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Testing CERES-Maize versions to estimate maize production in a cool environment

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Abstract

CERES-Maize is a relatively simple deterministic crop model that simulates maize development, growth and yield. Since its first release in 1986, slight changes in the original model have been proposed by different researchers, generating a number of official or unofficial versions of CERES-Maize. Nevertheless, these versions have not been extensively tested under cool environments. The objective of this work is to evaluate the performance of three different recent versions of CERES-Maize ((i) CERES-Maize-2003 (called thereafter CERES-2003), the most recent version proposed by Kiniry; (ii) that included in DSSAT V3.5 official release or CERES-3.5 and (iii) the recently released version with DSSAT V4.0 or CERES-4.0) in a cool environment, where water and nutrients are fully available, and to document and discuss the equations causing differences in model predictions among versions. To achieve these objectives, these versions were tested against field data sets, obtained in northwest Spain between 1998 and 2002. CERES-4.0 simulated more closely the biomass and grain yield under this relatively cool environment. CERES-2003 showed the poorest performance, mainly due to the 64% dry weight loss programmed to occur with dry matter translocation from stem to grain. Reasons for CERES-4.0 advantage are related to the new look-up temperature functions affecting radiation use efficiency (PRFT) and grain filling rate (RGFILL) that in V4.0, create less sensitivity to temperature. Nevertheless, under these growing conditions CERES-4.0 predictions may benefit from slightly more temperature sensitive PRFT or RGFILL functions, but more extensive testing is needed to confirm this fact.
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Keywords: Temperature; Crop model; Genetic coefficients; Grain filling rate; Potential yield

1. Introduction

CERES-Maize is a relatively simple deterministic crop model that simulates maize development, growth

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Table 1
CERES-Maize genetic coefficients for Clarica maize cultivar

P1	175.0	Growing degree days base 8 °C (GDD, °C day) from seedling emergence to the end of the juvenile phase
P2	0.0	Photoperiodic sensitivity (days delay in tassel initiation per hour increase in photoperiod 0 for non-sensitive cultivars)
P5	630.0	GDD from 75% silking to physiological maturity (°C day)
G2	936.0	Potential kernel number per plant
G3	8.0	Potential kernel growth rate (mg seed^{-1} day^{-1})

and yield (Jones and Kiniry, 1986). During the crop life cycle, it calculates the phenological evolution, growth rate and the partitioning of biomass into growing organs with a daily time step. Under non-limiting water and N conditions, the simulated processes are affected by the main environmental variables (daily solar radiation and maximum and minimum temperature), cultivar-specific factors (five genetic coefficients defined in Table 1) that define cultivar (cv.) characteristics and crop management practices (i.e. sowing date, density and row spacing). This crop model, as all those included in the DSSAT software (Jones et al., 2003), allows simulation of crop development and growth under water and nitrogen limiting environments when the water and nitrogen balance options are switched on.

Since its release in 1986 (Jones and Kiniry, 1986), CERES-Maize has been widely applied under different environments to test the hypothetical consequences of varying management practices (i.e. sowing date) or characteristics of cultivars (i.e. life cycle duration) on biomass production and grain yield (Epperson et al., 1992; Boote et al., 2001). In addition, it is well established that once validated for a defined environment, crop models can be used as a valuable tool to propose better adapted crop management strategies (Hook, 1994; Kovacs et al., 1995; Boote et al., 1996; Royce et al., 2001; Ruiz-Nogueira et al., 2001; Matthews et al., 2002; Jagtap and Abamu, 2003). In some cases, the multiple calibration, validation and adaptation processes done in many locations have led to many different CERES-Maize versions, each differing slightly from the original model and not always well described in the literature. This phenomenon is especially noticeable in relatively simple and widely used models such as CERES-Maize (Carberry et al., 1989; Lahrouni et al., 1993; Castrignano et al., 1998; du Toit et al., 2002; Ben Nouna et al., 2003), probably because they are easy to modify.

In addition, the CERES-Maize model developers (Jones, Kiniry, Ritchie and their successors) have tried to progressively improve the original model to correctly mimic maize growth under an increasing range of cropping systems and environments (Kiniry et al., 1997; Kiniry and Bockholt, 1998; IBSNAT, 1989; Jones et al., 2003). We highlight three recent versions of CERES-Maize: (i) CERES-Maize-2003 (called hereafter CERES-2003), the most recent version proposed by Kiniry and co-workers; (ii) that included in DSSAT V3.5 official release or CERES-3.5 and (iii) the recently released version with DSSAT V4.0 or CERES-4.0 (Jones et al., 2003). These versions have not been extensively tested in cool areas where the temperature pattern requires the use of short life cycle cultivars as for inland regions of northwest Spain, Galicia, where maize is mainly grown for silage production and is, therefore, harvested before physiological maturity.

Wilson et al. (1995) discovered that the radiation use efficiency (RUE; Monteith, 1977)-based model of Muchow et al. (1990) did not predict accurately biomass and grain yield in cool regions of New Zealand until RUE and grain growth functions were given temperature limitations below 16 and 19 °C, respectively.

As in most simple crop models, CERES-Maize uses, since its first release (Jones and Kiniry, 1986), the RUE concept to estimate potential biomass accumulation per plant (PCARB) and reduces to a minimum the number of equations needed to calculate net photosynthesis.

$$\mathrm{PCARB} = \mathrm{RUE}\frac{\mathrm{IPAR}}{\mathrm{PLTPOP}} \tag{1}$$

$$\mathrm{IPAR} = \mathrm{PAR}[1 - \exp(-\mathrm{EXT} \times \mathrm{LAI})] \tag{2}$$

where IPAR is photosynthetic active radiation (PAR) intercepted by the canopy, PLTPOP plant population, leaf area index (LAI) and EXT is PAR extinction coefficient of the canopy.

In addition, in all CERES-Maize versions, the actual daily biomass production per plant (CARBO) can be less than PCARB due to suboptimum temperature or deficits of water or nitrogen:

$$\mathrm{CARBO} = \mathrm{PCARB} \times \min(\mathrm{PRFT},\ \mathrm{SWFAC},\ \mathrm{NFAC},\ 1.0) \tag{3}$$

where PRFT, SWFAC and NFAC are temperature, water stress and nitrogen stress reduction factors that can vary between 0 (maximum stress) and 1 (no stress), respectively. The model partitions assimilates between roots and leaves from emergence to tassel initiation and to roots, stems and leaves from tassel initiation to silking. Ear growth (GROEAR) is computed beginning at silking. At that time, biomass accumulation in leaves stops but stems and roots can continue gaining mass if enough assimilates are available. Later, the model estimates grain number per plant (GPP) from the average daily plant dry weight increase between silking and beginning grain filling. When beginning grain filling starts, CERES-Maize estimates daily filling rate per grain using a source–sink-reserves procedure that allows deriving total grain growth rate per plant (GROGRN; Ritchie et al., 1998). If sufficient assimilates are available, reproductive growth is computed multiplying the genetic coefficient G3 (potential kernel growth of the cultivars at optimum temperature) by Relative Rate of Grain Fill (RGFILL) that can vary between 0 and 1, depending on temperature.

These are the main differences between the three versions of the model studied:

1.1. Photosynthetic Reduction Factor (PRFT)

PRFT is a daily calculated temperature function that varies between 0 and 1 that affects radiation use efficiency (Fig. 1 shows PFRT versus average temperature during daylight hours (TAVGD = 0.25 × TMIN + 0.75 × TMAX), where TMIN and TMAX are minimum and maximum daily temperature (°C), respectively). When water and nitrogen are non-limiting at optimum temperature, PRFT = 1 and RUE reaches its maximum value, while if PRFT = 0, RUE is null, and therefore, crop biomass does not increase.

In CERES-2003 and CERES-3.5, PRFT is computed as in the original version (Jones and Kiniry, 1986):

$$\mathrm{PRFT} = 1.0 - 0.0025((0.25 \times \mathrm{TMIN} + 0.75 \times \mathrm{TMAX}) - 26.0)^2 \quad (4)$$

$$\text{if } \mathrm{PRFT} < 0, \quad \mathrm{PRFT} = 0.0$$

The function is weighted toward TMAX in an effort to represent daytime mean temperature.

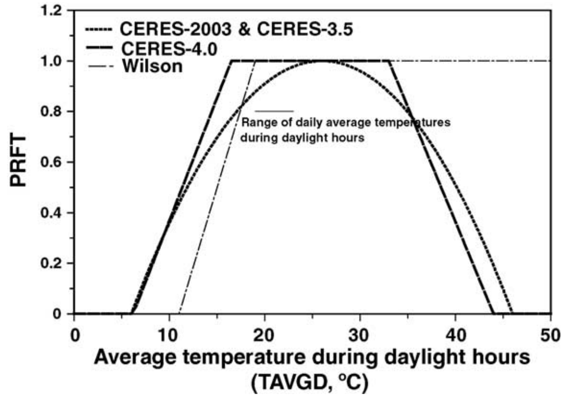

Fig. 1. Temperature-based function affecting Photosynthetic Reduction Factor (PRFT) in CERES-2003, CERES-3.5, CERES-4.0, and the temperature function proposed by Wilson et al. (1995), when temperature amplitude between day and night is 12 °C. Range of temperatures during daylight hours (TAVGD) along growing season of eight treatments is shown (TAVGD = 0.25 × TMIN + 0.75 × TMAX).

In CERES-4.0, PRFT follows a different 4-point temperature function: a linear function of TAVGD with the following cardinal temperatures (a base temperature (Tb) of 6.2 °C, a first optimum (Topt1) of 16.5 °C, a second optimum (Topt2) of 33 °C and a maximum (TMAX) of 44.0 °C (see Fig. 1)). CERES-4.0 in a new modular approach uses an external look-up function to define the shape of both PRFT and RGFILL (see below).

1.2. Relative Rate of Grain Fill

RGFILL is a temperature function computed daily that varies between 0 and 1. This function affects daily kernel growth (Fig. 2 shows RGFILL versus average daily temperature (Tavg = (TMIN + TMAX)0.5), assuming a 12 °C amplitude between minimum and maximum daily temperature similar to that occurring in the experimental fields). When water and nitrogen are non-limiting, at optimum temperature, RGFILL = 1 and daily kernel growth is equal to the genetic coefficient G3, while if RGFILL = 0, kernel growth is zero, and therefore, grain weight does not increase.

In CERES-2003 and CERES-3.5, RGFILL is computed as in the original version (Jones and Kiniry, 1986):

(1) eight temperature correction factors (TMFAC(*I*)) are calculated every 3 h (*I* = 1–8) to estimate 3 h

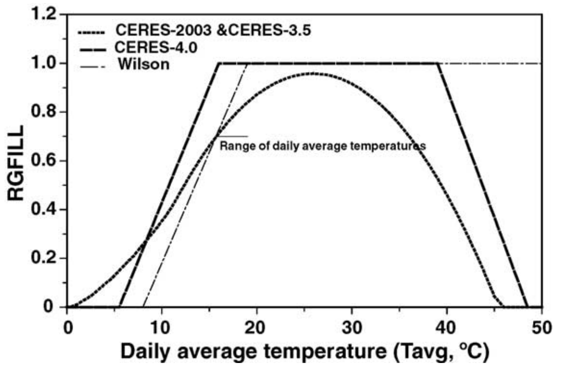

Fig. 2. Temperature-based function affecting Relative Rate of Grain Fill (RGFILL) in CERES-2003, CERES-3.5, CERES-4.0, and the maize model proposed by Wilson et al. (1995), when temperature amplitude between day and night is 12 °C. Range of temperatures during grain filling period of eight treatments is shown (Tavg = (TMIN + TMAX)0.5).

mean air temperature (TTMP),

$$\mathrm{TMFAC}(I) = 0.931 + 0.114 \times I - 0.0703 \times I^2 + 0.0053 \times I^3 \quad (5)$$

$$\mathrm{TTMP}(I) = \mathrm{TMIN} + \mathrm{TMFAC}(I) \times (\mathrm{TMAX} - \mathrm{TMIN}) \quad (6)$$

(2) RGFILL is obtained summing the following equations (from $I = 1$ to 8) if $\mathrm{TTMP}(I) > 6$,

$$\mathrm{RGFILL} = \mathrm{RGFILL} + \frac{1.0 - 0.0025(\mathrm{TTMP}(I) - 26.0)^2}{8.0} \quad (7)$$

In CERES-4.0, RGFILL follows a linear daily average temperature (Tavg) function (see Fig. 2) with the following cardinal temperatures: a base temperature (Tb) of 5.5 °C, a first optimum (Topt1) of 16.0 °C, a second optimum (Topt2) of 39.0 °C and a maximum (TMAX) of 48.5 °C.

1.3. Radiation use efficiency

In CERES-2003, RUE diminishes with vapour pressure deficit (VPD) and is computed following the equations proposed by Stockle and Kiniry (1990):

$$\text{if VPD} < 1\,\text{kPa}, \quad \mathrm{RUE} = 4.33\,\mathrm{g\,MJ^{-1}}\,(\mathrm{PAR}) \quad (8)$$

$$\text{if VPD} \geq 1\,\text{kPa}, \quad \mathrm{RUE} = 5.05 - 0.72 \times \mathrm{VPD} \quad (9)$$

In addition, VPD estimation in CERES-2003 is computed in a different way than in CERES-3.5 or CERES-4.0, using equations proposed by Diaz and Campbell (1988) and Stockle and Kiniry (1990) that do not require dew point temperature.

$$\mathrm{VPD} = \frac{\mathrm{PMEAN} - \mathrm{PMIN}}{1.0 - 0.3(\mathrm{PMEAN} - \mathrm{PMIN})} \quad (10)$$

$$\mathrm{PMEAN} = \exp\left(52.58 - \frac{6790.5}{\mathrm{TAVG} + 273} - 5.03 \times A \log(\mathrm{TAVG} + 273)\right) \quad (11)$$

$$\mathrm{PMIN} = \exp\left(52.58 - \frac{6790.5}{\mathrm{TMIN} + 273} - 5.03 \times A \log(\mathrm{TMIN} + 273)\right) \quad (12)$$

where PMEAN and PMIN are saturation vapour pressure (kPa) at daily mean and minimum temperature, respectively.

In CERES-3.5 and CERES-4.0, RUE is constant and equal to 4.2 g $\mathrm{MJ^{-1}}$ (PAR). In the original version (Jones and Kiniry, 1986), RUE is constant and equal to 4.5 g $\mathrm{MJ^{-1}}$ (PAR).

1.4. Extinction coefficient for PAR (EXT)

In CERES-2003, as in the original version (Jones and Kiniry, 1986), extinction coefficient for PAR is equal to 0.65.

In CERES-3.5 and CERES-4.0, EXT is a function of distance between rows and plant density (EXT = 0.59 when row spacing (ROWSPC) is 0.75 m and plant density is 100,000 plant $\mathrm{ha^{-1}}$).

$$\mathrm{EXT} = 1.5 - 0.768((\mathrm{ROWSPC} \times 0.01)^2 \times \mathrm{PLTPOP})^{0.1} \quad (13)$$

1.5. Efficiency of conversion of mobilized vegetative dry matter to grain

The model starts mobilizing dry matter to grain when actual daily biomass production per plant

(CARBO) is smaller than rate of grain growth (GROGRN). Then, a limited amount of vegetative dry weight can be translocated from stems and leaves.

In CERES-2003, 1.0 g of stem loss allows an increase of 0.36 g of grain weight according to Kiniry et al. (1992).

In CERES-3.5 and CERES-4.0, as in the original version (Jones and Kiniry, 1986), 1.0 g of stem loss allows an increase of 1.0 g of grain weight.

1.6. *Grains per plant computation*

In CERES-2003 for short season cultivars:

$$\mathrm{GPP} = 127 \times \mathrm{PSKER} + 10 \qquad (14)$$

as proposed by Kiniry et al. (2002), based on experimental results obtained by Tollenaar et al. (1992), where PSKER is daily average of biomass accumulation rate during “stage 4” (75% silking to beginning grain filling). Stage 4 is a relatively short period that lasts approximately 10–20 days. GPP is computed in this model without the G2 genetic coefficient (potential kernel number per plant; see Table 1).

In CERES-3.5 and CERES-4.0, GPP is computed as:

$$\mathrm{GPP} = \frac{\mathrm{G2} \times \mathrm{PSKER}}{7200.0} + 50.0 \qquad (15)$$

In addition, PSKER is computed slightly differently in CERES-2003 than in CERES-4.0 or CERES-3.5.

1.7. *Leaf area index computation*

In the three studied recent versions of CERES-Maize, leaf area computation equations are basically the same as used by the original version (Jones and Kiniry, 1986). The CERES-2003 coefficients used in these equations are identical to those described by Jones and Kiniry (1986), while CERES-4.0 and CERES-3.5 models use a slightly different set of coefficients that result in slightly greater LAI.

The objective of this research is to evaluate the performance of the three different recent versions of CERES-Maize ((i) CERES-2003, the most recent version proposed by Kiniry and co-workers; (ii) the official DSSAT V3.5 release or CERES-3.5 and (iii) the recently released version with DSSAT V4.0 or CERES-4.0) in a cool environment when water and nutrients are fully available, and to document and discuss the equations causing the possible differences between model predictions among versions. To achieve these objectives, these versions were tested against field data sets, obtained in Lugo (northwest Spain) between 1998 and 2002 with one short season cultivar grown under non-limiting water and N conditions at different sowing dates.

2. Materials and methods

2.1. *Experiments*

A common commercial cultivar of maize (*Zea mays* L.), Clarica, was grown in five consecutive years (1998–2002) at the experimental farm of the Universidad de Santiago de Compostela, located in Lugo, Galicia, northwest Spain (43°00′N; 7°30′W; 480 m elevation). The soil at the experimental site was a Typic Haplumbrept (USDA Soil Taxonomy) with a sandy–loam texture and has a pH in water of 5.6. Before sowing, soil was fertilized with ample amounts of N, P and K (see Table 2) to minimize limitation from these nutrients. A second N application was applied when plants had 8–10 visible collars and crop height was 0.60–0.80 m. Leaf analysis done during all experiments and treatments showed that N, P and K concentration were not limiting crop growth. Experiments in 1998, 1999 and 2000 had two sowing dates, while in 2001 and 2002, only one sowing date was implemented (see Table 2). Ten-day average TMIN was frequently 8–10 °C in May, early June and October, and TMIN, even in the warmest months was about 10–13 °C (see Table 3). In addition, TMAX was usually less than 20 °C in May and June and was only about 25–27 °C during the warmest months. In all experiments, row spacing and sowing depth were 0.75 and 0.05 m, respectively. Plant density was close to 10 plant m^{-2} (see Table 2; the actual field-sampled plant densities were used for model simulations). Plot size was 12.0 m × 7.0 m (16 rows of 7 m length) and had four replications. Drip irrigation was established for all plots and managed to avoid plant water stress. Irrigation was applied whenever one of the following thresholds for tensiometer measurements was surpassed: 0.07 MPa (30 cm depth tensiometer), 0.05 MPa (50 cm depth tensiometer) and 0.03 MPa (60 cm depth tensiometer). Irrigation amounts were recorded and

Table 2
Sowing date, harvest date, plant density, total N fertilization (amount of second application in brackets), P fertilization, and K fertilization of the different treatments of 1998, 1999, 2000, 2001 and 2002 experiments

Treatment	Sowing date (julian date in brackets)	Harvest date (julian date in brackets)	Plant density (plant m^{-2})	Total N fertilization (kg N ha^{-1})	Total *P* fertilization (kg P ha^{-1})	Total *K* fertilization (kg K ha^{-1})
1998—1st	May 14 (134)	September 22 (265)	9.8	320 (200)	26	133
1998—2nd	June 4 (155)	October 14 (287)	10.0	320 (200)	26	133
1999—1st	May 24 (144)	September 30 (273)	9.9	345 (165)	39	181
1999—2nd	June 7 (158)	October 14 (287)	10.0	345 (165)	39	181
2000—1st	May 18 (139)	October 4 (278)	9.7	390 (210)	39	181
2000—2nd	June 8 (160)	October 19 (293)	9.7	390 (210)	39	181
2001	May 19 (139)	September 26 (269)	9.8	390 (210)	39	181
2002	May 8 (128)	October 1 (274)	8.6	390 (210)	39	181

used for simulating soil water-balance. Before sowing, one TDR access tube was installed in the middle of the interrow of the center of each individual plot to a depth of 1.35 m, so soil water content could be monitored.

The main climatic variables (solar radiation, air temperature, relative humidity and precipitation) were measured with an automatic Delta-T weather station located close to the experiment. Temperature data for the experimental years are summarized in Table 3.

2.2. Dry matter sampling

Plant samples from 0.5 m^2 were taken in each plot at 15-day intervals throughout the entire crop life cycle in the experiments done between 1998 and 2001. A three-plant subsample was taken and separated into leaf blades, stem (leaf sheaths were included in the stem fraction as in the CERES-Maize model) and grain. All of the subsample components and remaining plants were dried separately to constant weight, in a convective oven at 70 °C for more than 48 h. At each sampling

Table 3
Mean daily maximum (TMAX) and minimum (TMIN) temperature every 10–11 days between May and October in 1998, 1999, 2000, 2001 and 2002

	1998		1999		2000		2001		2002	
	TMAX (°C)	TMIN (°C)	TMAX (°C)	TMIN (°C)	TMAX (°C)	TMIN (°C)	TMAX (°C)	TMIN (°C)	TMAX (°C)	TMIN (°C)
May 1–10	17.2	6.8	17.8	8.7	19.2	8.4	13.2	3.9	13.8	5.1
May 11–20	23.2	9.7	15.7	9.3	19.9	8.8	17.9	7.4	18.7	6.4
May 21–31	17.4	8.0	22.4	8.1	18.6	8.8	26.6	10.7	16.0	6.4
June 1–10	21.7	9.8	17.6	8.9	23.4	9.7	22.1	11.7	18.5	9.1
June 11–20	23.5	8.8	22.0	11.6	26.7	9.3	21.6	9.6	26.0	11.1
June 21–30	22.4	12.0	22.3	11.3	23.1	11.7	27.7	10.9	20.5	11.5
July 1–10	20.6	12.5	26.2	12.8	22.1	12.3	23.3	12.5	21.0	10.3
July 11–20	26.7	12.4	25.8	14.1	22.9	12.5	20.8	10.4	24.3	10.8
July 21–31	23.8	13.2	26.1	14.6	24.2	13.5	24.6	13.2	24.9	13.6
August 1–10	29.6	12.9	23.5	13.5	25.5	12.2	24.7	13.0	21.3	10.2
August 11–20	25.1	15.8	24.3	11.8	27.7	14.1	24.4	11.2	26.5	12.6
August 21–31	27.5	13.8	26.5	13.4	22.9	10.8	28.0	14.8	23.1	12.8
September 1–10	23.5	13.0	27.1	15.0	25.5	10.9	22.3	11.4	22.0	11.4
September 11–20	23.9	12.3	18.7	9.5	26.6	12.1	22.3	8.7	25.4	11.4
September 21–30	19.1	11.6	19.0	11.5	20.0	9.2	20.1	9.1	22.6	9.5
October 1–10	15.0	8.1	18.4	6.7	18.8	7.9	19.3	10.8	21.3	10.6
October 11–20	18.6	9.3	16.6	9.5	14.9	6.9	19.4	9.8	16.7	7.0
October 21–31	18.1	7.6	15.9	8.5	16.8	6.9	19.5	8.3	18.4	11.0

date, specific leaf area (SLA) was evaluated from the three-plant subsample leaf area with a Delta-T Image Analysis System in conjunction with the three-plant leaf weight, in order to estimate leaf area index from SLA and leaf weight per square meter.

Development was observed three times per week in all experiments, using the growth staging method described by Jones and Kiniry (1986). Tassel initiation was established when visible branching of the apex was detected through periodical observations with a magnifying glass of the apical meristem from the 4 to 6 collar stage.

At final harvest (at dates in Table 2), plants were hand harvested from an area of 6 m^2 from the central rows of each plot in all experiments. Seed yield, biomass and harvest weight were determined after each plant component was oven dried to constant dry weight at 70 °C. The weight of 1000 kernels was used to derive average kernel weight.

2.3. Determination of the genetic coefficients of cv. Clarica

In order to estimate the potential kernel number per plant (G2) and potential kernel growth rate (G3), a low density (4.8 plant m^{-2}) sowing (20 rows, 0.75 m apart with 15 m length) was established in 1999 at the same site, following the methodology proposed by Ritchie et al. (1986). Sowing date was the same used for the 1999—1st planting date shown in Table 2 (May 24). G2 was estimated at harvest, counting the number of kernels per plant in twenty randomly selected plants. G3 was estimated through periodical samplings during the grain filling period. We randomly collected six plants with two replicates at six sampling dates during grain growth (August 23 and 30; September 6, 14, 22 and 27) and kernel growth rate of the kernels from the middle of the ear was estimated through linear regression. The last two sampling dates data were excluded, because average temperature was low (below 20 °C; see Table 3) and kernel growth rate was reduced.

P1 and P5 were set to minimize error in phenology prediction by the three versions of CERES-Maize used in this work (see Section 2.4). The method used to minimize error in phenology prediction is described here: (1) using daily TMAX, TMIN, a Tb of 8 °C and phenology observations we calculated an average P1 and P5 considering the eight experimental treatments; (2) then, using this P1 value as a starting value, we minimized RMSE for silking through many iterations of P1 considering the three tested model versions altogether; (3) finally, P1 was set to this last value, and P5 was kept equal to the experimentally determined value. Through this approach, silking and physiological maturity were estimated with a maximum error of 5 and 9 days, respectively. Maximum errors in predicted physiological maturity were detected in later sowing dates, probably due to the slower thermal time accumulation at low temperatures registered at the end of the plant cycle.

2.4. CERES-Maize model versions

The three CERES-Maize versions used in this work can be obtained as follow: (i) CERES-3.5 and CERES-4.0 codes and executables, through the International Consortium for Agricultural Systems Applications (DSSAT) web-page (http://www.icasa.net/dssat/index.html), (ii) CERES-2003 code and executable, from Kiniry (USDA).

2.5. Model runs

Model runs with the three CERES versions were performed, with water balance simulation switched "on", using the Priestley–Taylor evapotranspiration equation as modified by Ritchie (Ritchie, 1985), soil characteristics and soil water content measured values at sowing date. As nitrogen supply proved to be not limiting, the model nitrogen-balance was switched "off".

2.6. Statistical and graphical procedures to evaluate the different CERES-Maize versions

The following criteria were used to assess performance of the different CERES-Maize versions: (i) intercept (a) and slope (b) values of linear regression between simulated and observed biomass at harvest, grain yield at harvest and maximum LAI using the eight treatments shown in Table 2; (ii) the root mean square error of these variables (RMSE) and (iii) an index of agreement (d, Willmott, 1982) that is an aggregate overall indicator that is of more value than R^2.

RMSE and d were computed as follow:

$$\mathrm{RMSE} = \left[N^{-1} \sum_{i=1}^{n} (P_i - O_i)^2 \right]^{0.5}$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|P'_i| + |O'_i|)^2} \right]$$

where N is the number of observed values, O_i and P_i are observed and predicted values for the ith data pair, $P'_i = P_i - \bar{O}$ (average of the observed) and $O'_i = O_i - \bar{O}$.

According to Willmott (1982), the model fit improves as d-index approaches unity and RMSE approaches zero.

Finally, predicted time series graphs of biomass, grain and LAI were also compared visually, with measurements to assess accuracy of time-series performance of the different CERES-Maize versions. Data from the in-season dry matter samplings (simulated versus observed) were used for calculating a, b, RMSE and d-index to compare the different model versions.

3. Results and discussion

3.1. Phenology prediction

Clarica genetic coefficients (P1, P5, G2 and G3) were established as described in Section 2. P2 was set to zero, as no photoperiod sensitivity was detected. P2 equal zero is the default value for short season cultivars. The linear regression that allowed G3 estimation had an R^2 of 0.998. The genetic coefficient values of cv. Clarica are shown in Table 1. With these coefficients, the three CERES-Maize versions were able to correctly predict the phenological evolution in different years and sowing dates. Estimated emergence date was always late (1.2 days (RMSE = 1.6) for CERES-2003; 2.4 days (RMSE = 2.6) for CERES-3.5 and CERES-4.0). Estimated flowering date computed by the three models (75% silking) had an average error below 2.5 days (RMSE < 3.2). Therefore, the phenology prediction accuracy of the three model versions was considered equivalent. Nevertheless, we want to highlight some inconsistency in the way Ritchie et al. (1986) proposed to estimate G3 in a low density experiment at mean daily temperature between 20 and 30 °C, that is supposed to be optimum for grain filling. Considering the RGFILL function, this assumption was fulfilled for CERES-4.0 but not for CERES-2003 or CERES-3.5 where optimum temperature, as in the original CERES-Maize version (Jones and Kiniry, 1986), is defined as 26 °C (Fig. 2). Therefore, if CERES-3.5 RGFILL temperature function is correct, we may be underestimating G3 in a low density experiment conducted under mean temperatures equal or just slightly higher than 20 °C, as occurred in this research.

3.2. Time series prediction accuracy of biomass, grain and LAI of the different CERES-Maize versions

The three models differed in simulated biomass, grain and LAI (Figs. 3 and 4). CERES-4.0 always simulated the highest biomass production, while CERES-2003 usually gave the lowest values for a given date. Even for CERES-4.0, the simulated biomass accumulation line was often below the experimental data, except for the 1999—2nd sowing date (results not shown) and 2001 treatments. Therefore, all models and especially CERES-2003 tended to underpredict biomass during the season. This situation was less perceptible when evaluated on final harvest data, where CERES-4.0 slightly overpredicted the average biomass of the eight treatments. It should be noted that small sampling areas (in-season samplings were 0.5 m^2) may tend to overestimate the actual biomass present in the final large plot samples, making the final harvest data (6 m^2) more reliable. This is confirmed by the fact that coefficients of variation were approximately four time greater for in-season samplings (ca. 12%) than at harvest (ca. 3%). In addition, “Gray literature” indicates 0–30% overestimation in the case of apparently homogeneous maize stands. Statistical analyses with the time series data confirmed that CERES-4.0 produced the most accurate predictions of biomass (Table 4; closest to 1.0 slope, intercept nearest to zero, lowest root mean square error and highest d-index). CERES-3.5 was similar to V4.0 except during grainfill, while CERES-2003 gave the poorest performance. A closer look to the CERES-2003 biomass curves (Fig. 3) shows that in every treatment, the simulated biomass curves showed an unexpected erratic shape (line with alternate positive and negative slopes), during much of the grain filling phase. These erratic biomass

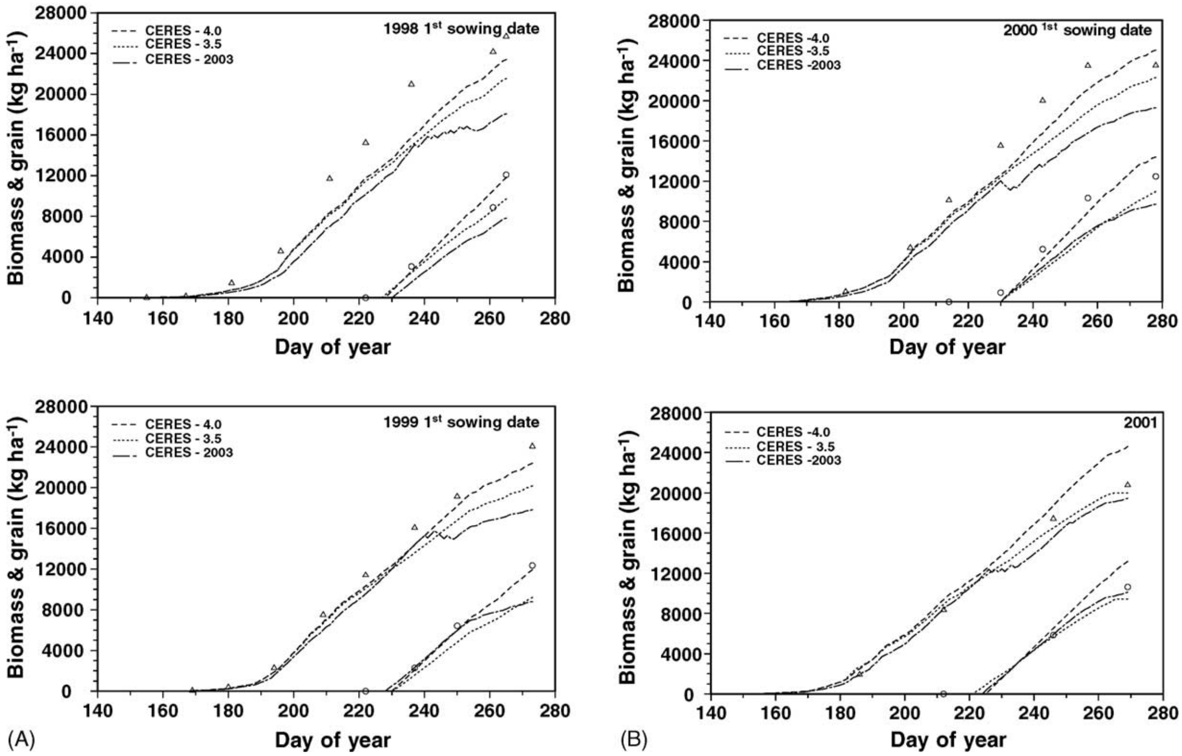

Fig. 3. Observed (points) biomass and grain yield (◯) and (△), respectively, and simulated (lines) dynamics for cv. Clarica grown under non-limiting conditions in 1998, 1999, 2000 and 2001 obtained with CERES-4.0, CERES-3.5 and CERES-2003 maize models.

accumulation curves do not correspond to observations made in this field and have not been described in the literature where crops are growing under non-limiting conditions. Therefore, the presences of erratic changes in simulated biomass suggest an inadequate formulation in the model code of some physiological process. In CERES-2003, during periods when GROEAR is less than PCARB, vegetative dry matter is mobilized and converted at 0.36 efficiency to grain. The result is that "0.64" of that mobilized dry matter is not accounted for or "lost", causing the erratic behavior in dry matter.

In a similar way we observe in Fig. 3, that CERES-4.0 always gave the highest grain dry matter accumulation and that CERES-2003 gave the lowest values of the three models, except in 2001. Here, the observed grain yields usually were very close or below the CERES-4.0 line, indicating that the model slightly overpredicted grain weight. Nevertheless, CERES-3.5 underpredicted grain accumulation in most of the treatments and CERES-2003 underpredicted in all of them. All time-series statistics in Table 4 confirm that biomass predictions of CERES-4.0 were the most accurate and those of CERES-2003 were the least accurate.

The LAI time course simulated by CERES-4.0 and CERES-3.5 were nearly identical and only began to show slight differences at 50 days after sowing (Fig. 4). After this time, CERES-4.0 generally gave a slightly higher LAI than CERES-3.5, except in 2001 where the difference was more accentuated. Both models correctly simulated LAI up to a value of 3.0; therefore, a correct solar radiation interception estimation can be expected during the crucial period of the crop cycle before full cover is reached. Nevertheless, as described for earlier versions of CERES-Maize (Lahrouni et al., 1993; Ben Nouna et al., 2003), the predicted maximum LAI was always clearly below the observed value and the end of season leaf senescence appears to be simulated too fast compared to recorded LAI. This last aspect can drive underestimation of late season solar radiation interception, and therefore, grain yield (Fig. 3).

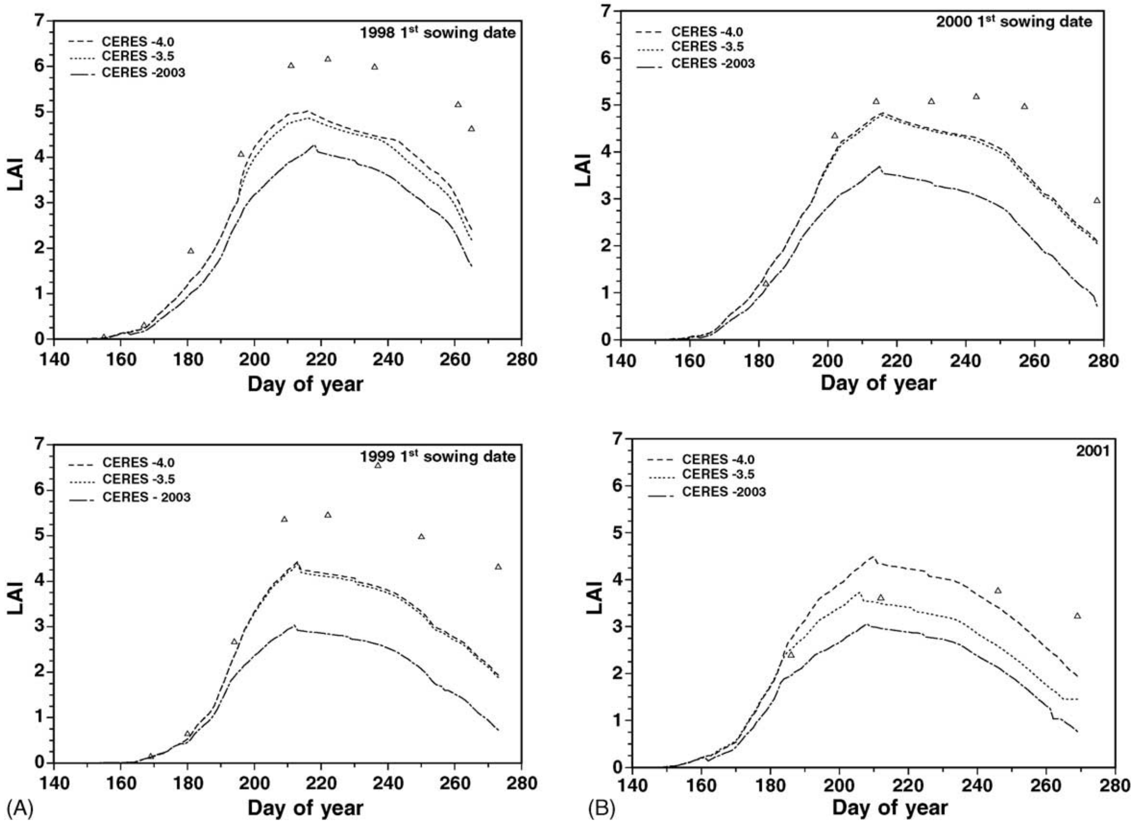

Fig. 4. Observed leaf area index (LAI, △) biomass and simulated (lines) dynamics for cv. Clarica grown under non-limiting conditions in 1998, 1999, 2000 and 2001 obtained with CERES-4.0, CERES-3.5 and CERES-2003 maize models.

Finally, simulated LAI by CERES-2003 was always lower than measured values and was clearly below the CERES-4.0 and CERES-3.5 simulations. Time series statistics (Table 4) confirm that again, CERES-4.0 had the best LAI estimations and CERES-2003 the worst. Future releases of CERES-Maize should address this problem of under-prediction of LAI, found in different environments and cultivars, in order to improve model predictability.

3.3. Accuracy of biomass and grain yield at harvest, and maximum leaf area index predictions of the different CERES-Maize versions

Statistics computed with final harvest data (large sampling areas; eight treatments) in Table 5 confirm the findings found with time-series statistics. The best simulations of biomass were obtained with CERES-4.0 (RMSE = 1974; $d = 0.637$) and the poorest with CERES-2003 (RMSE = 4683; $d = 0.360$). CERES-3.5 had an intermediate accuracy, but was closer to that of CERES-4.0 than CERES-2003. The same can be said for grain yield. Field observations showed that at the experimental plant density and considering all experiments, plants had at harvest time, an average of 1.08 ear per plant (average of the 5 May planting dates: 1.15 ear/plant; average of the 3 June planting dates: 1.00 ear/plant). No barren plants were found in the samplings. CERES-4.0, CERES-3.5 and CERES-2003 underpredicted the measured average kernel number per square meter of the eight experimental treatments by 21, 27 and 15%, respectively. CERES-4.0 and CERES-3.5 overpredicted average kernel weight by 38 and 16%, respectively. CERES-2003 underestimated average kernel weight by 15%. As a result, none of the three tested versions were able to simulate correctly

Table 4
Time series statistics for estimating the accuracy of biomass ($kg\,ha^{-1}$), grain ($kg\,ha^{-1}$) and maximum LAI predicted by four maize models (CERES-4.0, CERES-3.5, CERES-2003 and CERES-4.mod[a]) during 1998–2001 experiments: *a* and *b* values of linear regression of predicted vs. observed data, root mean square error (RMSE) and *d*-index of agreement (Willmott, 1982)

Model	Variable	*a*	*b*	RMSE	*d*
CERES-4.0	Biomass	−3.9	0.922	2202	0.982
CERES-3.5	Biomass	311.7	0.828	2729	0.970
CRES-2003	Biomass	297.8	0.740	3909	0.935
CERES-4.mod[a]	Biomass	88.4	0.899	2226	0.982
CERES-4.0	Grain	−252.8	1.055	1315	0.980
CERES-3.5	Grain	−134.3	0.825	1785	0.954
CERES-2003	Grain	39.6	0.730	2194	0.924
CERES-4.mod[a]	Grain	−111.4	0.914	1334	0.976
CERES-4.0	LAI	0.29	0.694	1.211	0.875
CERES-3.5	LAI	0.25	0.672	1.328	0.852
CERES-2003	LAI	0.08	0.542	1.996	0.720
CERES-4.mod[a]	LAI	0.29	0.694	1.211	0.875

[a] CERES-4.mod is identical to CERES-4.0, except the PRFT and RGFILL functions have been replaced by the temperature functions proposed by Wilson et al. (1995).

Table 5
Average biomass at harvest, grain yield and LAImax measured and simulated by four maize models (CERES-4.0, CERES-3.5, CERES-2003 and CERES-4.mod[a]) during 1998–2002 experiments, and statistics for estimating the accuracy of their predictions (root mean square error (RMSE) and *d*-index of agreement (Willmott, 1982))

Model	Variable	Mean	RMSE	*d*
CERES-4.0	Biomass ($kg\,ha^{-1}$)	22584	1974	0.637
CERES-3.5	Biomass ($kg\,ha^{-1}$)	20107	2527	0.600
CERES-2003	Biomass ($kg\,ha^{-1}$)	17732	4863	0.360
CERES-4.mod[a]	Biomass ($kg\,ha^{-1}$)	21847	1682	0.720
Measured	Biomass ($kg\,ha^{-1}$)	22185		
CERES-4.0	Grain ($kg\,ha^{-1}$)	12137	1472	0.611
CERES-3.5	Grain ($kg\,ha^{-1}$)	9527	1954	0.474
CERES-2003	Grain ($kg\,ha^{-1}$)	8410	2942	0.393
CERES-4.mod[a]	Grain ($kg\,ha^{-1}$)	10479	1231	0.652
Measured	Grain ($kg\,ha^{-1}$)	11148		
CERES-4.0	LAImax	4.5	0.93	0.541
CERES-3.5	LAImax	4.3	1.04	0.583
CERES-2003	LAImax	3.5	1.86	0.418
CERES-4.mod[a]	LAImax	4.5	0.93	0.541
Measured	LAImax	5.2		

[a] CERES-4.mod is identical to CERES-4.0, except the PRFT and RGFILL functions have been replaced by the temperature functions proposed by Wilson et al. (1995).

yield components. The CERES models frequently have problems predicting these two yield components. In this case, it appears that CERES-4.0 and CERES-3.5 would benefit from a higher G2 and a lower G3. The existing CERES models do not have prolificacy, or allow a second ear. If the model accounted for the higher ear number, much of the underprediction of kernel number per square meter would have been accounted for. Finally, maximum LAI estimations of CERES-4.0 and CERES-3.5 were almost equivalent (RMSE $\approx$ 1.0), and better than CERES-2003 (RMSE = 1.86).

3.4. Primary causes for differences in model outputs

As shown in Figs. 1 and 2, the temperature functions affecting RUE (PRFT) and grain growth (RGFILL) in CERES-4.0 are different from those used in CERES-3.5 and CERES-2003. CERES-4.0 functions are less sensitive to temperature as they have a wider optimum plateau. In addition, the differences between the outputs of the two PRFT and RGFILL functions, respectively, are especially large in the range of temperatures that occurred during maize growth and grain filling seasons in Lugo (see Figs. 1 and 2; Table 6). Therefore, we can expect that in this range of temperature, CERES-4.0 will produce the highest biomass and grain yield predictions. When we inserted the CERES-4.0 PRFT function into the CERES-3.5 code, that change accounted for 41 and 20% of the difference in biomass and grain yield, respectively, caused by CERES-4.0. When we inserted CERES-4.0 RGFILL function in the CERES-3.5 code, that change accounted for 44 and 68% of the difference in biomass and grain yield, respectively, caused by CERES-4.0. Finally, when we inserted both functions into CERES-3.5, the changes accounted for 92 and 100%, respectively, of the difference in biomass and grain yields, caused by CERES-4.0. Therefore, both functions explain almost all the existing differences between the two models. It is important to remember that CERES-4.0 code is modular (and restructured from V3.5) and the order of the processes simulated may differ slightly between CERES-4.0 and CERES-3.5, and this difference may cause slight divergences in the final outputs of the two versions (Jones et al., 2003).

The detected differences between CERES-2003 and CERES-3.5 are more numerous than those between

Table 6
Mean maximum daily temperature (TMAX), mean minimum daily temperature (TMIN), mean average daily temperature (Tavg = (TMAX + TMIN)0.5) during three crop growing phases (emergence-anthesis, anthesis-beginning grain filling and beginning grain filling-harvest) of the different treatments

Treatment	Emergence-anthesis			Anthesis-beginning grain filling			Beginning grain filling-harvest		
	TMAX (°C)	TMIN (°C)	Tavg (°C)	TMAX (°C)	TMIN (°C)	Tavg (°C)	TMAX (°C)	TMIN (°C)	Tavg (°C)
1998—1st	22.3	11.0	16.6	30.2	15.4	22.8	24.9	13.4	19.1
1998—2nd	24.9	12.4	18.6	25.6	15.3	20.5	21.2	11.4	16.3
1999—1st	23.6	12.3	17.9	23.6	12.9	18.3	22.9	12.2	17.6
1999—2nd	24.5	13.2	18.9	25.3	12.3	18.8	21.1	11.1	16.1
2000—1st	23.9	11.7	17.8	26.8	12.9	19.8	23.2	10.6	16.9
2000—2nd	24.5	12.5	18.5	24.0	12.1	18.1	21.1	9.3	15.2
2001	23.8	11.3	17.6	25.0	13.1	19.0	23.5	11.4	17.5
2002	21.8	10.4	16.1	25.2	12.8	19.0	23.2	11.2	17.2

CERES-3.5 and CERES-4.0. We tried to change them one at a time in CERES-2003. When we fixed RUE at 4.2 g MJ^{-1} (PAR) in CERES-2003 code instead of using the equations that allows RUE to vary with VPD, the change in biomass and grain yield output was very small, and only accounted for 4% and less than 0.5%, respectively, of the difference between models.

The reduction of EXT from 0.65 to 0.59, equivalent to that computed by CERES-3.5 for the approximate experimental plant density (10 plant m^{-2}) caused a small reduction in light interception, thus slightly decreased biomass and grain yield estimations (ca. 3 and 5%, respectively).

Changing the translocation function to one that allows for 1 g gain in grain weight per 1 g lost from stems, as it is in CERES-3.5, made a considerable difference. In addition to eliminating the bumps from the biomass accumulation curves, it increased biomass and yield 12 and 18%, respectively. This change accounted for 88 and 132% of biomass and grain yield differences, respectively, between the two models. So with this change alone, CERES-2003 gives higher yield predictions than CERES-3.5. The fact that 36% of the mobilized dry matter goes to grain and 64% is lost is apparently the main reason of the poor performance of CERES-2003.

Changing the equations to calculate grain number per plant (GPP) produced a drop of 2 and 9% in average biomass and grain yield predicted, respectively.

Finally, changing the equations to calculate LAI (similar to that of V3.5) increased biomass and grain yield by 9 and 5%, respectively. Therefore, this change accounted for 38 and 65% of biomass and grain yield, respectively, differences between the two models.

3.5. Which temperature functions are correct?

CERES-4.0 more closely predicts the biomass and grain yield under this relatively cool environment. Reasons for CERES-4.0 advantage are related to the new look-up functions for PRFT and especially RGFILL that create less sensitivity to temperature. Is this correct for all environments? While CERES-4.0 was best for this environment, are the temperature modifications appropriate and correct for all temperature environments? The maize model developed by Muchow et al. (1990) was tested in environments where average temperature varied between 18.0 and 28.9 °C and that model did not allow any possible effects of temperature on RUE. This was considered evidence that RUE of C_4 species was stable for this temperature range, an aspect also supported by literature (Brown and Wilson, 1983; Sinclair and Muchow, 1999). Nevertheless, Wilson et al. (1995), taking into account their own data and that of Andrade et al. (1993) created a temperature function to modify RUE to improve model predictions under widely varying temperature environments (Tavg between 30.3 and 14.2 °C). In Wilson's new temperature function, the RUE is maximum when average temperature during daylight hours (TAVGD) is higher than 19 °C (when temperature amplitude between day and night is 12 °C) and is zero when it drops below 11 °C. When TAVGD is below 19 °C, this function reduces RUE slightly more than the current PRFT of CERES-4.0 which has a first optimum temperature (Topt1) of

16.5 °C and Tb of 6.2 °C (Fig. 1). Using the Wilson temperature function in the Galicia temperature range (Table 6), RUE will usually be maximum, as it is with CERES-4.0 PRFT (Fig. 1). Finally, while the original Muchow et al. (1990) model did not consider any effect of temperature on the rate of increase in harvest index during the grain filling period (a proxy for RGFILL), Wilson et al. (1995) in order to improve model fit under their wide range of Tavg, considered that the harvest index increase rate was maximum while Tavg was above 19 °C and decreased linearly from this threshold value to zero when temperature dropped below 8 °C. This function is more temperature sensitive than the corresponding RGFILL in CERES-4.0 (Fig. 2). In the experimental temperature range experienced during grain filling, the output of both functions is quite different. The Wilson et al. (1995) function gives intermediate outputs between those of CERES-3.5 (the most limiting) and CERES-4.0, the less temperature sensitive. The over-prediction of average kernel weight by CERES-4.0 compared to CERES-3.5 (38% versus 16%) could also be evidence that the CERES-3.5 RGFILL function with greater temperature-sensitivity is more appropriate. Experience has shown that setting the yield components of the CERES models via G2 and G3 is typically difficult, because of problems of discerning G2 from the maximum grain number per plant at low sowing density, and the G3 (grain growth rate) from grains sampled in a supposedly optimum temperature (20–30 °C daily average range is too broad if 26 °C is defined as the optimum for grain growth rate, RGFILL).

We decided to try Wilson et al. (1995) temperature functions in CERES-4.0 and looked at their effect on the accuracy of model predictions. The changes had no effect on LAI predictions (Tables 4 and 5). The alternate RGFILL by itself produced a 3 and 14% reduction in biomass and grain yield prediction at harvest, respectively (Table 5), which improved *d*-indexes from 0.637 to 0.720 for biomass, and from 0.611 to 0.652 for grain yield. With this change, average simulated biomass was very close to the measured, but average simulated grain yield was 6% too low. The alternate PRFT by itself produced a 2 and 4% reduction in biomass and grain yield simulated at harvest, respectively. This improved *d*-indexes from 0.637 to 0.682 for biomass, and from 0.611 to 0.682 for grain yield. When both functions were changed, simulated biomass was reduced by 5% and grain yield by 14%. These changes improved *d*-indexes from 0.637 to 0.713 for biomass, and from 0.611 to 0.629 for grain yield. Therefore, individual changes had better consequences on simulated values. We consider that CERES-4.0 with Wilson et al. (1995) RGFILL temperature function (called CERES-4.mod) had particularly good performance (Table 5). This is confirmed by the time series statistics (Table 4), where we note that CERES-4.0 and CERES-4.mod had equivalent performance. If we consider that measurements made on small area basis (in-season measurements) may tend to overestimate biomass and grain, we can infer that CERES-4.mod is better than CERES-4.0 for this environment. Finally, because part of CERES-4.0 underestimation of biomass can be attributed to underprediction of LAI and too rapid senescence of the LAI (Fig. 4), once this aspect of the model is solved, both of the Wilson et al. (1995) temperature functions may lead to better simulation of biomass and grain weight at harvest.

We conclude that under the tested environment, CERES-4.0 was better than CERES-3.5 or CERES-2003, but that CERES-4.0 could benefit from slightly more temperature sensitivity for its simulations of biomass and grain yield. The temperature functions proposed by Wilson et al. (1995) seem reasonable to achieve this objective. Nevertheless, testing CERES-Maize with these temperature functions under a wider range of environments would be helpful to confirm that they are correct.

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