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MODELING

Maize and Sorghum Simulations with CERES-Maize, SORKAM, and ALMANAC under Water-Limiting Conditions

Yun Xie, James R. Kiniry,* Vernon Nedbalek, and Wesley D. Rosenthal

ABSTRACT

While crop models often are tested against long-term mean grain yields, models for aiding decision making must accurately simulate grain yields in extreme climatic conditions. In this study, we evaluated the ability of a general crop model (ALMANAC) and two crop-specific models (CERES-Maize and SORKAM) to simulate maize (*Zea mays* L.) and sorghum [*Sorghum bicolor* (L.) Moench] grain yields in a dry growing season at several sites in Texas. The root mean square deviation values were 0.36 Mg ha^{-1} for sorghum with ALMANAC, 0.71 for sorghum with SORKAM, 0.56 for maize with ALMANAC, and 0.83 for maize with CERES-Maize. For maize, values for coefficient of determination (r^2) between measured and simulated grain yields were 0.95 for ALMANAC and 0.88 for CERES-Maize. For sorghum, r^2 values were 0.86 for ALMANAC and 0.45 for SORKAM. ALMANAC and SORKAM should be useful tools to simulate dryland sorghum in drought, as indicated by their root mean square deviation values of <0.8 Mg ha^{-1}. The mean errors for irrigated maize were 2.0% for CERES and 6.2% for ALMANAC. For dryland maize, mean errors were 6.2% for ALMANAC and −2.2% for CERES. In CERES, simulated leaf area index (LAI) and kernel weight appeared to be overly sensitive to drought stress. Further study on the response of LAI and kernel weight to drought in CERES would be valuable. The soil, weather, and crop parameter data sets developed for this study could be useful guidelines for model applications in similar climatic regions and on similar soils.

Maize and sorghum are grown in a wide range of soils and climatic conditions, causing them to be vulnerable to late-spring freezes, drought, and high temperatures during grain growth. Producers need to make effective decisions on planting date, maturity type, planting rate, and fertilizer rates to maximize profit and minimize risks associated with unpredictable weather conditions. Crop models offer hope as tools to optimize such management practices. Robust crop models can provide a quantitative means to predict crop yields under different environmental and climatic conditions. Crop consultants, using accurate runoff curve numbers, depth of soil layers, and soil water-holding capacity as well as updated weather data, could provide producers with realistic predictions on the outcome of various management alternatives. Likewise, crop advisory information could be linked to soil type and measurements of soil layer depths in individual fields.

ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) (Kiniry et al., 1992), CERES-Maize (Crop–Environment REsource Synthesis) (Jones and Kiniry, 1986), and SORKAM (SORghum, Kansas, A&M) (Rosenthal et al., 1989a) were developed to simulate critical growth processes. ALMANAC was developed to simulate the impacts of various field-level management alternatives on the soil and water environment and on crop yields. The crop model in ALMANAC was designed to simulate a wide range of plant species in a general way that can be easily transferred to new environments and easily applied to different plant species. CERES-Maize and SORKAM were developed to simulate phenological processes and yield components of maize and sorghum and to describe how different hybrids produce grain in different environments.

Adapted versions of CERES-Maize simulated dryland and irrigated maize grain yields in Kenya at 1 to 9 plants m^{-2} (Keating et al., 1988) and simulated maize grain yields with variable planting density, sowing dates, and N rates in Kenya (Wafula, 1995). CERES-maize was used to simulate maize grain yields in Kansas with weed and insect stresses (Retta et al., 1991). The model "gave excellent predictions of yield trends" when used to simulate variability within a field in Iowa, proving

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Abbreviations: HI, harvest index; LAI, leaf area index.

to be "a viable and powerful tool in developing and evaluating management prescriptions across a field" (Paz et al., 1999). The model was tested in the semiarid tropics under conditions with measured grain yields of 1.7 to 8.3 Mg ha^{-1} (Carberry et al., 1989). CERES failed to simulate differences among data sets for high-yielding conditions (11.7–16.7 Mg ha^{-1}) in Argentina, but the mean simulated grain yield was only 4% smaller than the mean measured grain yield (Otegui et al., 1996). An adaptation of CERES-Maize to simulate sorghum was tested in Australia using data with measured grain yields ranging from 1.6 to 6.3 Mg ha^{-1} (Birch et al., 1990). ALMANAC and CERES-Maize were used to simulate crop yields in nine states with diverse soils and climate (Kiniry et al., 1997) and at nine sites in Texas (Kiniry and Bockholt, 1998). To be effective as tools, crop models must be capable of simulating crop yields in average rainfall years and in unusual rainfall years such as with drought or excess moisture.

The SORKAM model has been used in various applications across the USA. Gerik et al. (1988) used the model to evaluate the feasibility of ratooning sorghum in Texas and Georgia. Gerik and Rosenthal (1989) used the model to evaluate optimum planting dates, sowing rates, and plant populations for several areas within Texas. Gerik et al. (1992) expanded this analysis to other areas in the grain-producing regions of the USA. Hill et al. (1999) recently used the model to analyze Texas sorghum production as affected by El-Nino/Southern Oscillation. Rosenthal et al. (1989b) also linked the model with a sorghum midge (*Contarinia sorghicola* Coquillett) development model to aid in evaluating the potential for midge damage in southern sorghum-producing areas.

In 1998, Texas experienced a severe drought during the growing season. The long-term average annual rain for the three weather districts studied was 409 mm during March through July, critical months during the maize and sorghum growing seasons (NOAA, 1993) (Table 1). In 1998, the annual rain for our sites was 30% of the long-term mean for March through July. Mean maize grain yield was 58% of the mean of the previous 20 yr for the 13 counties in this study. Correspondingly, mean sorghum grain yield was 87% of the 20-yr mean for these counties.

Rogers (1999) reported dryland and irrigated maize and sorghum grain yields in yield trials at several sites in these regions, which provided excellent data for testing grain yield simulation under severe drought conditions. The objective of this study was to evaluate the ability of CERES to simulate maize grain yields, SORKAM to simulate sorghum grain yields, and ALMANAC to simulate both crops under these dry conditions at several yield-trial sites in central and southern Texas in 1998. We evaluated the ability of the models to simulate grain yield under extreme drought by comparing the simulated grain yields with measured grain yields and by analyzing for possible sources of errors.

MODEL DESCRIPTIONS

The ALMANAC, CERES-Maize, and SORKAM models simulate processes of crop growth and soil water balance including light interception by leaves, dry matter production, and partitioning of biomass into grain. A major difference between these models is in their approach to simulate grain yield. ALMANAC simulates grain yield based on harvest index (HI), which is grain yield as a fraction of total aboveground dry matter at maturity. CERES simulates maize seed number per plant (based on plant growth) and average mass per seed (based on potential seed growth rate). Similarly, SORKAM simulates sorghum tillering, seed number per tiller, and average mass per seed.

We applied SORKAM version 2000 (W.D. Rosenthal and R.L. Vanderlip, personal communication, 2000) and recent versions of ALMANAC and CERES-Maize as described by Kiniry et al. (1997). Improvements since

Table 1. Measured monthly rain during the growing season at several sites in central and southeastern Texas in 1998. Values in italic are the long-term means for the Texas climate divisions.

County	Town	March	April	May	June	July	Seasonal total
				mm^{-1}			
North Central		*59*	*89*	*121*	*81*	*54*	*404*
Bell	Temple	42	39	23	13	32	149
Falls	Otto	72	32	9	83	75	271
Williamson	Hutto	63	17	9	7	18	114
South Central		*50*	*74*	*96*	*76*	*68*	*364*
Guadalupe	Seguin	59	5	20	6	37	127
Medina	Lacoste	72	1	9	21	5	108
De Witt	Yorktown	50	45	1	9	24	129
San Patricio	Sinton	74	6	0	0	25	105
San Patricio	W. Sinton	53	19	0	4	24	100
Refugio	Austwell	51	13	0	0	26	90
Lavaca	Moulton	42	25	7	69	17	
Upper Coast		*68*	*83*	*114*	*80*	*114*	*459*
Victoria	Inez	56	21	0	6	17	100
Wharton	El Campo	37	23	1	7	15	83
Wharton	Wharton	42	28	5	32	42	149
Jackson	Edna	56	21	0	6	17	100
Jackson	Ganado	56	21	0	6	17	100
Nueces	Agua Dulce	38	0	0	42	15	95
Nueces	Bishop	33	11	0	4	34	82

Kiniry et al. (1997) included extinction coefficients (k) based on row spacing for ALMANAC and a new seed number algorithm in CERES.

For ALMANAC, the extinction coefficient is a linear function of row spacing for maize and sorghum (Flénet et al., 1996):

$$k = 0.685 - 0.209 \times \text{ROWS} \quad [1]$$

where ROWS is the row spacing (m) for maize and sorghum, k is the light extinction coefficient (unitless), 0.685 is the y-intercept, and 0.209 is the slope (m^{-1}). This function was not included in CERES-Maize because it reduced the accuracy of grain yield simulation.

Number of seeds per plant (SEEDS) for CERES is now estimated by a linear function of growth [GROWTH (g plant^{-1} d^{-1})] from silking to the beginning of grain growth (Kiniry et al., unpublished data, 2001):

$$\text{SEEDS} = 90 \times \text{GROWTH} \quad [2]$$

where SEEDS is constrained to not exceed a genotype-specific potential number of seeds plant^{-1}. While Andrade et al. (2000) and Otegui and Andrade (2000) described nonlinear seed number equations due to increased barrenness at abnormally high planting densities, for this study, we used Eq. [2], which is similar to the function of Keating et al. (1988).

Critical for grain yield simulation in water-limited conditions is the simulated water demand. The three models calculate effects of soil water on crop growth and grain yield with similar functions. Potential evaporation (E_o) is calculated first, and then potential soil water evaporation (E_s) and potential plant water transpiration (E_p) are derived from E_o and leaf area index (LAI). Based on the soil water supply and crop water demand, a water stress factor is estimated to decrease daily crop growth and grain yield. However, some water balance equations differ between the models. For this study, E_o was estimated by the Penman (1948) method in ALMANAC and by the Priestley-Taylor (Priestley and Taylor, 1972) method in CERES-Maize and SORKAM. In ALMANAC, E_S and E_P were estimated by

$$E_P = E_o(\text{LAI}/3) \qquad 0 \leq \text{LAI} \leq 3.0 \quad [3]$$

$$E_P = E_o \qquad \text{LAI} > 3.0 \quad [4]$$

E_S is either $E_o \exp(-0.1\text{BIO})$ or $E_o - E_p$, whichever is smallest, where BIO is the sum of aboveground biomass and crop residue (Mg ha^{-1}). In CERES-Maize and SORKAM

$$E_P = E_o [1 - \exp(-\text{LAI})] \qquad 0 \leq \text{LAI} \leq 3.0 \quad [5]$$

$$E_P = E_o \qquad \text{LAI} > 3.0 \quad [6]$$

$$E_S = E_o(1 - 0.43\text{LAI}) \qquad 0 \leq \text{LAI} \leq 1.0 \quad [7]$$

$$E_S = E_o \exp(-0.4\text{LAI})/1.1 \qquad \text{LAI} > 1.0 \quad [8]$$

If $E_p + E_s > E_o$, then $E_p = E_o - E_s$

Water stress factor is the ratio of water use to water demand (E_p) in all three models, and water use is a function of plant extractable water and root depth. If available water in the current rooting zone is sufficient to meet demand, then water use equals E_p. Otherwise, water use is restricted to the water available in the current rooting zone. In CERES-Maize and SORKAM, there are two water stress factors: One factor (WSF1) influences plant assimilation and the other factor (WSF2) influences leaf expansion growth. The first is calculated as

$$\text{WSF1} = \text{WU}/E_P \quad [9]$$

where WU is water use. The more sensitive, WSF2, is calculated as

$$\text{WSF2} = 0.67\text{WU}/E_P \quad [10]$$

Thus, when soil water becomes limiting, the WSF2 factor for leaf expansion is 33% smaller than the WSF1 factor for plant assimilation.

DATA SETS

This study consisted of data from 17 field sites (Table 2) in central and southeastern Texas (Rogers, 1999), important maize and sorghum production zones with high risk of drought during anthesis and grain filling. Nine sites had only maize, six had only sorghum, and two had both maize and sorghum. Maize was irrigated

Table 2. Measured maize and sorghum grain yields at several sites in central and southeastern Texas in 1998 (Rogers, 1999).

County	Town	Maize		Sorghum		Management
		Garst 8325	Garst 8225	Garst 5616	Garst 5319	
		Mg ha^{-1}				
Medina	Lacoste	5.64	6.28			Irrigated
Wharton	Wharton	6.61	5.64			Irrigated
Victoria	Inez	7.81	7.13			Irrigated
Falls	Otto	3.01				Dryland
Bell	Temple	1.83	1.85			Dryland
Lavaca	Moulton	4.83	4.27			Dryland
Guadalupe	Seguin	2.63	1.94			Dryland
Jackson	Ganado	2.41	1.76			Dryland
De Witt	Yorktown	4.10	4.02			Dryland
Williamson	Hutto	2.69	2.04	3.60		Dryland
Wharton	El Campo		5.21	4.05		Dryland
Jackson	Edna			4.48		Dryland
Refugio	Austwell			4.03	4.26	Dryland
San Patricio	Sinton			3.75	4.37	Dryland
	W. Sinton			4.45	4.79	Dryland
Nueces	Agua Dulce			1.91	1.55	Dryland
	Bishop			2.85	3.38	Dryland

at three sites while all the sorghum sites were dryland. Data at each site included hybrids grown, grain yields, planting and harvest date, row spacing, and irrigation amounts. The most commonly used hybrids in the yield trials were selected for this study: 'Garst 8285' and 'Garst 8325' for maize and 'Garst 5616' and 'Garst 5319' for sorghum. Daily maximum and minimum air temperatures and precipitation (Natl. Climatic Data Cent., 1999) were from the nearest available weather station for each data set. These stations, with one exception, ranged from as close as 4 km from the plot at Otto to as far as 28 km for Ganado (Table 3). At Lacoste, the weather station was 51 km from the field site. However, because this site was irrigated, inaccuracy in rain data due to this distance did not appear to be a problem. Daily solar irradiance values were long-term monthly averages derived from the Climatic Atlas of the United States (NOAA, 1993). The maize and sorghum simulations began with the 1997 weather data to obtain reasonable values for initial soil water for 1998. At planting, 100 and 51 kg ha^{-1} N and P, respectively, were applied to all sites.

Soil parameters were important because they determined the capacity to store fall and winter rain for plant use when growing season rain was limited. The soil type for each site was determined from the soil survey of each county. In addition, we collected soil samples from all of the sites. A total of 47 soil cores were collected from the sites of the yield trials. Using the procedure of Baumer et al. (1994), soil parameters were derived from the soil texture of each layer from each soil survey, and soil layer depths were set to values measured on the soil cores (Table 3). Plant available water at field capacity ranged from 0.197 m at Temple to 0.451 m at Wharton.

For the models, crop parameters were descriptive of the Garst maize and sorghum hybrids simulated. For ALMANAC, the sums of degree days (base 8°C) from planting to maturity were 1600 for maize and 1500 for sorghum. The HI of maize was 0.54. This value was from the experimental data collected in 1999 for the two Garst hybrids at Temple, TX (Kiniry et al., unpublished data, 2001) and was similar to the 0.53 value used before (Kiniry and Bockholt, 1998). The HI of sorghum was 0.45 (Prihar and Stewart, 1990). In ALMANAC, near anthesis, the water stress coefficient can reduce HI. This sensitive interval for HI begins when 45% of the degree days from planting to maturity have accumulated and ends when 60% have accumulated. Five days of severe drought during this interval reduces HI to a crop-specific minimum. This minimum for maize was set to 0.30, based on results of Sobriano and Ginzo (1975), Griffin (1980), and Costa et al. (1988). Because ALMANAC requires the minimum HI to be less than potential HI, minimum HI for sorghum was 0.44 to allow only minimal decreases.

Just as for ALMANAC, crop parameters for CERES were identical at all sites. Maize values were 220 degree days during the juvenile stage (P1), 0.52 for the photoperiod sensitivity coefficient (P2), 880 degree days from silking to physiological maturity (P5), 500 potential number of seeds per plant (G2), and 9.8 and 8.9 for potential kernel growth rate (G3) of hybrids Garst 8325 and Garst 8285, respectively. Parameters P1, P2, and P5 were the same as used previously in Texas (Kiniry and Bockholt, 1998), but the G2 and G3 values were derived from experimental results in 1999 at Temple (Kiniry et al., unpublished data, 2001). While actual plant stands were not measured, planting densities were 5 and 19 plants m^{-2} for maize and sorghum, respectively.

Irrigation dates and amounts were supplied by the producers. At Wharton, plots were irrigated on 14 and 28 May and 14 and 28 June. There were 38 mm applied each day, and the total was 152 mm. At Inez, two irriga-

Table 3. Planting and harvest date, weather, and soil data for maize and sorghum plots in central and southeastern Texas in 1998. Plant available water (PAW) is at field capacity.

County	Town	Plant date	Harvest date	Weather station†	Soil type	Soil depth	Plant available water
						m	m
Maize							
Medina	Lacoste	5 Mar.	27 July	San Antonio (51)	Victoria Clay	3.03	0.353
Wharton	Wharton	21 Mar.	27 July	Wharton (23)	Norwood Silt Loam	3.05	0.451
Victoria	Inez	6 Mar.	21 July	Edna (26)	Dacosta Sandy Clay	2.03	0.244
Falls	Otto	2 Apr.	3 Aug.	Riesel (4)	Branyon Clay	1.95	0.268
Bell	Temple	2 Apr.	3 Aug.	Temple (18)	Houston Black Clay	1.89	0.197
Lavaca	Moulton	6 Mar.	24 July	Flatonia (16)	Branyon Clay	1.82	0.242
Guadalupe	Segiun	6 Mar.	24 July	Seguin (15)	Branyon Clay	2.23	0.285
Jackson	Ganado	13 Feb.	30 June	Edna (28)	Laewest Clay	2.13	0.230
De Witt	Yorktown	6 Mar.	30 July	Yorktown (8)	Monteola Clay	2.20	0.236
Williamson	Hutto	11 Mar.	24 July	Taylor (11)	Branyon Clay	1.95	0.279
Wharton	El Campo	9 Mar.	12 July	Danevang (27)	Lake Charles Clay	1.83	0.264
Sorghum							
Williamson	Hutto	25 Mar.	15 July	Taylor (11)	Branyon Clay	1.95	0.279
Refugio	Austwell	26 Mar.	13 July	Aransas (15)	Victoria Clay	2.27	0.280
Jackson	Edna	26 Mar.	30 June	Edna (26)	Dacosta Sandy Clay Loam	2.20	0.303
Nueces	Bishop	22 Mar.	30 June	Kingsville (14)	Orelia Fine Sandy Loam	2.81	0.398
Nueces	Agua Dulce	30 Mar.	29 June	Alice (16)	Victoria Clay	2.00	0.249
San Patricio	Sinton	22 Mar.	29 June	Sinton (18)	Victoria Clay	2.50	0.316
San Patricio	West Sinton	7 Mar.	29 June	Sinton (20)	Orelia Sandy Clay Loam	2.45	0.366
Wharton	El Campo	25 Mar.	7 July	Danevang (27)	Lake Charles Clay	1.95	0.296

† Values in parenthesis are the distances in kilometers from the weather station to the plots.

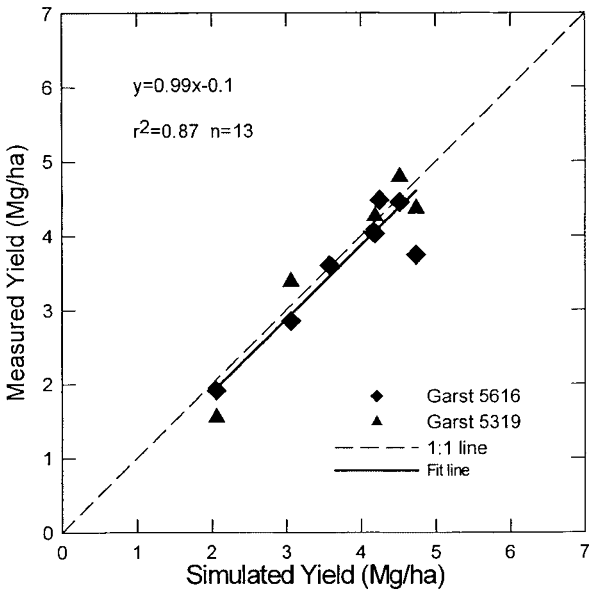

Fig. 1. Sorghum simulations with ALMANAC at eight locations in Texas. The solid line is the regression, and the dashed line is the 1:1 line through the origin. Each point is for one hybrid at a site.

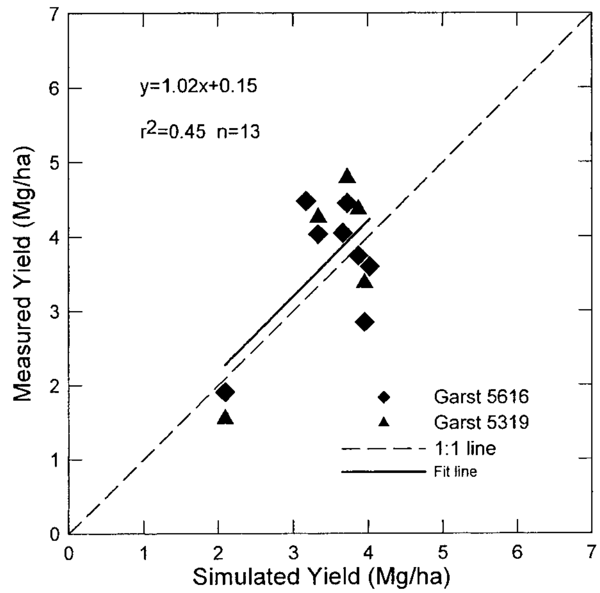

Fig. 2. Sorghum simulations with SORKAM at eight locations in Texas. The solid line is the regression, and the dashed line is the 1:1 line through the origin. Each point is for one hybrid at a site.

tions of 102 mm each were applied, one in the middle of May and one in the middle of June. At Lacoste, two 51-mm irrigations were applied, one at the end of April and one in the middle of June.

The models were evaluated by addressing several questions. First, could these models simulate the grain yields under these dry conditions? This was accomplished by regressing the measured grain yields on the simulated grain yields and seeing how close the regression line was to the 1:1 line. Second, comparing maize grain yields simulated by ALMANAC and CERES with measured grain yields, what were the differences between the results of the two models under drought stress? We compared differences between the models' simulated results and attempted to identify causes of such differences.

Next, a series of analyses were conducted that addressed weaknesses of these regression analyses (Harrison, 1990; Mitchell, 1997; Kobayashi and Salam, 2000). The bias values (measured minus simulated yields) were examined to see how many values exceeded a predetermined criterion of 0.5 Mg ha^{-1} (Mitchell, 1997). Also, the mean squared deviation was calculated as well as its three components: lack of correlation weighted by the standard deviations, the squared difference between standard deviations, and the squared bias (Kobayashi and Salam, 2000).

RESULTS AND DISCUSSION

The models simulated grain yields with mean errors <20% for this dry year. CERES and ALMANAC simulated grain yields at 11 maize sites, and ALMANAC and SORKAM simulated grain yields at eight sorghum sites. ALMANAC's mean error [(simulated grain yield − measured grain yield)/measured grain yield] was 12.9% for sorghum and 9.4% for maize. CERES's mean error was 18.6%. SORKAM's mean error was −6.3%.

The models differed in their ability to simulate site-to-site differences in grain yields under the dry climatic conditions. Regressions for sorghum with ALMANAC and SORKAM (Fig. 1 and 2) and for maize with ALMANAC and CERES (Fig. 3 and 4) were all significant ($\alpha = 0.01$). The y-intercepts were not significantly different from zero, and the slopes were not significantly different from 1.0. With the exception of SORKAM, all simulations described >85% of the variability in measured grain yields, as shown by the r^2 values. Maize simulations by ALMANAC had a greater value for r^2 than

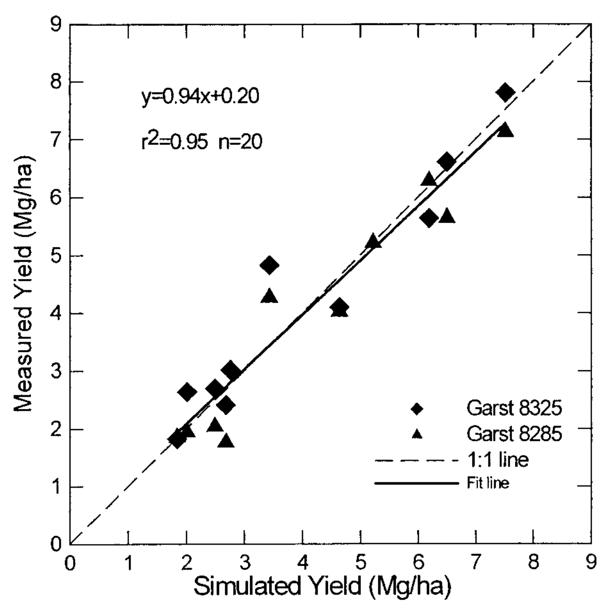

Fig. 3. Maize simulations with ALMANAC at 11 locations in Texas. The solid line is the regression, and the dashed line is the 1:1 line through the origin. Each point is for one hybrid at a site.

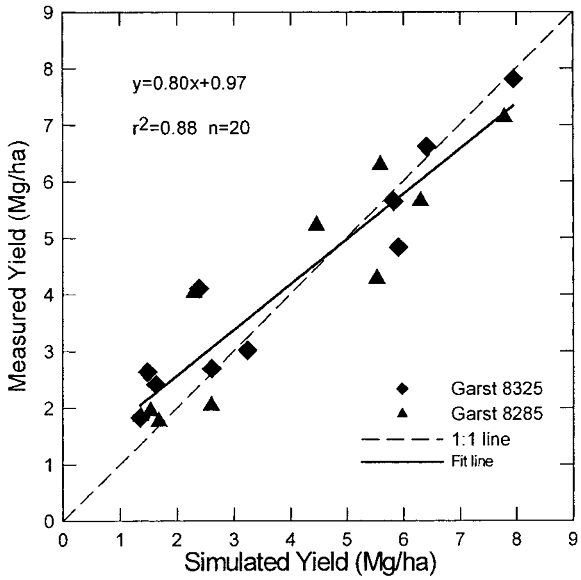

Fig. 4. Maize simulations with CERES at 11 locations in Texas. The solid line is the regression, and the dashed line is the 1:1 line through the origin. Each point is for one hybrid at a site.

CERES. Similarly, sorghum simulations by ALMANAC had a greater value for r^2 than simulations by SORKAM. Thus, the more general model, ALMANAC, with canopy LAI and HI, showed simulated grain yields with a higher correlation with measured grain yields than the more detailed, single crop models for both crops.

The simulation errors (simulated − measured grain yields) exceeded 0.5 Mg ha^{-1} more often for single crop models than for ALMANAC. ALMANAC's errors exceeded 0.5 for 23% of the sorghum data sets and for 35% of the maize ones. CERES' errors exceeded 0.5 Mg ha^{-1} for 55% of the data sets, and SORKAM's errors exceeded 0.5 Mg ha^{-1} for 69% of the data sets. Likewise, ALMANAC with both sorghum and maize grain yields had smaller values for mean squared deviation than grain yields for the single crop models (Fig. 5). The CERES and SORKAM simulations had greater values than ALMANAC for lack of correlation weighted by the standard deviations and for squared difference between standard deviations. This showed that CERES and SORKAM did not simulate the magnitude of fluctuation among the measurements as well as ALMANAC and did not simulate the pattern of fluctuation across measurements as accurately. The squared bias values of the maize simulations were similar: 0.044 for ALMANAC and 0.036 for CERES. The squared bias values for sorghum were 0.0163 for ALMANAC and 0.043 for SORKAM.

Table 4. Simulated error† (%) of maize for ALMANAC and CERES. The first three locations were irrigated.

		Simulated error			
		ALMANAC		CERES	
Town	County	Garst 8325	Garst 8225	Garst 8325	Garst 8225
		%			
Medina	Lacoste	6.6	−4.3	3.4	−11.0
Wharton	Wharton	2.0	19.4	−3.0	11.6
Victoia	Inez	2.0	11.7	1.8	9.3
Falls	Otto	2.6		7.6	
Bell	Temple	5.7	4.1	−26.1	−26.6
Lavaca	Moulton	−3.5	9.2	41.3	49.9
Guadalupe	Seguin	−22.5	5.0	−0.9	32.8
Jackson	Ganado	1.2	38.4	−32.4	−4.7
De Witt	Yorktown	2.15	23.9	−41.7	−40.1
Williamson	Hutto	−10.9	17.7	−3.1	27.5
Wharton	El Campo		−13.9		−14.5

† Simulated error = [(simulated grain yield − measured grain yield)/measured grain yield] × 100.

The ALMANAC model had larger mean errors than CERES for both irrigated and dryland maize (Table 4). For irrigated sites, the mean error was 6.2% for ALMANAC and 2.0% for CERES. For dryland maize, the mean error was 6.2% with ALMANAC and −2.2% with CERES-Maize. Two factors contributed to the lower simulated grain yields for CERES. One was that the drought stress occurred mainly during grain filling, resulting in low simulated kernel mass: 0.11 g for the dryland sites and 0.19 g for irrigated sites. In contrast, ALMANAC simulates the grain yields using HI. The other factor was that LAI was more sensitive to drought stress in CERES than in ALMANAC. While not measured in this study, LAI simulated by CERES was lower

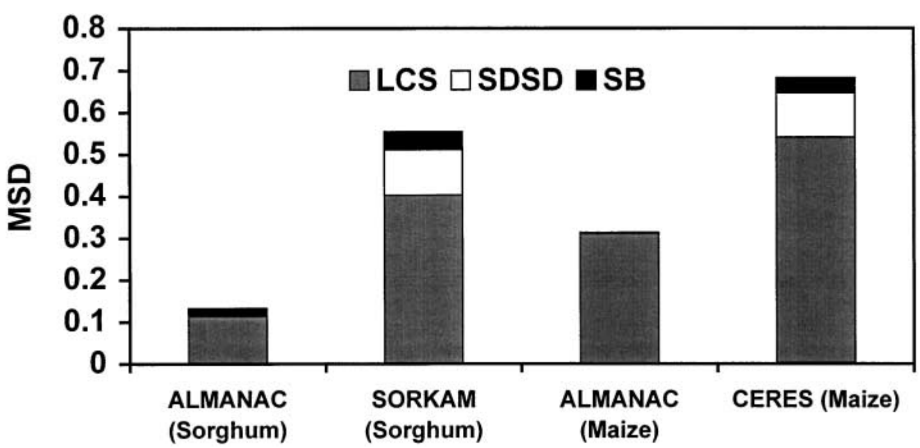

Fig. 5. Comparison of the mean squared deviation (MSD) and its components—lack of correlation weighted by standard deviations (LCS), squared difference between standard deviations (SDSD), and squared bias (SB)—for sorghum simulated with ALMANAC and SORKAM and maize simulated with ALMANAC and CERES-Maize.

Table 5. Simulated LAI (leaf area index) and seasonal plant transpiration (E_p) of maize for ALMANAC and CERES. The first three sites were irrigated.

		ALMANAC		CERES	
County	Town	LAI	E_p	LAI	E_p
			mm		mm
Medina	Lacoste	3.19	355	2.89	400
Wharton	Wharton	3.18	313	2.91	351
Victoia	Inez	3.18	386	2.81	400
Falls	Otto	3.21	219	1.79	262
Bell	Temple	3.16	138	3.02	286
Lavaca	Moulton	3.16	247	2.90	322
Guadalupe	Seguin	3.15	160	1.90	235
Jackson	Ganado	3.09	212	2.81	251
De Witt	Yorktown	3.19	234	2.25	268
Williamson	Hutto	3.14	197	2.40	314
Wharton	El Campo	3.15	240	2.97	296
Avg.					
Total		3.19	242	2.60	308
Irrigated		3.15	311	2.87	384
Dryland		3.20	202	2.51	279

than that in ALMANAC for all sites (Table 5). However, potential plant water transpiration (E_p) was greater for CERES and so was the water stress factor. For dryland maize, the mean simulated potential plant water transpiration was 279 mm with CERES and 202 mm with ALMANAC. The mean maximum simulated maize LAI was lower for CERES as were the means for irrigated and dryland sites. Thus, the large value for potential plant water transpiration in CERES was due to larger simulated potential evapotranspiration and not greater LAI. During the growing season of maize, simulations of plant transpiration in CERES were greater than in ALMANAC. Further study of LAI and kernel weight response to the drought stress in CERES would be valuable.

For sorghum, ALMANAC nearly always had lower simulated errors than SORKAM (Table 6) and consistently had smaller maximum LAI than SORKAM (Table 7). In only three cases were errors >10% for ALMANAC, whereas SORKAM had 10 errors >10%. The average LAI for ALMANAC was 65% of the average for SORKAM. The mean seasonal plant transpiration for ALMANAC was similar to the dryland maize average for ALMANAC. Seasonal transpiration is not output by SORKAM.

Harvest index for maize in ALMANAC was decreased

Table 6. Simulated error† of sorghum grain yields for ALMANAC and SORKAM.

		Simulated error			
		ALMANAC		SORKAM	
Town	County	Garst 5616	Garst 5319	Garst 5616	Garst 5319
		%			
Williamson	Hutto	−0.4		−11.6	
Wharton	El Campo	0.7		−9.6	
Jackson	Edna	−7.6		−29.2	
Refugio	Austwell	0.9	−4.5	−17.4	−21.8
San Patricio	Sinton	22.5	5.1	3.2	−11.5
	West Sinton	−0.9	−7.9	−16.4	−22.3
Nueces	Agua Dulce	8.4	33.6	9.5	35.0
	Bishop	−2.4	−17.8	38.7	16.9

† Simulated error = [(simulated grain yield − measured grain yield)/measured grain yield] × 100.

Table 7. Simulated LAI (leaf area index) and seasonal plant transpiration (E_p) of sorghum for ALMANAC and SORKAM.

		ALMANAC		SORKAM	
County	Town	LAI	E_p	LAI	E_p†
			mm		mm
Williamson	Hutto	2.59	226	4.07	–
Wharton	El Campo	2.57	257	3.07	–
Jackson	Edna	2.61	250	2.83	–
Refugio	Austwell	2.60	245	3.52	–
San Patricio	Sinton	2.58	268	4.48	–
	West Sinton	2.59	261	3.60	–
Nueces	Agua Dulce	2.54	94	5.74	–
	Bishop	2.62	147	4.48	–
Avg.		2.59	219	3.97	–

† Not output by SORKAM.

by drought stress, especially at the dryland sites. The mean simulated HI was 0.45 for irrigated maize and 0.38 for dryland maize. For sorghum, HI was essentially stable, not allowed to decrease below 0.44 as discussed above.

In conclusion, for this water-limited year, CERES and ALMANAC simulated grain yields with r^2 values >0.85 while SORKAM simulations had an r^2 value of 0.45. While in previous studies (Kiniry et al., 1997; Kiniry and Bockholt, 1998), ALMANAC and CERES accurately simulated mean long-term grain yields for diverse locations, the present study demonstrated that the models could also simulate single-year grain yields under extreme climatic conditions for several sites. These models could be valuable tools for risk assessment of grain production. The models showed promise for application in climates with high probability of drought stress. ALMANAC simulated maize grain yields more accurately than CERES in these dry conditions because LAI and kernel weight simulated in CERES appeared to be overly sensitive to drought stress. However, the detailed phenology and yield components in CERES and SORKAM are suitable when evaluating hybrid characteristics in different environments and with different stresses. Further study on response of LAI and kernel mass to drought stress in CERES would be valuable. At the irrigated sites, the models had similar simulated maize grain yields. Drought stress reduced HI of maize to 0.38 for the dryland sites. ALMANAC does not allow the HI of sorghum to decrease below 0.44. It should be emphasized that these simulations used actual soil parameters determined with soil cores taken at the sites. In future model applications, especially in drought-limited conditions, the importance of representative soil parameters should be considered.

The models and data sets can be obtained by sending three 3.5-inch diskettes to the corresponding author.

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