

## Testing the CERES-Maize Simulation Model in a Semi-Arid Tropical Environment

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### ABSTRACT

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Crop simulation models are proposed as tools for agricultural risk analysis in order to explore potential cropping locations and appropriate farming systems in the semi-arid tropics. This study takes the initial step of independently validating the STANDARD CERES-Maize simulation model in the semi-arid tropics, and reports some modifications made to improve its performance. The CERES-Maize model did not accurately predict grain-yield of cultivar Dekalb XL82 which was grown over a range of sowing dates and water regimes at Katherine, N.T. Experimental yields (at 15.5% moisture) ranged from 0 to 9840 kg ha<sup>-1</sup>. Calibration of CERES-Maize reduced the root mean square deviation (RMSD) for observed grain-yields from 3480 to 2015 kg ha<sup>-1</sup>. Functions describing phenology, leaf growth and senescence, assimilate production and grain growth were revised and validated against field data. The revisions to CERES-Maize not only provide a model more applicable to the semi-arid tropics but also identify the parameters that may require calibration for other maize genotypes and locations in this climatic zone. Further validations of the functions describing nitrogen cycling and rainfall infiltration and runoff are required to increase the model's applicability to risk-analysis studies.

### INTRODUCTION

Of the three main cereal-grain crops of the sub-humid to semi-arid tropics, maize has the highest production when water and soil fertility are ample, but it is the least tolerant of stress (Kassam et al., 1975; Muchow, 1989b). Maize traditionally has been grown where rainfall is high, being replaced by sorghum and pearl millet as rainfall declines. However, the development of short-season maize cultivars and the lack of success in breeding bird-resistant grain sorghum have resulted in a new interest in expansion of maize production in the semi-arid tropics.

Any promising new cropping technology needs to be assessed for several

growing seasons before it is implemented. Because season-to-season rainfall in the semi-arid tropics is so variable, assessment over a sufficient sample of years is costly. A partial alternative is to use a crop growth-and-yield simulation model to estimate a yield probability distribution by using existing weather records. Generally, it is cheaper to use an existing model rather than to develop a new one, so long as certain criteria are met. The model must be conceptually appropriate to the research in hand, it must have input requirements which can be practically met, and it must give reasonable predictions. We selected the CERES-Maize model (Jones and Kiniry, 1986) because it filled these criteria, and because it was also being tested over a wide range of environments by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT; Anonymous, 1985). It was tested using weather and crop data from Katherine, N.T., a site typical of the semi-arid tropics (Williams et al., 1985).

The first objective of this study was to compare the predictions of CERES-Maize with observed data from field trials. Validation was done using the STANDARD model, which assumes that nitrogen is non-limiting, together with a series of field experiments which ranged in sowing date and moisture regime but where nutrition was adequate. Where the performance of CERES-Maize could be improved, a second objective was to revise the functions or parameters of the model which were sensitive to altered climatic conditions or to changing the genotype. The revised model and the original version are compared by the use of independent data sets.

## MATERIALS AND METHODS

### *Field experimentation*

Two experiments examining the response of maize (cv. Dekalb XL82) to water deficits were conducted on an alfisol soil at Katherine Research Station, N.T., Australia (latitude 14°28'S, longitude 132°18'E, altitude 108 m). Katherine has a mean annual rainfall of 1012 mm (cv 21%), 90% of which falls between November and March. There were two sowings in the 1983/1984 experiment and three sowings in the 1984/1985 experiment (Table 1).

At each sowing, one water regime was fully irrigated, whereas irrigation was withheld and water deficits developed at different stages of growth in the other water regimes (Table 1). The severity of water stress imposed on each treatment is illustrated in Table 1 by the timing of withheld irrigation, its duration, and the irrigation shortfall from the fully irrigated treatment. Each treatment was replicated 4 times.

Cultural practices, which were similar in all sowings, are fully described for the 1984/1985 experiment by Muchow (1989a). In brief, maize was grown at 70 000 plants ha<sup>-1</sup> under high-input conditions (240 kg N ha<sup>-1</sup>; 30 kg P ha<sup>-1</sup>) and weeds, insects and diseases were rigorously controlled. In the 1984/1985

TABLE 1

Description of experiments and observed data utilized in the testing and calibration of CERES-Maize

Data set	Sowing date	Irrigation (mm)	Day-length (h)	Mean Temp. (°C)	Tassel Init. (°C d)	50% Silking (°C d)	Maturity (°C d)	Leaf no.	Maximum L	Grain-yield (kg ha <sup>-1</sup> )	Biomass at maturity (kg ha <sup>-1</sup> )	Grain count (no. m <sup>-2</sup> )
<b>A. 1984/1985 experiment</b>												
1	10 Oct. 84	571	13.35	30.4	—	996.4	1978.9	18.3	3.7	8170	17389	2830
2		345 (35-57)				996.4	1978.9	18.4	3.5	0	6517	0
3		385 (41-57)				996.4	1978.9	—	—	855	8352	530
4	06 Feb. 85	479	13.22	26.2	—	988.9	1980.2	17.5	3.5	8090	15920	3240
5		414 (53-85)				988.9	1980.2	—	—	7734	16067	3020
6		221 (53-108)				988.9	1913.4	—	—	5911	12190	2620
7	20 Aug. 85	505	12.62	28.7	—	1115.7	2059.7	19.2	3.4	7628	17753	3220
8		372 (20-44)				1135.5	2080.9	19.6	3.4	5216	11705	2050
9		355 (64-92)				1115.7	2096.3	—	—	1709	9915	1260
<b>B. 1983/1984 experiment</b>												
10	25 Nov. 83	263	13.76	28.9	346.0	1011.4	2007.5	—	—	8315	17037	3187
11		135 (10-28)				1075.5	2064.4	—	—	7418	14112	2694
12	07 Feb. 84	553	13.21	26.6	296.9	946.9	1840.1	—	—	8088	16293	3674
13		118 (51-89)				965.7	1677.6	—	—	4199	10845	2787

The stress periods for each moisture regime, where irrigation was withheld, are given in brackets as days after sowing (DAS). Daylength was that for 18 DAS, mean temperature was that for the actual growing season. Thermal times (°C d) taken from sowing till each phenological stage were calculated on a base temperature of 8 °C and a maximum of 34 °C. Grain-yield and biomass are given as oven-dry weights.

experiment, detailed observations were taken on phenology, leaf growth, soil water extraction, biomass accumulation and grain growth (Muchow, 1989a,b) whereas only phenology, biomass and grain-yield were recorded in the 1983/1984 experiment.

### *Crop growth simulations*

The CERES-Maize model simulates daily growth, development and production of a maize crop under given climatic and cultural conditions. It has been described by Jones et al. (1984) and Godwin et al. (1984). In this paper, CERES-Maize refers to the STANDARD version (i.e. without N-supply sub-routines) described by Jones and Kiniry (1986).

STANDARD CERES-Maize was used to simulate the growth of the cultivar Dekalb XL82 for the experiments listed in Table 1, by using daily weather and irrigation data collected in association with the experiments. Data-set 1 was used extensively in the calibration of CERES-Maize, although data-sets 10 and 12 were used to derive an alternative function for tassel initiation, and data-set 4 was used to derive functions for grain growth. The remainder of the data were reserved for independent validation of the revised model. The accuracy of model predictions of crop development, growth and grain yield was estimated using the root-mean-square deviation (RMSD), which is the mean weighted difference between observed and predicted values.

The input parameters needed to run CERES-Maize are listed in Table 2; parameter values used for the commercial cultivar Dekalb XL82 and Tippera clay loam soil are presented in Table 3. Most of the genetic data on XL82 were either measured directly or calculated from data-set 1 (Table 1). The thermal time from seedling emergence to the end of juvenile stage ( $P_1$ ) was set to that required to produce the observed number of leaves in data-set 1 as calculated by CERES-Maize. The photoperiod sensitivity coefficient ( $P_2$ ) was given the value of 0.52 as specified for other tropical hybrids by Ritchie et al. (1986). The duration of grain-filling ( $P_5$ ) was as observed in data-set 1. Potential kernel number ( $G_2$ ) and growth rate ( $G_3$ ) are the calibrated values required to achieve the correct simulation of grain yield for data-set 1. The values for the lower, drained upper and saturated limits of available soil water (LL, DUL, SAT) were based on those measured in the 1984/1985 experiment (Muchow, unpublished data, 1987).

In most of the experiments, 50% seedling emergence occurred 3 days after sowing (DAS) but was observed after 8 days in the experiment described in data-sets 7-9 (Muchow and Carberry, 1989). The delayed emergence could not be simulated by CERES-Maize. A concession was made in simulation of data-sets 7-9, in that simulated emergence date was set equal to the actual emergence date.

TABLE 2

Input data required for the STANDARD CERES-Maize simulation model (Jones and Kiniry, 1986)

Parameter or Variable	Acronym	Units
<b>Location data</b>		
Latitude	LAT	degrees
<b>Planting data</b>		
Sowing date	ISOW	day of year
Plant population	PLANTS	plant m <sup>-2</sup>
Sowing depth	SDEPTH	cm
<b>Climatic data</b>		
Year	IYR	—
Day	JDATE	day of year
Maximum temperature	TEMPMX	°C
Minimum temperature	TEMPMN	°C
Solar radiation	SOLRAD	langleys
Rainfall	RAIN	mm
<b>Irrigation data</b>		
Irrigation day	JDAY	day of year
Irrigation amount	AIRR	mm
<b>Genetic data</b>		
Cultivar name	NAME	—
Thermal time from emergence to end of juvenile stage	P1	°Cd
Photoperiod sensitivity coefficient	P2	day h <sup>-1</sup>
Thermal time from silking to physiological maturity	P5	°Cd
Potential kernel number	G2	kernels plant <sup>-1</sup>
Potential kernel growth rate	G3	mg kernel <sup>-1</sup> day <sup>-1</sup>
<b>Soil data</b>		
Soil albedo	SALB	—
Stage-1 soil evaporation coefficient	U	mm
Whole-profile drainage rate coefficient	SWCON	—
Runoff curve number	CN2	—
Layer thickness	DLAYR	cm
Lower limit of plant-extractable water for each layer	LL	cm cm <sup>-1</sup>
Drained upper limit for each layer	DUL	cm cm <sup>-1</sup>
Saturated water-content for each layer	SAT	cm cm <sup>-1</sup>
Root-distribution weighting factor for each layer	WR	—

TABLE 3

Genetic data for cultivar Dekalb XL82 and soil data for Katherine Research Station, as employed in the validation of CERES-Maize

Genetic data					
NAME	<i>P</i> 1	<i>P</i> 2	<i>P</i> 5	<i>G</i> 2	<i>G</i> 3
XL82	171.2	0.52	982.5	520.0*	8.70
Soil data					
SALB	<i>U</i>	SWCON	CN2		
0.20	4.0	0.10	85		
DLAYR	LL	DUL	SAT	WR	
15.0					
15.0	0.216	0.368	0.380	0.86	
15.0	0.222	0.360	0.371	0.64	
15.0	0.222	0.362	0.381	0.47	
15.0	0.273	0.368	0.381	0.35	
15.0	0.287	0.362	0.389	0.26	
30.0	0.309	0.351	0.395	0.19	
30.0	0.321	0.348	0.388	0.12	
30.0	0.330	0.342	0.377	0.07	
	0.326	0.344	0.354	0.04	

\*For the revised model  $G2 = 680.0$ .

## RESULTS

### *Experimental observations*

A summary of observations from the field experiments is given in Table 1; detailed analyses of these data are presented elsewhere (Muchow, 1989a,b; Muchow and Carberry, 1989). In brief, maize yields were consistently high under fully irrigated conditions, approaching 10 000 kg ha<sup>-1</sup> at 15.5% moisture. The extent of reduction in grain-yield where irrigation was withheld depended on the degree and timing of water deficits. No grain-yield was produced in data-set 2 (Table 1) because of the failure of maize in this experimental treatment to set any cobs. Consequently, a wide range of yields was observed with which the model simulations could be compared.

### *Model predictions*

The original simulations using CERES-Maize generally predicted grain-yields much higher than those observed (Fig. 1a). Total biomass at maturity was also overestimated (Fig. 2a). A revised CERES-Maize model, in which various changes were made using data-set 1 (Table 4), improved the accuracy of model predictions when tested against the remaining data-sets. Marked improvement in the prediction of grain-yield, especially low yields, by the revised

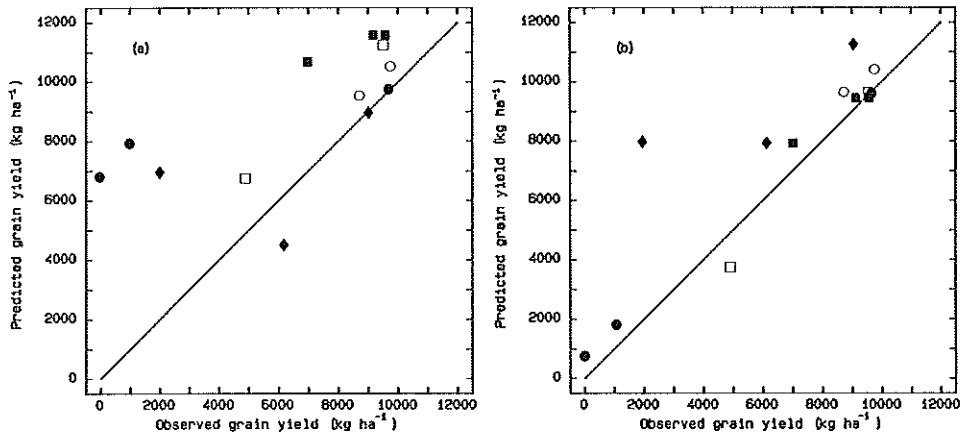


Fig. 1. Comparison between observed grain-yield (at 15.5% moisture) and that predicted by (a) the CERES-Maize model and (b) the revised model for data sets 1-3 (●), 4-6 (■), 7-9 (◆), 10-11 (○) and 12-13 (□).

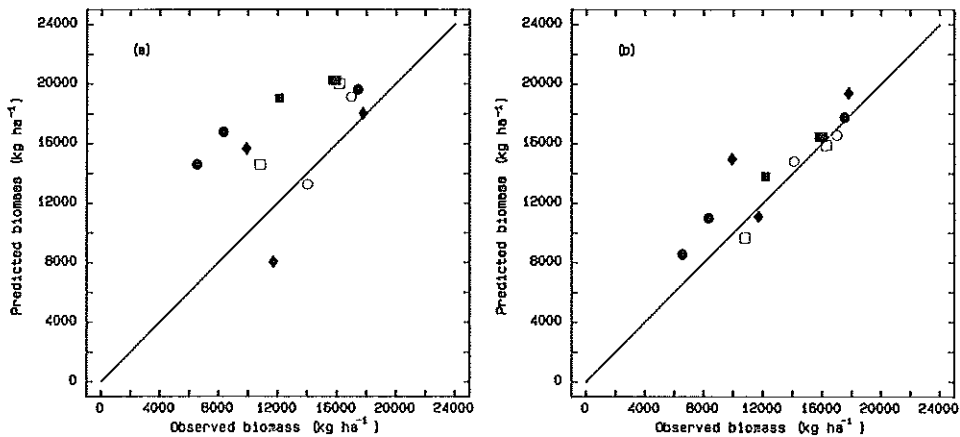


Fig. 2. Comparison between observed total biomass at maturity and that predicted by (a) the CERES-Maize model and (b) the revised model for data sets 1-3 (●), 4-6 (■), 7-9 (◆), 10-11 (○) and 12-13 (□).

model compared to the original CERES-Maize is shown in Fig. 1b. A similar improvement for the prediction of biomass is shown in Fig. 2b.

Table 5 presents RMSD values for the prediction of a number of crop variables by both the original and revised CERES-Maize models. For grain-yield, RMSD was reduced from 3480 kg ha<sup>-1</sup> for predictions of CERES-Maize to 2015 kg ha<sup>-1</sup> for the revised model. Similarly for biomass, RMSD was reduced from 5084 to 2160 kg ha<sup>-1</sup>. The poor predictions of the original model were partly the result of poor prediction of silking date, and this was corrected in the revised CERES-Maize (Fig. 3; Table 5). An improvement in the prediction of maturity

TABLE 4

Revisions made to the CERES-Maize simulation model (definitions of variables are given in either Table 2 or in Appendix 1)

Function	Units	Condition	CERES-Maize	Revised version
<b>Phenology</b>				
1. Duration of ISTAGE=2	°Cd	—	4.0 + P2 * (HRLT - 12.5)	— 88.4 * (HRLT - 12.5)
2. Duration from emergence to silking	°Cd	—	(TLNO - 2) * 38.9 + 96.0	(TLNO - 2) * 41.4 + 275.8
<b>Leaf growth and senescence</b>				
3. Leaf initiation rate	°Cd leaf <sup>-1</sup>	ISTAGE=1,2 1,2,9	21.0	— 23.2
4. Leaf appearance rate	°Cd leaf <sup>-1</sup>	CUMPH=1-4 5-TLNO	0.66 + 0.068 * CUMPH 38.9	73.5 41.4
5. Leaf area	cm <sup>2</sup> leaf <sup>-1</sup>	XN=1-3 4-11 12-(TLNO-4)	3.5 * XN 3.5 * XN * XN 595	9.8 * XN 5.45 * XN * XN 546.6
6. Cumulative leaf area senescence	cm <sup>2</sup> plant <sup>-1</sup>	(TLNO - 3) - TLNO ISTAGE=1,2 3 4 5	595 / (XN + 5 - TLNO) * 0.5 SUMDDTT * PLA / 10 000 PLA / 1000 PLA * (0.05 + SUMDDTT / 170.0 * 0.05)	520 / (XN + 5 - TLNO) * 0.5 PLA / 1000 SUMDDTT * PLA / 10 000 PLA * (0.06 + SUMDDTT / 170.0 * 0.04) PLA * (0.09 + 0.6 * (SUMDDTT / P5) * 3
7. Specific leaf area	cm <sup>2</sup> g <sup>-1</sup>	Total plant New leaves	P5) * 3 267 * 1.25 / PLA * 0.25 223 * 1.25 / PLA * 0.25	375 * 1.25 / PLA * 0.25 334 * 1.25 / PLA * 0.25



**Assimilate production**

8. Conversion efficiency	g MJ <sup>-1</sup>	ISTAGE=1-4	5.0	3.40
		5,6	5.0	2.15
9. Temperature stress factor			$1 - 0.0025 * ((0.25 * \text{TEMPMN} + 0.75 * \text{TEMPMX}) - 26) ** 2$	—
		8.0 > TEMP > 50.0	—	0.0
		20.0 < TEMP < 40.0	—	1.0
		8.0 < TEMP < 20.0	—	0.083 * TEMP - 0.66
		40.0 < TEMP < 50.0	—	5.0 - 0.1 * TEMP
10. Stem weight during ISTAGE=5,6	g plant <sup>-1</sup>	STMW > SWMAX	STMW	STMW
<b>Grain growth</b>				
11. Relative grain-filling rate factor			$(1 - 0.0025 * (\text{TTMP} - 26) ** 2) / 8$	$(1 - 0.0065 * (\text{TTMP} - 30) ** 2) / 8$
12. High-temperature stress factor in ISTAGE=4		TEMPMX > 38.0	—	$1 - (\text{TEMPMX} - 38.0) * 0.019$
<b>Soil water balance</b>				
13. Runoff curve no.		RAIN + AIRR	CN2	—
		RAIN	—	CN2
		AIRR	—	67

TABLE 5

The root mean square deviations for predictions by the original and revised CERES-Maize simulation models

Variable	CERES-Maize	Revised version
Days to silking	10.6	1.1
Dry weight at silking ( $\text{kg ha}^{-1}$ )	1470	811
$L$ at silking	1.14	0.99
Leaf number	2.49	0.33
Days to maturity	10.2	5.4
Grain yield ( $\text{kg ha}^{-1}$ , 15.5% moisture)	3480	2015
Grain size (g)	0.103	0.089
Grain number ( $\text{m}^{-2}$ )	1065	697
Grain number ( $\text{cob}^{-1}$ )	127.8	86.8
Biomass at maturity ( $\text{kg ha}^{-1}$ )	5084	2106
Stover at maturity ( $\text{kg ha}^{-1}$ )	2421	1128
$L$ at maturity	1.14	0.78

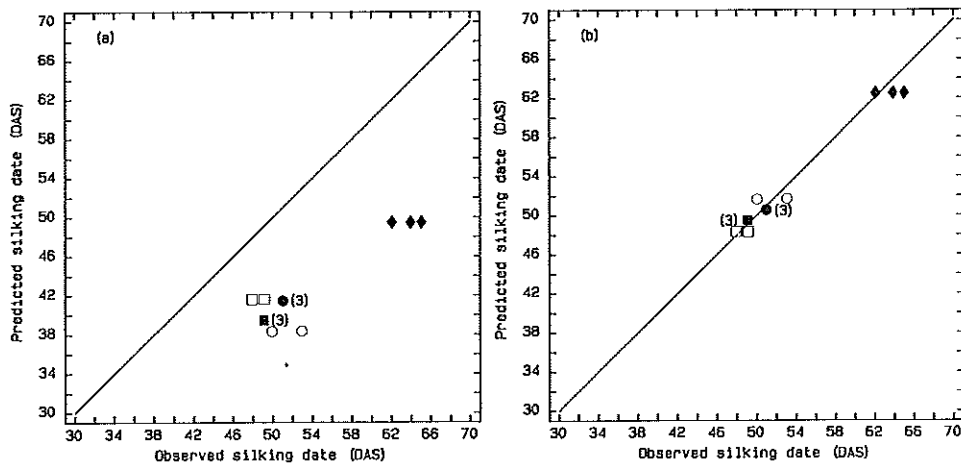


Fig. 3. Comparison between observed number of days after sowing (DAS) for silking and that predicted by (a) the CERES-Maize model and (b) the revised model for data-sets 1-3 (●), 4-6 (■), 7-9 (◆), 10-11 (○) and 12-13 (□).

date was also achieved by the revised model compared to the original (Fig. 4). Significant improvements in estimates by the revised CERES-Maize in comparison with the original were obtained for dry-weight at silking, leaf numbers, leaf area index ( $L$ ), grain size, grain numbers and stover weight (Table 5).

#### Model revisions

The revisions made to improve model predictions were mainly calibrations of existing functions, but alternative functions were sometimes required. The

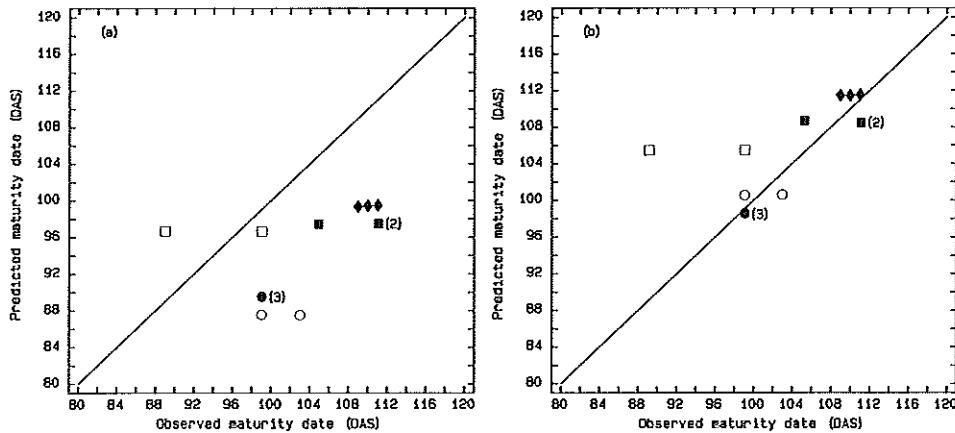


Fig. 4. Comparison between observed number of days after sowing (DAS) for physiological maturity and that predicted by (a) the CERES-Maize model and (b) the revised model for data-sets 1-3 (●), 4-6 (■), 7-9 (◆), 10-11 (○) and 12-13 (□).

major areas in which modification was needed were phenology, leaf growth and senescence, assimilate production and grain growth. A minor alteration was also required for more accurate predictions of plant available soil water in the tested environment.

#### (i) Phenology

The date of tassel initiation in CERES-Maize is dependent on a photoperiod-sensitive function (Table 4), where tassel initiation requires at least 4 days after the end of the juvenile stage. The duration from the end of the juvenile stage to tassel initiation increases at a rate of  $P2$  days for each extra 1-h daylight above the base photoperiod of 12.5 h. Ritchie et al. (1986) suggest a value for  $P2$  of  $0.52 \text{ day h}^{-1}$  for two tropical hybrids. For the tropical hybrid XL82 this value contributed to large underpredictions of silking date by CERES-Maize (Fig. 3a). The calibrated value of  $P2$ , using data-sets 10 and 12 (Table 1), was approximately  $4.0 \text{ day h}^{-1}$ , which was significantly outside the range of  $0-0.8 \text{ day h}^{-1}$  found for 42 cultivars grown throughout North America (Ritchie et al., 1986). A linear regression of thermal time from emergence to tassel initiation on photoperiod was determined from data-sets 10 and 12 (Muchow and Carberry, 1989). This alternative function (Table 4) when used in the revised CERES-Maize helped improve the prediction of silking date for all data sets (Fig. 3b; Table 5).

Silking date in the model is assumed to occur when the last leaf is fully expanded (Jones et al., 1986). Its thermal duration from emergence is calculated from the total number of leaves that has been initiated at the time of tassel initiation (Table 4). The calibration of this function for the genotype

XL82, using data-set 1, also contributed to the improved predictions of silking date by the revised model (Fig. 3b).

*(ii) Leaf growth and senescence*

In CERES-Maize the functions which control the initiation, emergence, expansion and senescence of maize leaves do not contain genotype-specific parameters. However, the values of the parameters used in most of these functions differed from those which were observed for cultivar XL82 in data-set 1 and thus incorporated in the revised CERES-Maize (Table 4). Final leaf number in the revised model is calculated as the thermal duration from germination (rather than from seedling emergence) to tassel initiation, divided by a leaf-initiation rate (Muchow and Carberry, 1989).

Given the leaf appearance rates specified in CERES-Maize, the full expansion of all initiated leaves occurs significantly before the silking date predicted by the phenology function. This is in contrast to the assumption of Jones et al. (1986), that predicted silking date and appearance of the ligule of the last leaf coincide in the model. In other words, leaf production prior to silking is not constrained to the predicted number of initiated leaves and so extra leaves are predicted to emerge. In the example of 18 leaves being initiated, 19.7 emerged leaves would be predicted. Emerged-leaf number therefore was constrained to equal initiated-leaf number. This created a phenological period in the revised CERES-Maize from the end of leaf-growth until silking which is equivalent to the observed phase of tassel and cob growth in cultivar XL82 prior to silking.

The area of each fully expanded leaf in data-set 1 and the simulated areas from the original CERES-Maize model are shown in Fig. 5a. CERES-Maize underestimated leaf sizes, especially the size of early-emerged leaves. When the functions describing the size of leaves were revised based on the observed data-set 1 (Table 4), estimation of the area of each leaf was greatly improved (Fig. 5a). CERES-Maize simulates on a daily basis the development of plant leaf-area from the sequential sum of the maximum area of each leaf for the cumulative expanded leaf number (CUMPH) plus the area of the presently expanding leaf (XN, which equals CUMPH + 1). Muchow and Carberry (1989) showed that cultivar XL82 produced a number of simultaneously expanding leaves and that total plant leaf-area corresponded more closely to the sum of areas of the fully expanded leaves plus the expanded area of the next 2 leaves. Thus, when CUMPH leaves have emerged, leaf-area per plant in the revised model is simulated as the sequential sum of the maximum area of CUMPH + 2 leaves.

A similar procedure was followed with respect to leaf-area senescence per plant. The observed senescence for data-set 1 and the corresponding original and revised simulations are shown in Fig. 3b; the improvement by the revised functions, shown in Table 4, demonstrate the sensitivity of leaf-area senescence to small changes in coefficients. Examination of the original senescence

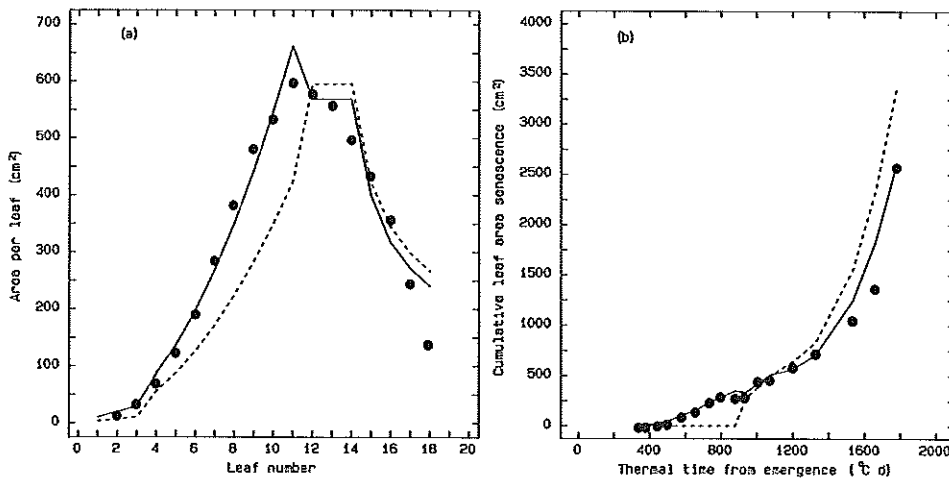


Fig. 5. The observed values for data set 1 (●) and those simulated by the CERES-Maize (-----) and revised (—) models for (a) area of individual leaves, and (b) cumulative leaf area senescence versus thermal time after emergence.

functions for growth-stages 1 and 2, and for growth-stage 3 (see Appendix 1) suggested that these functions need to be interchanged; this was confirmed by the calibration with data-set 1 (Table 4).

Specific leaf-area, or its reciprocal, specific leaf-weight, is required in CERES-Maize to determine the partitioning of assimilate to the leaves, based on the leaf-area expansion that occurs on a given day. Because stem-growth is related to leaf-growth in the model, these functions influence partitioning within the whole shoot. Although no measurements of specific leaf-area were available from the experiments described in this paper, subsequent experiments have indicated that the original functions significantly underestimate actual specific leaf area for cultivar XL82 (Muchow, unpublished data, 1986). The coefficients of the functions describing specific leaf-area for the original and revised CERES-Maize models are shown in Table 4.

### (iii) Assimilate production and partitioning

CERES-Maize assumes a potential conversion efficiency of 5 g of dry-matter per MJ of intercepted photosynthetically active radiation (PAR) from emergence till maturity. In data-set 1, the measured value was 2.36 g MJ<sup>-1</sup> (Muchow, 1989a), but this does not account for root mass and leaf senescence. If root weight was assigned to data-set 1 for the period until silking, using the minimum limits to the theoretical root-partitioning scheme of CERES-Maize, an apparent conversion efficiency of 3.2 g MJ<sup>-1</sup> would be determined for XL82. In the revised CERES-Maize model, a conversion efficiency of 3.4 g MJ<sup>-1</sup> (Warren Wilson, 1969) is used until linear grain-growth. Thereafter, it is re-

duced to the average conversion efficiency observed during grain-filling in data set 1 of  $2.15 \text{ g MJ}^{-1}$  (Muchow, 1989a).

The revised CERES-Maize model improved predictions of shoot biomass (Fig. 2; Table 5). However, when the differences in conversion efficiencies used in the original and revised CERES-Maize models were considered, the effects on the prediction of shoot biomass were not as proportionally great. This was because the partitioning scheme used in CERES-Maize permitted excess assimilate not used for shoot growth, to be partitioned in an unrestricted manner to roots throughout the complete growing-season.

In the narrow range of temperatures experienced during six different growing seasons at Katherine (Table 1), the reduction of conversion efficiency in the model (via a temperature-stress factor) when temperature deviated from a sharply optimal point (Table 4) proved inadequate and was discarded in the revised model. Duncan and Hesketh (1968) and McPherson and Slatyer (1973) have shown that the rate of photosynthesis of  $C_4$  grasses is not greatly affected by temperature over a considerable optimal range. A temperature-stress coefficient ranging from 0 to 1, similar to that used in the SORGF model (Maas and Arkin, 1978), was inserted in CERES-Maize (Table 4). The coefficient is set to 1 if the mean daily temperature is between 20 and 40°C (Duncan and Hesketh, 1968) and linearly declines to 0 at the two temperature extremes of 8°C and 50°C.

The original CERES-Maize does not permit partitioning of assimilate to stems after silking, yet post-silking increase in stem weight has been recorded for cultivar XL82 in this environment (Muchow, 1988, 1989a,b). This restriction was removed in the revised model (Table 4). Similar findings have been observed for tropically adapted genotypes grown in Kenya (B. Keating and B. Wafula, ACIAR/CSIRO Dryland Project, Nairobi, personal communication, 1987).

#### *(iv) Grain growth*

Although CERES-Maize incorporates a function for barrenness in its calculation of grain number, the large overprediction of grain-yield for data-set 9 (Fig. 1) was principally due to overprediction of fertile cob number by the original and revised models. This function was not calibrated in the revised model due to the limited number of independent data-sets available for validation.

Although not incorporated in CERES-Maize, the effects of high temperature on pollen viability in maize have been reported by Herrero and Johnson (1980) and Schoper et al. (1986). In data-set 1, high maximum temperatures corresponded with anthesis and appeared to account for reduced grain-numbers per ear in XL82 (Table 1). A high-temperature stress function therefore was incorporated into the revised model so that grain-number was reduced if maximum temperatures exceeded 38°C during the critical period in growth-stage 4 (Table 4).

Finally, the grain growth-rate function in CERES-Maize is temperature-dependent and needed calibration for data-set 1. The optimum temperature for grain-filling was set to 30°C, rather than 26°C as specified in the model (Table 4).

*(v) Soil water*

Part of the revision of CERES-Maize was to partition daily precipitation into rainfall and irrigation, for the purpose of determining the amount of water that infiltrates or runs off. This revision enabled a lower runoff potential to be given to irrigation compared to rainfall (Table 4). This requirement is needed given the high-intensity rainfall generally incident during the monsoon season in the semi-arid tropics. The resultant simulation of soil water balance by the revised CERES-Maize was generally good (data not presented).

## DISCUSSION

The performance of the STANDARD CERES-Maize simulation model, when applied to cultivar XL82 grown at Katherine, suggests that it is not applicable to predicting the growth of a maize genotype adapted to and grown in a semi-arid tropical environment. Its poor performance is not surprising, considering that data mostly collected under temperate conditions were used in development and initial validation of the model (Jones and Kiniry, 1986). Calibration of CERES-Maize substantially improved the predictive accuracy of the revised model. This was accomplished mainly by modifying existing functions, although some functions were replaced and other facilities added. The most important modifications improved the prediction of tassel initiation date and silking date, corrected the rate processes for leaf-growth and senescence, simulated the appropriate level of dry-matter assimilation, and improved the prediction of grain-growth in the tested environment (Table 4). Similar calibration processes may improve predictions for alternative cultivars or for other locations in this climatic zone.

The calibration for different genotypes of functions for the initiation, emergence, expansion and senescence of leaves is essential for accurate model predictions. Different environments may also necessitate recalibration of growth functions. Increased specific leaf-area at high temperatures (Warren Wilson, 1969; Thiagarajah and Hunt, 1982) may explain the higher specific leaf-area of XL82 grown at Katherine compared to that specified within CERES-Maize developed under temperate conditions (Table 4). The optimal temperature regimes specified in CERES-Maize also display clear differences to those expected in tropical environments. Parameters which are known to vary among genotypes or environments need to be read in as inputs for CERES-Maize to become more universal.

The validation of CERES-Maize presented in this paper confirmed the ap-

prehension of Kiniry and Jones (1986) that the phenological model could be inadequate for use in the tropics (Fig. 3a; Fig. 4a). The predictions of silking date (Fig. 3b) and final leaf number (Table 5) by the revised CERES-Maize model were greatly improved by adjusting the relationship between leaf number and silking date and by inserting an alternative function to determine the date of tassel initiation. This latter function was used due to the relative insensitivity to photoperiod, compared to cultivar XL82, of the genotypes for which the original function was developed (Jones and Kiniry, 1986). The tropically adapted genotype XL82 was far more responsive to changes in photoperiod ( $88^{\circ}\text{Cd h}^{-1}$ , Table 4) than the most sensitive temperate genotypes found by Rood and Major (1980,  $29^{\circ}\text{Cd h}^{-1}$ ) or Kiniry et al. (1983,  $36^{\circ}\text{Cd h}^{-1}$ ).

Since no experimental root-weights were available, no definite assertions can be made on the accuracy of the assumed conversion efficiency for maize of  $3.4\text{ g MJ}^{-1}$  compared to  $5.0\text{ g MJ}^{-1}$  used in CERES-Maize. High respiration losses in the tropics, due to high temperatures, may justify the lower conversion efficiency than that required for temperate regions. Values in the  $3\text{--}4\text{ g MJ}^{-1}$  range have been recorded for early maize growth by Williams et al. (1968), Stapper and Arkin (1980) and Sivakumar and Virmani (1984). The modelled decline in the efficiency of conversion of PAR to assimilate during grain-growth, due essentially to leaf-ageing, has been reported for maize by Stapper and Arkin (1980), Muchow (1989a), and by Muchow and Davis (1988), who have, in fact, shown that shoot conversion efficiency can vary during the growing season as a function of specific leaf nitrogen. More detailed studies on the efficiency of conversion of radiation to biomass (shoot plus root) are required before a potential ceiling can be assigned with confidence.

As the potential grain-yield of the maize crop is a model input via parameters  $P_5$ ,  $G_2$  and  $G_3$  (Table 2), CERES-Maize acts to reduce this potential as a result of sub-optimal environmental conditions. Direct experimental determination of these parameters for a specific genotype requires collecting data from low-population experiments under non-limiting temperature, water and nutrient conditions. An alternative is to calibrate these values by running the model on existing data sets (Jones and Kiniry, 1986), and this approach proved adequate in our testing of CERES-Maize.

Grain number per plant is predicted as a hyperbolic function of assimilate production in growth-stage 4. This function was taken from Edmeades and Daynard (1979) but its coefficient of determination was relatively low ( $r^2=0.62$ ). Grain number was consistently overpredicted in the initial validation of CERES-Maize (Kiniry and Jones, 1986). Due to lack of an acceptable alternative, the function was retained in the revised model. Stapper and Arkin (1980) predicted grain number in maize based on dry-matter at anthesis, but this approach also resulted in poor validations (Wright and Keener, 1982). The function that predicts grain number of maize in this test environ-



ment needs to account for both barren cobs and the effects of high-temperature stress on pollen viability. The latter requirement in simulation models is also identified by Stapper and Arkin (1980), Neild (1982) and Wright and Keener (1982).

As important as the improvements in yield predictions were, the testing and calibration of CERES-Maize is incomplete in two important respects. Probably the two main sources of error in predicting maize yields in the semi-arid tropics are in respect of (a) soil nitrogen supply and (b) partitioning of rainfall into infiltration and runoff. These areas are the subject of continuing research.

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#### APPENDIX 1

##### Definition of variable names used in CERES-Maize.

CUMPH	Cumulative fully expanded leaf number
HRLT	Daylength (h)
ISTAGE	Phenological stage: 7 - Presowing 8 - Sowing to germination 9 - Germination to emergence 1 - Emergence to end of juvenile stage 2 - End of juvenile stage to tassel initiation 3 - Tassel initiation to end of leaf growth and silking 4 - Silking to beginning of effective grain-filling period 5 - Effective grain-filling period 6 - End of effective grain-filling to physiological maturity
PLA	Total plant leaf area ( $\text{cm}^2 \text{ plant}^{-1}$ )
STMWT	Stem weight ( $\text{g plant}^{-1}$ )
SUMDTT	Thermal time for a given phenological stage ( $^{\circ}\text{C d}$ )
SWMAX	Stem weight at the beginning of the effective grain-filling
TEMPM	Mean daily air temperature ( $^{\circ}\text{C}$ )
TLNO	Total number of leaves produced per plant
TTMP	3-h mean air temperature ( $^{\circ}\text{C}$ )
XN	Number of the oldest expanding leaf

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