.0 and 1.0, respectively, based on the *t* test.

Yield Simulation from 1976 to 1984

Grain yields of CSH 6 were simulated for five plant densities ranging from 4 to 20 plants m^{-2} using climatic data from the ICRISAT Center between 1976 and 1984 (Table 4). Observed grain yield data were available for one plant density (13 plants m^{-2}). The results show that the observed grain yield data at 13 plants m^{-2} were close to the simulated data using a plant population density of 12 plants m^{-2} or more. For example, simulated grain yield data using 12 plants m^{-2} were within 3% in 6 yr (1976, 1977, 1979, 1980, 1981, and 1984). In the other 3 yr, the model underestimated grain yield by 11 to 20% compared to the observed data.

CONCLUSIONS

The difference between observed and simulated TDM and grain yield showed that on average, the model underestimated TDM by 8% and overestimated grain yield by 2%. Good agreement between observed and simulated values was supported by the insignificant differences of the observed and simulated values from a one-to-one line (based on the test of significance of the intercept and the slope of the regression line).

Both the observed and simulated grain yield data of the two sorghum cultivars confirmed the superiority of CSH 6 to SPV 351 at higher plant densities. Greater harvest index and greater dry-matter accumulation rates in CSH 6 during the grain filling period at higher plant densities resulted in greater grain yield in CSH 6 than SPV 351. The use of a cultivar-specific harvest index as input data in the model allowed the greater grain yield simulation in CSH 6 than SPV 351.

Comparisons of simulated and observed grain yields showed that observed grain yields did not increase beyond 16 plants m^{-2} for both sorghum cultivars, although simulated yield increased up to the highest plant density used (20 plants m^{-2}). One reason for this discrepancy at the highest plant density could be that though the SORGF model assumes well-fertilized conditions, the amount of N (18 g m^{-2}) applied during the crop growing season in the high rainfall environment of 1983 (1021 mm) was probably insufficient for maximum yield response. Fischer and Wilson (1975) and Freyman and Venkateswarlu (1977) reported increased grain yields with plant densities up to 64.5 plants m^{-2} (for cv. RS 610), and 22 plants m^{-2} (for cv. CSH 5), respectively. The increase in simulated grain yield above 20 plants m^{-2} (results not shown) is quite small (less than 0.5 t ha^{-1}) for each additional 10 plants m^{-2}, and the rate of increase in simulated grain yield is progressively less with increasing plant densities. Thus, further investigation may be needed to verify the yield response of the model at very high plant densities such as 64.5 plants m^{-2} as reported by Fischer and Wilson (1975).

This study showed that the SORGF model responds to changes in plant density and thus appears useful for simulating the effect of plant density on the growth and yield of well-managed sorghum when input data on cultivar characteristics (total number of leaves, maximum area for each leaf, daylength and temperature relationships for phenological development, and dry-matter distribution coefficients), water holding capacity of soils, latitude of the location, climate data (daily rainfall, maximum and minimum air temperatures, and solar radiation), and agronomic management input (planting date and depth, row spacing, and plant density) are available.

ACKNOWLEDGMENTS

Thanks are due to Mr. J. G. Sekaran for his assistance in data analysis. The author is grateful to Drs. J. L. Monteith and K. J. Boote, and other anonymous reviewers for their valuable comments, which helped improve this manuscript.

REFERENCES

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

Balasubramanian, V., D. Gangadhar Rao, and C. Hanumantha Rao. 1982. Crops and cropping systems for drylands. p. 26-47. *In* A decade of dryland agricultural research in India, 1971-80. All India Coordinated Research Project for Dryland Agriculture (Central Research Institute for Dryland Agriculture), Hyderabad, A.P., India.

Blum, A. 1967. Effect of soil fertility and plant competition on grain sorghum panicle morphology and panicle weight components. Agron. J. 59:400-403.

———. 1970. Effect of plant density and growth duration on grain sorghum yield under limited water supply. Agron. J. 62:333-336.

Eastin, J.D. 1972. Photosynthesis and translocation in relation to plant development. p. 214-246. *In* N.G.P. Rao and L.R. House (ed.) Sorghum in the seventies. Oxford and IBH, Bombay, India.

Fischer, K.S., and G.L. Wilson. 1975. Studies of grain production in *Sorghum bicolor* (L.) Moench. V. Effect of planting density on growth and yield. Aust. J. Agric. Res. 26:31-41.

Freyman, S., and J. Venkateswarlu. 1977. Intercropping on rainfed red soils of the Deccan Plateau, India. Can. J. Plant Sci. 57:697-705.

Huda, A.K.S., and C.K. Ong. 1988 (in press). Crop simulation models and some implications for agroforestry systems. Presented at the ICRAF/WMO/UNEP Workshop on the Application of Meteorology for Agroforestry Systems Planning and Management, Nairobi, Kenya. 9-13 Feb. 1987. (Limited distribution.) Proceedings to be published by the Int. Council for Res. in Agroforestry, Nairobi, Kenya.

———, M.V.K. Sivakumar, S.M. Virmani, N. Seetharama, Sardar Singh, and J.G. Sekaran. 1984. Modeling the effect of environmental factors on sorghum growth and development. p. 277-287. *In* Proc. Int. Symp. on Agrometeorology of Sorghum and Millet in the Semi-Arid Tropics, ICRISAT, Patancheru, A.P., India. 15-20 Nov. 1982. ICRISAT, Patancheru, A.P., India.

———, ———, ———, and J.G. Sekaran. 1982. Proceedings of a meeting on collaborative multilocation sorghum modeling experiment. Agroclimatology Progress Rep. 9. ICRISAT, Patancheru, A.P., India. (Limited distribution.)

———, S.M. Virmani, M.V.K. Sivakumar, and J.G. Sekaran. 1980. Proceedings of a meeting on collaborative multilocation sorghum modeling experiment. Agroclimatology Progress Rep. 4. ICRISAT, Patancheru, A.P., India. (Limited distribution.)

Jordan, W.R., and C.Y. Sullivan. 1982. Reaction and resistance of grain sorghum to heat and drought. p. 131-142. *In* Sorghum in the eighties. Vol. I. Proc. Int. Symp. on Sorghum, ICRISAT, Patancheru, A.P., India. 2-7 Nov. 1981. ICRISAT, Patancheru, A.P., India.

Monteith, J.L. 1986a. Significance of the coupling between saturation vapour pressure deficit and rainfall in monsoon climates. Exp. Agric. 22:329-338.

———. 1986b. How do crops manipulate water supply and demand? Philos. Trans. R. Soc. London, A 316, 245-259.

Myers, R.J.K., and M.A. Foale. 1981. Row spacing and population density in grain sorghum—a simple analysis. Field Crops Res. 4:147-154.

Natarajan, M., and R.W. Willey. 1980. Sorghum-pigeonpea intercropping and the effects of plant population density. 1. Growth and yield. J. Agric. Sci. 95:59-65.

Russell, M.B. 1980. Profile moisture dynamics of soil in Vertisols and Alfisols. p. 75-87. *In* Proc. Int. Workshop on the Agroclimatological Research Needs of the Semi-Arid Tropics, ICRISAT Patancheru, A.P., India. 22-24 Nov. 1978. ICRISAT, Patancheru, A.P., India.

Stapper, M., and G.F. Arkin. 1980. CORNF: A dynamic growth and development model for maize (*Zea mays* [L.]). Texas Agric. Exp. Stn. Program and model documentation 80-2.

Stickler, F.C., and M.A. Younis. 1966. Plant height as a factor affecting responses of sorghum to row width and stand density. Agron. J. 58:371-373.