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Development and evaluation of a sorghum model based on CERES-Maize in a semi-arid tropical environment

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ABSTRACT

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This paper reports on the development and evaluation of a grain sorghum model (CERES-Sorghum(SAT)) for use in the semi-arid tropics. The model was developed from a version of CERES-Maize, previously adapted for use in this climatic zone. Functions for phenology, leaf growth, leaf senescence, assimilate accumulation and grain growth were modified using a small subset of sorghum data and validated against a much larger field-data set. When tested with cultivar De Kalb DK55 at Katherine, Northern Territory, the model successfully predicted grain-yield with a root mean square deviation of 0.972 to ha^{-1} over a range of sowing dates and water regimes resulting in observed yields ranging from 1.56 to 6.28 t ha^{-1}. Deviations of predicted from observed yields were no greater than those of maize predictions by the parent model. Prediction of components of yield and biomass were also satisfactory. Calibration required 28 changes to the CERES-Maize(SAT) model, of which 15 were changes to coefficients in equations rather than substantial changes to the model. Because of the ease of conversion and the time-use efficiency found in these analyses, the techniques used in this paper could have application where locally calibrated models are required.

INTRODUCTION

Research for agricultural development in the semi-arid tropics (SAT) is frustrated by high year-to-year climatic variability. Crop yield-simulation models provide a means of placing crop and environment information collected at a site during a particular season into the context of the variation in seasons for that and similar sites. Models are presently available for many of

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the crops which are well-adapted to this zone. Generally, these have been developed in temperate locations and with a bias toward high-input agriculture. Adequate prediction in the SAT of the performance of cultivars adapted to low-input agricultural systems in the SAT cannot be assumed. For the CERES-Maize crop simulation model (Jones and Kihiry, 1986), changes were required to obtain satisfactory agreement with maize (*Zea mays* L.) data in the semi-arid tropics of northern Australia (Carberry et al., 1989). The present paper represents a further step toward the objective of providing, for the major SAT crops, a family of models which have been intensively tested and adapted for performance in this climatic zone.

CERES-Maize was chosen because it was a readily available, widely used process model which treated crop physiology and soil water and nitrogen dynamics at a level of organization appropriate for our purposes (Carberry et al., 1989). In the selection of a model for grain sorghum (*Sorghum bicolor* (L.) Moench), similar criteria were applied. Neither the widely used sorghum model SORGF (Maas and Arkin, 1978), nor its descendant SORKAM (Rosenthal et al., 1989), simulate nitrogen supply to the crop, whereas CERES-Maize does. In addition the retention of the CERES-Maize structure for a grain-sorghum model maintains the operational efficiency of a family of crop models sharing a common framework of functions and common input/output formats.

Although we had access to a draft version of CERES-Sorghum (J.T. Ritchie, Michigan State University, East Lansing, and G. Alagarswamy, ICRISAT, Patancheru, India, personal communication, 1988) we chose for two reasons to adapt the semi-arid tropical version of CERES-Maize (CERES-Maize (SAT); Carberry et al., 1989), using data that had been collected simultaneously with that used for developing and testing CERES-Maize(SAT). The extent of modifications necessary in the calibration of CERES-Maize(SAT) indicated that similarly extensive calibration of CERES-Sorghum would also be required for this climatic zone, and we believed that using CERES-Maize(SAT) as the starting point would allow easier conversion than using the draft CERES-Sorghum model. Further, as the draft version of CERES-Sorghum was possibly subject to major changes before publication, there was no valid reference point for calibration of CERES-Sorghum.

This paper describes the development and testing of a grain-sorghum model, CERES-Sorghum(SAT). An important result of this process will be the identification of deficiencies in the model and thus areas for future research.

MATERIALS AND METHODS

Field experimentation

Field studies examining the response of grain sorghum (cv. DeKalb DK55) to water deficits were conducted at Katherine Research Station, Northern

Territory Australia (latitude 14° 28′S, longitude 132° 18′E, and altitude 108 m). Katherine has a well-defined hot, wet season from November to March and a warm dry season for the remainder of the year. Mean annual rainfall is 1012 mm, with a coefficient of variation of 21% (Williams et al., 1985). Crops were sown from 1983 to 1987 (Table 1) on Fenton clay loam (Lucas et al., 1987), a well-drained red earth or Alfisol (USDA Soil Taxonomy: Oxic or Rhodic Paluestalf). Soil water extractable by sorghum on this soil at Katherine varies from 100 to 170 mm (R.C. Muchow, unpublished data, 1985).

Cultural details, similar in all sowings, are fully described by Muchow (1988; 1989a). To recap briefly, sorghum was grown in 50-cm rows at 25 plants m^{-2} in the November 1983 and February 1984 sowings, and at 16 plants m^{-2} in the remaining sowings (Table 1). Subsequent studies have shown no grain-yield response to population density in the range of 8–25 plants m^{-2} in this

TABLE 1

Summary of sowings, treatments and grain-yield (on an oven-dry basis) for each sowing where irrigation[1] was withheld and water deficits developed

Dataset[2]	Sowing date	Irrigation withheld	Grain-yield ($g\ m^{-2}$)
1	25 Nov. 1983	nil	523
2	25 Nov. 1983	10–28 DAS[a]	528
3	07 Feb. 1984	nil	453
4	07 Feb. 1984	50 DAS–mature	399
5	10 Oct. 1984	nil	446
6	10 Oct. 1984	25–57 DAS	268
7	10 Oct. 1984	41–57 DAS	337
8	06 Feb. 1985	nil	560
9	06 Feb. 1985	53–65 DAS	527
10	06 Feb. 1985	53 DAS–mature[b]	509
11	20 Aug. 1985	nil	467
12	20 Aug. 1985	20–44 DAS	369
13	20 Aug. 1985	64 DAS–mature	420
14	29 Jan. 1986	nil	628
15	30 Aug. 1986	nil	446
16	30 Aug. 1986	19–45 DAS[c]	349
17	19 Feb. 1987	21 DAS–mature[d]	156
18	28 Feb. 1987	nil	624
19	13 Nov. 1987	nil	542
20	13 Nov. 1987	25 DAS–mature[e]	557

[1]Nil indicates fully irrigated. No rain fell during the periods irrigation was withheld, unless otherwise indicated.
[2]Datasets 1–13 have comparable data sets for maize, referred to in Table 4.
(a) DAS, – days after sowing.
(b) Rainfall 105 mm 66–71 DAS.
(c) Rainfall 63 mm on 30 DAS.
(d) Additional irrigation, 14 mm on 28 DAS, 52 mm on 48 DAS.
(e) Rainfall: 170.5 mm, 35–43 DAS; 44.5 mm, 49–53 DAS; 54.0 mm, 60–66 DAS; 50.5 mm, 79–88 DAS.

environment (R.C. Muchow, unpublished data, 1985). All crops were grown under high-input conditions (24 g N and 3 g P m^{-2}) and weeds, insects, diseases and grain-eating birds were rigorously controlled. All sowings had four replicates, except the February 1987 sowing which had three.

At each sowing date, different water regimes were imposed as summarised in Table 1. In most sowings, one water regime was sprinkler-irrigated to restore the soil-water profile after four rain-free days. In the other water regimes, irrigation was withheld during specified, generally rainless periods to allow study of the effect of water deficits.

Time to emergence was recorded in each trial. The dates of panicle initiation were determined on the February 1984 and November 1987 sowings and the dates of anthesis and physiological maturity were established on all sowings, as outlined by Muchow (1988; 1989a). Radiation interception and soil-water extraction were recorded throughout the growth of these crops (Muchow, 1989b). At anthesis and maturity, 2-m^2 quadrats were taken and above-ground biomass and grain-yield were determined using procedures given in Muchow (1988; 1989a,b).

Crop growth simulations

CERES-Maize (Jones and Kiniry, 1986), was modified for sorghum by applying, as a guide, the analyses of Carberry et al. (1989), who used data from maize crops planted on the same dates as most of the sorghum crops in Table 1. Similar to the maize calibration, sorghum dataset 5 (Table 1) was used for specifying most functions of the model for sorghum grown under non-stressed conditions, although datasets 1, 3, and 5 were used to calibrate phenological development and datasets 5 and 8 to calibrate grain-growth parameters. The remaining datasets were retained for independent validation of the model.

Accuracy of prediction was quantified using the root mean square deviation (RMSD) between a number (n) of predicted (P) and observed (O) paired results where

$$\text{RMSD}=[(\Sigma(O-P)^2/n)]^{0.5}$$

The RMSD is a measure of the accuracy of the prediction and represents a weighted average difference between predicted and observed data. It was chosen to allow comparison with the maximum and minimum values of the observed parameter (Table 4). Moreover, Willmott (1982) argues that RMSD is one of the ‘best’ overall measures of model performance as it summarises the mean difference between observed and predict values.

Many of the inputs (crop management, soil characteristics etc.) required to run CERES-Maize(SAT) have been reported elsewhere (Carberry et al., 1989). The same or similar inputs are required to run CERES-

Sorghum (SAT); parameter values for the genetic constants describing cultivar DeKalb DK55 and for the Fenton clay loam are given in Table 2.

The thermal time from germination (assumed to be one day after sowing) to emergence was set to the observed value for each data set. Although the CERES models nominally simulate germination and emergence, the functions did poorly in this case. This may be due to variations in planting depth or imprecise assessment of emergence date. The thermal time from seedling emergence to the end of the juvenile stage (P1) and the photoperiod-sensitivity coefficient (P2) used in calculation of the thermal time from the end of the juvenile stage to panicle initiation (P2D) were calculated from datasets 1 and 3. The thermal time from the end of leaf growth to the beginning of linear grain fill (P4) and from anthesis to maturity (P5) were derived from dataset 5.

Potential kernel number (G2) and potential kernel growth rate (G3) were calibrated values which simulated the correct grain-yield, grain number per plant and kernel size in dataset 5.

The values for lower, drained upper and saturated limits for soil water content (LL, DUL, SAT) in Table 2 were based on field measurements recorded in dataset 6.

TABLE 2

Genetic data[1] for cultivar DeKalb DK55 and soil data[1] for Fenton clay loam, Katherine Research Station

Genetic data

NAME	P1	P2	P5	G2	G3
DeKalb DK55	423.0	65.0	600.0	3160.0	0.67

Soil data

SALB	*U*	SWCON	CN2
0.20	4.0	0.10	85

Soil-layer data

DLAYR	LL	DUL	SAT	WR
15.0	0.236	0.368	0.380	0.860
15.0	0.232	0.369	0.371	0.640
15.0	0.228	0.357	0.381	0.470
151.0	0.267	0.368	0.381	0.350
15.0	0.272	0.378	0.389	0.260
15.0	0.275	0.384	0.395	0.190
30.0	0.279	0.377	0.388	0.120
30.0	0.296	0.366	0.377	0.070
30.0	0.323	0.356	0.377	0.040

[1]Variables as defined in Appendix 1.

RESULTS

Experimental data

The results of the field experiments are summarised in Table 1. Oven-dry sorghum grain-yields ranged from 1560 kg ha^{-1} (dataset 17) to 6280 kg ha^{-1} (dataset 14). The extent of reduction in grain-yield in water-deficit treatments depended on the severity and timing of the deficit. However, both the degree of reduction and range of grain-yields were less than for maize grown under the same conditions (Muchow, 1988a,b).

Model calibration

Calibration of functions that exist in CERES-Maize(SAT) and substitution of alternative functions were required for the development of the sorghum model. Modifications were needed to phenology, leaf growth and senescence, assimilate production and grain growth; these are summarised in Table 3. The reasons for and extent of the modifications are described below.

(i) Thermal time
Thermal time was calculated from daily maximum and minimum temperatures, allowing for a base temperature of 7°C during all growth stages as reported by Arkin et al. (1983). An optimum temperature for development was not implemented in the sorghum model because predictions without an optimum were better for sorghum grown at Katherine than with an optimum temperature set to 34°C, as in CERES-Maize.

(ii) Phenology
The thermal duration of the first phenological period (P1), from emergence to the end of the juvenile stage was 423 degree-days (°C d), calculated from the regression of thermal time to panicle initiation against photoperiod in excess of 12 h (sunrise to sunset plus civil twilight). The durations from the end of the juvenile stage to panicle initiation depended on a genotype-specific photoperiod-sensitivity factor (P2) of 65°C d h^{-1} for DK55. The approach here was similar to that used by Carberry et al. (1989), showing a sensitivity of approximately 3°C d h^{-1} for sorghum compared to 4°C d h^{-1} for maize used in CERES-Maize(SAT). The base photoperiod was assumed at 12 h (Thomas, 1980) (Table 3, item 3).

The duration from emergence to anthesis was calculated from dataset 5 in a similar manner to that in the CERES-Maize(SAT) and depended on the prediction of leaf number and leaf appearance rate (Table 3, item 4). In CERES-Maize(SAT), leaf growth ceases prior to silking to allow for a period of tassel and cob growth, whereas silking and the end of cob growth coincided in the original model. The former approach is used in CERES-Sorghum (SAT) since anthesis occurs later than the end of leaf growth and close to the beginning of grain-filling. Anthesis was observed in dataset 5 at 197°C d after the end of leaf growth (Table 3, item 4), with linear grain-filling starting a further 33°C d after anthesis (Table 3, items 5).

(iii) Leaf growth and senescence

In simulating leaf-area development of sorghum, CERES-Sorghum (SAT) departs from the procedures in CERES-Maize, which simulates leaf area on a per-plant basis as a function of the appearance of leaf tips, but is similar to CERES-Maize (SAT) by simulating the emergence and expansion of individual leaves. Leaf-initiation and appearance rates, and functions for leaf growth and senescence determined for sorghum cultivar DK55 from dataset 5, are shown in Table 3 (items 7,8,9 and 10). Final leaf number is calculated from thermal time from germination to panicle initiation divided by the rate of leaf initiation. Total leaf area on a given day is calculated by addition of the day's leaf expansion to the leaf area of the previous day, then accounting for leaf senescence. A subroutine was added to calculate daily leaf expansion on the basis of four simultaneously expanding leaves. The proportion of daily leaf growth allocated to each of the four expanding leaves was determined from dataset 5. Leaf-senescence functions depend on plant leaf area (emergence to panicle initiation), and plant leaf area and thermal time from panicle initiation to the start of linear grain-filling and during grain-filling, and are similar to those in CERES-Maize.

Leaf-area production is converted to potential assimilate demand for leaves via specific leaf area (cm^2 leaf area g^{-1} leaf dry-matter) functions. Use of the function from CERES-Maize (SAT) for total leaf area of grain sorghum proved acceptable. However the function for new leaves, i.e. those being expanded on a given day, was unsuitable and a new coefficient was developed from dataset 5 (Table 3, item 11).

(iv) Assimilate production and partitioning

CERES-Maize (SAT) assumes conversion efficiencies for maize of 3.4 g MJ^{-1} from emergence to the start of linear grain-growth, and 2.15 g MJ^{-1} subsequently. Muchow and Davis (1988) reported lower conversion efficiencies in sorghum than in maize. Those used in CERES-Sorghum (SAT) are based on observed sorghum values but adjusted for pre-anthesis root growth. We adopted conversion efficiencies of 3.0 g MJ^{-1} until anthesis and 1.8 g MJ^{-1} thereafter (Table 3, item 12).

Generally, we have adopted the same responses to high temperature as in the modified CERES-Maize (Carberry et al., 1989). Those authors described the rationale for using a broad temperature range (20–40°C) over which photosynthesis of C4 grasses remains essentially constant. The temperature-

TABLE 3

Revisions made to CERES-Maize(SAT) to create CERES-Sorghum(SAT)[1]

Function	Conditions	CERES-Maize(SAT)	CERES-Sorghum(SAT)
Thermal time			
1. Base temperature (°C)	ISTAGE=9	10	7
	ISTAGE=1 to 6	8	7
2. Optimum temperature (°C)		34	—
Phenology			
3. Base photoperiod (h)	—	12.5	12.0
4. Emergence to anthesis (°C d)	—	(TLNO−2)*41.4+275.8	(TLNO−1)*60.9+197
5. Anthesis to start of grain filling (°C d)	—	170	33
Leaf growth and senescence			
6. Leaves present at emergence	—	0.5	1.0
7. Leaf initiation rate (°C d $leaf^{-1}$)	—	23.2	46.9
8. Leaf appearance rate (°C d $leaf^{-1}$)	CUMPH=1 to 4	73.5	—
	CUMPH=5 to TLNO	41.4	—
	All leaves	—	60.9
9. Leaf area (cm^2 $leaf^{-1}$)	XN=1 to 3	9.8*XN	—
	XN=4 to 11	5.45*XN**2	—
	XN=1 to 11	—	0.331*XN**3 (r^2=0.99)
	XN=12 to TLNO-4	546.6	495.0
	XN=TLNO-3 to TLNO	520/(XN+5−TLNO)**0.5	495.0−69.0*(XN+4−TLNO) (r^2=0.98)
10. Cumulative leaf senescence (cm^2 $leaf^{-1}$)	ISTAGE=1,2	PLA/1000	PLA/275 (r^2=0.86)
	ISTAGE=3	SUMDTT*PLA/1000	PLA*(0.0121+0.154*(SUMDTT/P3)**2) (r^2=0.98)
	ISTAGE=4	PLA*(0.06+SUMDTT/170+0.04)	PLA*(0.179+0.317*SUMDTT/(P4+P5−33)) (r^2=0.99)
	ISTAGE=5	PLA*(0.09+0.6(SUMDTT/P5)**3)	PLA*(0.179+0.317*SUMDTT/(P4+P5−33)) (r^2=0.99)

11. Specific leaf area (cm^2 g^{-1})	New leaves	334**1.25/PLA**0.25	286**1.25/PLA**0.25 (r^2=0.96)
Assimilate production			
12. Conversion efficiency (g MJ^{-1})	ISTAGE=1 to 4	3.40	3.00
	ISTAGE=5	2.15	1.80
13. Temperature stress factor	8<TEMPM<20	0.083*TEMPM−0.66	—
	7<TEMPM<20	—	0.077*TEMPM-0.61
14. Stem growth (g plant^{-1})	XN<13	GROLF*0.0182*(XN-XNTI)**2	GROLF*0.0150*(XN−XNTI)**2 (r^2=0.83)
	XN<(TLNO-3)	3.1*3.5*TI	GROLF*0.0150*(XN−KNTI)**2 (r^2=0.83)
	ISTAGE=4	GROEAR*0.4	GROPAN*2.4
Grain growth			
15. Ear/head growth	ISTAGE=4	0.22*DTT*SWDF2	0.024*DTT*SWDF2 (r^2=0.85)
16. Relative grain filling rate factor	ISTAGE=5	1−0.00647*(TTMP-30)**2/8	1−0.003154*(TTMP−30)**2/8
17. High temperature stress factor	TEMPMX>38.0	1−(TEMPMX−38.0)*0.019	—
18. Minimum grains per plant	—	GPP=51	GPP=240
19. Barrenness	GPP, G2*0.55	EARS=PLANTS*(GPP−50)/ (G2−50)**0.33	—
Soil water			
20. Drained lower limit	DEPTH>110 cm	DLL=0.008*(CUMDEP−110)* (DUL(NLAYR)−LL(NLAYR)+ LL(NLAYR)	—

[1]Variables are defined in Appendix 1.

stress coefficient is similar to that used in the SORGF model (Maas and Arkin, 1978), except for alteration at temperatures below 20°C of the cutoff point and coefficient because of reduction in the base temperature (Table 3, item 13).

Functions for stem growth in CERES-maize(SAT) substantially overpredicted stem weight for sorghum, especially after 12 leaves had appeared, a time at which the panicle becomes a major sink for assimilate in sorghum. Because the panicle of sorghum is much smaller than the ear of maize, only one function (rather than two as in CERES-Maize) was developed from dataset 5 for stem growth until the end of leaf growth. From then until the beginning of linear grain-filling, another function was developed from dataset 5 (Table 3, item 14).

(v) Grain growth

Changes in the method of calculating grain growth are modifications of functions used in CERES-Maize(SAT) on the basis of dataset 5 (Table 3, items 15–19). The lower coefficient for panicle (head) growth (Table 3, item 15) reflects the much lower weight of the panicle of sorghum compared to the ear of maize.

The equation used for calculating grain number per head is the same as in CERES-Maize(SAT), based on a relationship developed by Edmeades and Daynard (1979). In the model, this equation depends on the calculation of potential grain number from average assimilate accumulation over a nominated period. CERES-Maize uses assimilate accumulation from silking to the start of linear grain-filling, a period of 170°C d. We retained this approach and calibrated the functions for potential and actual grain number per plant on assimilate accumulation from the end of leaf growth to the start of linear grain-filling, a duration of 230°C d.

The relative rate of grain-filling in CERES-Sorghum(SAT) is temperature-dependent, and was calibrated using datasets 5 and 8 with an optimum temperature of 30°C for grain-filling (Table 3, item 16). The high-temperature stress factor necessary in CERES-Maize(SAT) was omitted in CERES-Sorghum(SAT) (Table 3, item 17).

Finally, a lower limit to grain number per plant was set by calibration of CERES-Maize (Table 3, item 18). There was no evidence of barren plants in our datasets and so the function used in CERES-Maize(SAT) to reduce the number of maize ears in response to barrenness was deleted (Table 3, item 19).

(vi) Soil water

The changes to soil water calculation introduced by Carberry et al. (1989) were retained. The lower limit of plant-extractable water used for sorghum was lower than that used in CERES-Maize (SAT). The lower level was based on measured levels of residual water in each soil layer after sorghum (and maize) crops had reached permanent wilting point at Katherine Research Station (R.C. Muchow, unpublished data, 1985). Thus, the function to compensate for the inability of plants to extract soil water to permanent wilting point at depths greater than 110 cm was unnecessary. With these changes, simulation of soil water balance was generally good (data not presented).

Model predictions

The RMSD values for predictions of CERES-Sorghum(SAT) for all 20 data sets are shown in Table 4. To enable a comparison between the performances of CERES-Sorghum(SAT) and CERES-Maize(SAT), the RMSD values were calculated for the first 13 datasets where sorghum and maize were grown under identical conditions.

The predicted time to anthesis are compared to observed times in Fig. 1.

TABLE 4

Maximum and minimum observed values and RMSD[1] of predictions for sorghum by CERES-Sorghum(SAT) for all 20 data sets and RMSD for the subset of 13 data sets which contained equivalent sowings of maize

Variable	Number of datasets[2]			
	Sorghum			Maize
	20	Range	13	13
Days to anthesis (sorghum)/ silking(maize)	3.0	57–74	3.0	1.1
Dry-weight at anthesis/ silking (kg ha^{-1})	1274	5820–10150	1298	811
L at anthesis/silking	0.9 (12)	2.84–6.37	0.84 (5)	0.99
Leaf number	1.46(18)	15.4–20.1	1.66(11)	0.33
Days to maturity	6.3	85–107	6.0	5.4
Grain-yield (kg ha^{-1} dry-weight)	972	1560–6280	827	1703
Grain size (mg)	3.8	11–21	3.3	8.9
Grain number m^{-2}	4606	11770–3600	4625	697
Grain number plant^{-1}	298	730–2465	264	86.8
Biomass at maturity (kg ha^{-1})	1687	5860–16440	1569	2106
Stover at maturity (kg ha^{-1})	1136	4310–10160	1243	1128
L at maturity	0.9(12)	0.35–4.13	0.86 (5)	0.78

[1]RMSD of predictions of CERES-Maize(SAT; Carberry et al., 1989) are also included for comparison
[2]Unless shown in parenthesis beside RMSD value

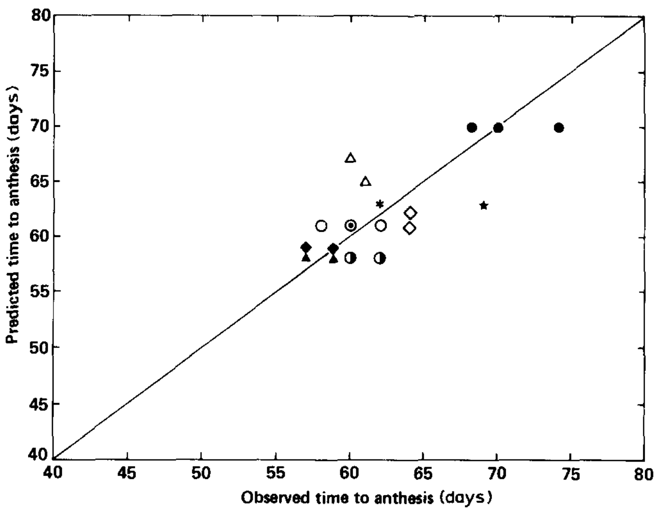

Fig. 1. Comparison of predicted and observed time (days) from sowing to anthesis for datasets 1–2 (▲), 3–4 (△), 5–7 (○), 8–10 (◇), 11–13 (●), 14 (•), 15–16 (◑), 17 (★), 18 (*), 19–20 (♦). Solid line represents the 1 : 1 line.

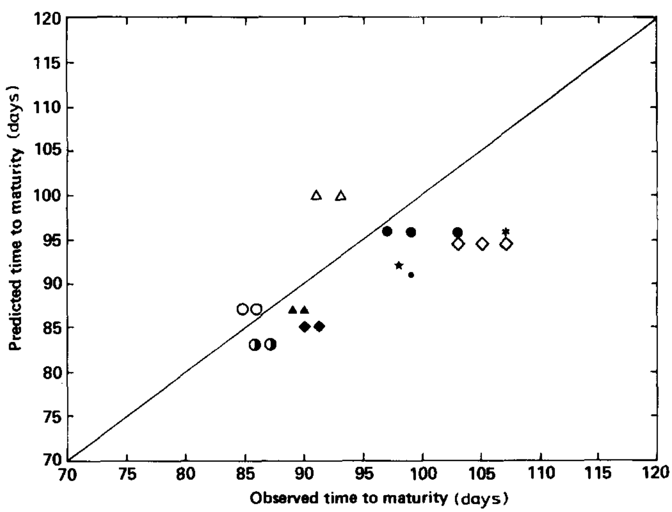

Fig. 2. Comparison of predicted and observed time (days) from sowing to maturity for datasets 1–2 (▲), 3–4 (△), 5–7 (○), 8–10 (◇), 11–13 (●), 14 (•), 15–16 (◑), 17 (★), 18 (*), 19–20 (♦). Solid line represents the 1 : 1 line.

The range of predictions (58–70 days) was not as broad as that for the experimental data (57–74 days), primarily because the observed effects of water deficits on phenology are not accounted for in the CERES models. Most er-

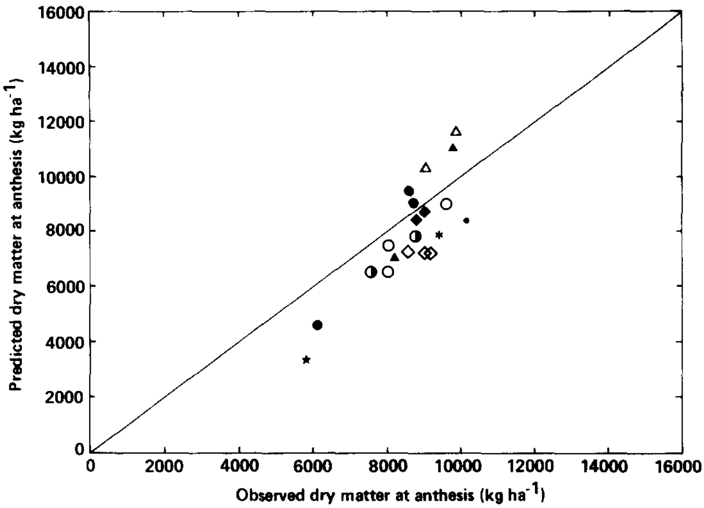

Fig. 3. Comparison of predicted and observed dry matter (kg ha^{-1}) at anthesis of grain sorghum grown at Katherine Research Station for datasets 1–2 (▲), 3–4 (△), 5–7 (○), 8–10 (◇), 11–13 (●), 14 (•), 15–16 (◑), 17 (★), 18 (*), 19–20 (◆). Solid line represents the 1 : 1 line.

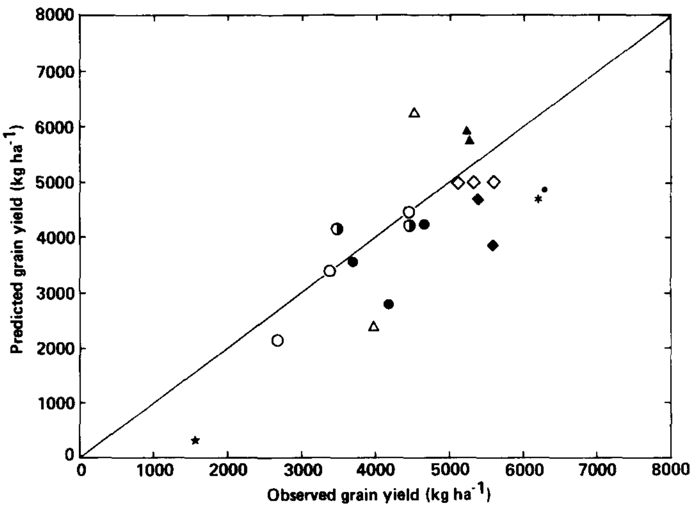

Fig. 4. Comparison of predicted and observed grain-yield (kg ha^{-1}, oven-dry basis) of grain sorghum grown at Katherine Research Station for datasets 1–2 (▲), 3–4 (△), 5–7 (○), 8–10 (◇), 11–13 (●), 14 (•), 15–16 (◑), 17 (★), 18 (*), 19–20 (◆). Solid line represents the 1 : 1 line.

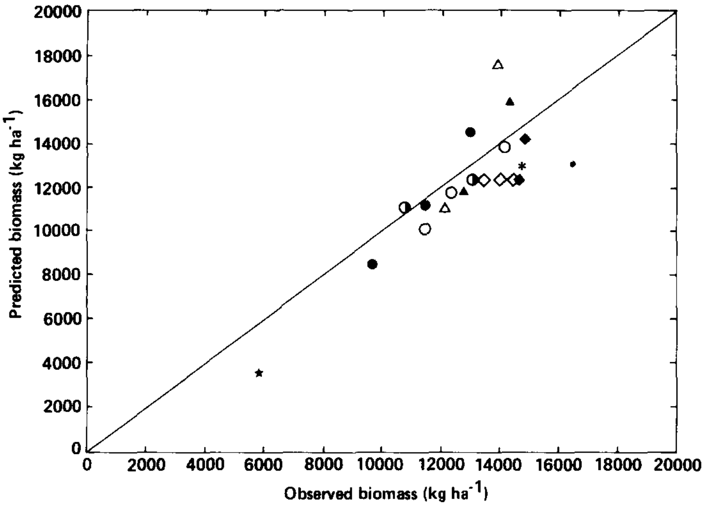

Fig. 5. Comparison of predicted and observed biomass yield at maturity (kg ha^{-1}, oven-dry basis) of grain sorghum grown at Katherine Research Station for datasets 1–2 (▲), 3–4 (△), 5–7 (○), 8–10 (◇), 11–13 (●), 14 (•), 15–16 (◑), 17 (★), 18 (*), 19–20 (♦). Solid line represents the 1 : 1 line.

rors associated with the prediction of time to maturity (Fig. 2) were due to the discreptancies in the prediction of time to anthesis.

CERES-Sorghum(SAT), using values for leaf-initiation and appearance rates of 46.9 and 60.9°C d leaf^{-1}, respectively, predicted leaf number to within 10% of observed in most datasets. Underprediction of leaf number was usually associated with observed leaf numbers of 18 or above, while some overprediction occurred if water deficit occurred prior to panicle initiation. The prediction of leaf-area index (L) at anthesis was generally consistent with that of leaf number in datasets for well-watered crops, but where water deficits were imposed the model underpredicted leaf area.

Dry-matter production at anthesis (Fig. 3) tended to be underpredicted except at the highest values. Deviation of more than 10% from observed dry-matter yield at anthesis was associated with prediction of time to anthesis more than one day early or four days late.

Figure 4 presents predicted grain-yield versus observed yield. For most data sets the predictions were close to the 1 : 1 line, although some data were noticeably underpredicted. These outliers flag two probable weaknesses in CERES-Sorghum(SAT), the prediction of grain number per plant and the effect of stress on phenology. Although largely compensatory, errors occurred in the prediction of grain number and grain size. The underprediction of time to maturity in some datasets resulted from variations in observed thermal time for the grain-filling stage, thus the underprediction of grain size would be expected.

The prediction of biomass at maturity (Fig. 5) and stover followed the same patterns as for grain-yield. Some overprediction at high yields was associated with plant populations of 25 plants m^{-2}.

DISCUSSION

CERES-Maize (Jones and Kiniry, 1986) provided the framework for a sorghum model and the adaptation of the same model for the SAT, CERES-Maize(SAT) (Carberry et al.,1 989), provided guidelines for possible revision. The extent of modification of CERES-Maize(SAT) to develop CERES-Sorghum(SAT) is shown in Table 3. Of the changes made, 15 were changes to coefficients which could be placed in files external to the program. The techniques used should enable efficient calibration of models for local conditions elsewhere.

The range of crops for which simulation models have been developed is now quite large (Whisler et al., 1986; Joyce and Kickert, 1987). In the main, one is impressed by the individuality of the models rather than their similarities.

Significant additional learning of model structure and operation is often required when moving from one model to another. An exception is the CERES group of models. In the development of a family of models for the semi-arid tropics, we place high value on varying the software as little as possible and have adopted CERES as the standard. The expediency of using the CERES structure for sorghum has been confirmed in this paper.

The predictive accuracy of CERES-Sorghum(SAT) was quantified through comparison of predicted and observed parameters. A comparison of predictive accuracy between the CERES-Maize(SAT) and CERES-Sorghum(SAT) models, for crops of maize and sorghum grown under identical conditions (datasets 1–13 in Table 1), showed that their performances were similar for most aspects of crop growth, given the differences in absolute parameter values between maize and sorghum crops (Table 4). The exception, where CERES-Sorghum(SAT) appeared less accurate, was in the prediction of phenological development.

Some comment is warranted on performance relative to that of the draft CERES-Sorghum supplied by Ritchie and Alagarswamy. After rigorous calibration of the required parameter specifications for the variety used (DeKalb DK55), soil and weather data using the same data sets for calibration and tested against the same independent datasets as for CERES-Sorghum(SAT), the RMSD value for grain-yield was 2207 kg ha^{-1} compared to 972 kg ha^{-1} for CERES-Sorghum(SAT). The importance of this difference is the indication of the relative merit of CERES-Sorghum(SAT) and the draft CERES-Sorghum at the time of development of CERES-Sorghum(SAT). An adequate comparison of the performance of the CERES-Sorghum of Ritchie and Alagarswamy and CERES-Sorghum (SAT) must await the publication of the former.

Subsequent revisions of CERES-Sorghum (SAT) will benefit from (a) more extensive use of existing data sets in specifying functions, (b) collection of data to eliminate deficiencies in present datasets; and (c) testing at more locations.

Data previously reserved for validation purposes can now be utilized to further improve the functions (Table 3). For example, the photoperiod sensitivity (P2) of DK55 is larger, when all available data was used in its calibration, than the value calculated from the datasets used for calibration purposes in the present work (Table 2). This partly explains the lack of spread in the predicted time from sowing to anthesis (Fig. 1) and maturity (Fig. 2) compared to that observed. Further work using existing data is needed on the simulation of phenology under water-deficit conditions and the prediction of grain numbers.

At present, CERES-Sorghum (SAT) does not contain functions to predict date of emergence or tiller development. Data used in the present paper did not contain measurements of sowing depth, soil seed cover or emergence percentages. No tillering occurred in the Katherine studies used for model development; a tillering function is needed for the model to be used in high-altitude SAT and in the sub-tropics.

To date, the model is based entirely on data from Katherine, N.T. However, by varying the sowing date and water regime (by the use of supplementary irrigation) on the one site, much of the respective domains of photoperiod, temperature and soil water regime that exist in the northern Australia SAT are reflected in the present model with less of the variation that would occur with a multi-site study. Further testing of CERES-Sorghum (SAT) both for other genotypes and at different locations are priority areas in our current research.

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APPENDIX 1: DEFINITION OF VARIABLE NAMES

Variable	Definition
Phenological stage	
ISTAGE	9, germination to emergence
	1, Emergence to the end of the juvenile phase
	2, End of juvenile stage to panicle initiation
	3, Panicle initiation to end of leaf growth
	4, End of leaf growth to start of grain filling
	5, Anthesis to physiological maturity

Genetic constants

NAME	Cultivar name
P1	Thermal duration (°C d, base = 7°C) of ISTAGE = 1
P2	Photoperiod sensitivity coefficient (°C d h^{-1})
P2D	Thermal duration (°C d, base = 7°C) of ISTAGE = 2
P3	Thermal duration (°C d, base = 7°C) of ISTAGE = 3
P4	Thermal duration (°C d, base = 7°C) of ISTAGE = 4
P5	Thermal duration (°C d, base = 7°C) of ISTAGE = 5
P9	Thermal duration (°C d, base = 7°C) of ISTAGE = 9
G2	Maximum grains per plant of the cultivar used
G3	Potential grain growth rate (mg $seed^{-1}$ day^{-1})

Soil and program variables

CN2	Curve number input to calculate daily runoff
CUMDEP	Cumulative depth of soil profile (cm)
CUMPH	Cumulative number of fully expanded leaves
CUMDTT	Cumulative thermal time after germination (°C d)
DLAYR	Thickness of soil layer *I* (cm)
DTT	Daily thermal time (°C d)
DUL	Drained upper limit for soil water content for soil layer (cm cm^{-1})
EARS	Ear number (ears m^{-2})
GPP	Grain number (grains $plant^{-1}$)
GROEAR	Daily ear growth-rate (g ear^{-1} day^{-1})
GROLF	Daily leaf growth-rate (g $plant^{-1}$ day^{-1})
GROPAN	Daily panicle growth-rate (g $panicle^{-1}$ day^{-1})
HRLT	Daylength (h)
LFWT	Leaf weight (g $plant^{-1}$)
LL	Lower limit of plant extractable water for soil layer (cm cm^{-1})
NLAYR	Number of soil layer
PLA	Total plant leaf area (cm^2 $plant^{-1}$)
PLAG	Leaf area that expands on a day (cm^2 $plant^{-1}$ day^{-1})
PLANTS	Plant population (plants m^{-2})
SALB	Bare-soil albedo
SAT	Saturated water content for soil layer (cm cm^{-1})
SDEPTH	Sowing depth (cm)
STMWT	Stem weight (g $plant^{-1}$)
SUMDTT	Thermal time for a phenological stage (°C d)
SWCON	Soil water-conductivity constant
SWDF2	Soil water-deficit factor used to calculate cell expansion
TEMPM	Mean daily air temperature (°C)
TEMPMX	Maximum daily air temperature (°C)
TLNO	Total number of leaves the plant produces
TTMP	3-h mean air temperature (°C)
U	Upper limit of stage-1 evaporation (mm)
WR	Weighting factor for soil depth to determine root distribution in each layer
XN	Number of the latest expanding leaf