Modeling

Improving the CERES-Maize Model Ability to Simulate Water Deficit Impact on Maize Production and Yield Components

Francisco X. López-Cedrón, Kenneth J. Boote, Juan Piñeiro, and Federico Sau*

ABSTRACT

Crop models are potential tools for designing water-efficient strategies and should be tested for accurate prediction of water deficit effects on production. The objective of this research was to test and improve the CERES-Maize model (CERES-4.0) for ability to predict accurately maize biomass and grain yield components under water-limiting conditions in an environment where the model had previously given good predictions under irrigated conditions. Under a water-limited environment in northwest Spain, CERES-4.0 failed to simulate sufficiently high growth and yield; thus we evaluated aspects of model believed responsible for the poor performance. The model was tested with two evapotranspiration options [Priestley-Taylor (PT) and Penman–Monteith reference method (PFAO56, FAO no. 56 manual)] and with two values for the coefficient (KEP) that partitions evapotranspiration (ET) between crop transpiration and soil evaporation (default: KEP = 0.685; alternate: KEP = 0.500). The PT option with KEP = 0.685 underpredicted grain yield and biomass due to too early and too severe simulated water extraction. Predictions of biomass and grain yield with both PT and PFAO56 were improved when a KEP of 0.500 was used instead of the default 0.685. The PFAO56, the less water demanding of the tested crop reference (ETo) equations, gave the best predictions. In addition, a systematic underprediction of grain number and grain size with the default model in response to water deficit was observed, regardless of ET option or KEP value. Model predictions of the latter two variables was improved by replacing the default CERES-4.0 function that computes seed number per plant with the function of Edmeades and Daynard (1979).

Water is generally considered as the primary limiting factor of agricultural systems worldwide. So long as water is still available at relatively low cost in many areas, irrigation is seen as the principal means to intensify cropping systems. Nevertheless, as world population and water requirements of other economic sectors keep growing, water use in agriculture must be managed more efficiently. In addition, the global climate change that may take place is generating more uncertainty about water availability and price in the future. In some areas, such as the Iberian Peninsula, a future predicted increase in temperature and decrease in precipitation may make efficient water use even more important. Thus in the future, water-efficient cropping strategies will need to be designed to adapt to new circumstances generated by a changing climate.

During the last 20 yr, crop modeling has proven to be a valuable tool that can shorten significantly the experimental process needed to improve rainfed cropping-strategies or water management in irrigated systems, using long term, multiyear weather simulations (Egli and Bruening, 1992; Hook, 1994; Muchow et al., 1994; Wilks and Wolfe, 1998; Ruíz-Nogueira et al., 2001; Jagtap and Abamu, 2003; Nijbroek et al., 2003). Crop models have also been used for predicting climate change impacts on agricultural systems (Tubiello et al., 2002; Mínguez et al., 2007). Nevertheless, the utility of crop models for this objective depends on the accuracy and reliability of their predictions of grain yield under the given environment and management systems, so there is a continuing need to test the models under a wide range of environments and cropping practices (Kiniry and Bockholt, 1998). This testing will allow finding possible flaws of the model, and help propose modifications to improve their predictions and reliability (Sau et al., 1999).

Possibly due to its relative simplicity, CERES-Maize (Jones and Kiniry, 1986; Jones et al., 2003) is one of the most used, among the multiple maize models that exist. Since its first release in 1986 (Jones and Kiniry, 1986), CERES-Maize has been widely applied under different environments and purposes (Epperson et al., 1992; Kiniry and Bockholt, 1998; Boote et al., 2001; Jagtap and Abamu, 2003; Tubiello et al., 2002; Mínguez et al., 2007). It is a deterministic model that predicts the timing of the different phenological stages of the crop (emergence, tassel initiation, anthesis, and harvest maturity), growth rate and the partitioning of biomass to growing organs (roots, stem, leaves, and kernels) with a daily time step. Under nonlimiting conditions (water and N fully available), the simulated processes are affected by main three environmental variables (daily solar radiation, maximum temperature, and minimum temperature), cultivar-specific factors (five genetic coefficients that define cultivar characteristics (Jones and Kiniry, 1986), and crop management practices (i.e., sowing

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Abbreviations: ET, evapotranspiration.

date, density, row spacing, and dates and amounts of irrigation and N fertilization). 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 N-limiting environments when the water and N balance options are switched on. The daily-soil water balance in the CERES-4.0 model, as all the DSSAT 4.0 models, uses the Ritchie (1985) one-dimensional "tipping bucket" soil water balance, which predicts soil water flow and root water uptake for each of up to 10 soil layers. Using this method requires each layer (L) of the soil profile to be defined by a characteristic drained upper limit or field capacity (DUL(L), cm^3 H_2O cm^{-3} soil), a lower limit or wilting point [LL(L), cm^3 H_2O cm^{-3} soil], a saturated soil water content [SAT(L), cm^3 H_2O cm^{-3} soil], and a soil-rooting preference function [SRGF(L); relative root length distribution factor (0.00–1.00) in soil layer L] that quantifies the potential root hospitality of a particular layer.

The daily biomass accumulation (CARBO, for abbreviations, see appendix) and its partitioning between the different organs are described for the original CERES-Maize model by Jones and Kiniry (1986). The main differences from the older model versions to the current CERES-4.0 are highlighted by López-Cedrón et al. (2005). Because this present paper is focused on the ability of CERES-4.0 to predict water deficit effects on biomass and grain yield, the important equations of this model version that quantify water deficit and its effects on biomass accumulation and partitioning are described below.

Evapotranspiration Options in CERES-4.0

Currently CERES-4.0 allows the use of different equations to compute daily potential evapotranspiration (ET) (E0, mm d^{-1}), here considered equivalent to the "crop ET under standard conditions" (ETc) as defined and employed by Allen et al. (1998), including: (i) Priestley-Taylor (formulated by Ritchie (1972, 1985; called PT hereafter)), and (ii) Penman-Montieth-FAO56 (Allen et al., 1998; called PFAO56 hereafter). The Priestley-Taylor (i) is the default option and is the most widely used, mainly because it requires less input (daily solar radiation and minimum and maximum temperatures). PFAO56 (ii) requires additional weather data (daily average dew point temperature and wind speed) and is currently computed with a crop coefficient (Kc) of 1.00 for the entire crop cycle and thus does not allow E0 to exceed the hypothetical grass reference surface ET (ETo; E0 = ETc = Kc × ETo). Allen et al. (1998) uses a variable Kc coefficient that varies with crop cover and height and can reach 1.15–1.20 as a maximum for a maize crop, taking into account its lower aerodynamic resistance by comparison with the grass reference. The use of these different E0 options for the CROPGRO-faba bean model are described by Sau et al. (2004); however these ET options have not been tested for CERES-Maize model V4.0.

Partitioning of Potential Evapotranspiration between Evaporation and Transpiration in CERES-4.0

The models partition E0 to potential soil evaporation (ES0) and potential plant transpiration (EP0), following the Ritchie (1972, 1985) approach, which considers the portion of solar radiation (SR) reaching the soil that can be spent as latent energy to evaporate water from the soil surface if the soil is wet. The fraction of SR reaching the soil is a function of leaf area index (LAI) (Eq. [1]). Actual soil evaporation (ES) and plant transpiration (EP) subsequently depend on the availability of water to meet these potential rates.

The potential soil evaporation (ES0) in DSSAT V4.0 is calculated from E0 as follows:

$$\text{ES0} = \text{E0} \times \exp(-\text{KEP} \times \text{LAI}) \quad [1]$$

where KEP is the extinction coefficient of the canopy for total solar irradiance and is currently set to 0.685 in DSSAT V4.0. The KEP for ES0 in CERES V3.5 and CERES-2003 (used in López-Cedrón et al. (2005) was approximately 0.45 (although computed more complexly, see Jones and Kiniry, 1986).

The DSSAT V4.0 models follow the premise (Ritchie, 1985) that actual soil evaporation takes place in two stages: (i) the constant stage or energy limited (stage 1) and (ii) the falling rate stage (stage 2). During stage 2, ES is smaller than ES0.

Partitioning of E0 to climatic potential transpiration of the crop (EP0) is calculated using Eq.[2] and [3], with the same extinction coefficient (KEP = 0.685) used for ES0 computation.

$$\text{EP0} = \text{E0} \times [1.0 - \exp(-\text{KEP} \times \text{LAI})] \quad [2]$$

$$\text{IF EP0 + ES > E0 THEN EP0 = E0 - ES} \quad [3]$$

Note that, in V4.0 the same KEP = 0.685 correctly applies to both ES0 and EP0 (see Eq. [1] and [2]). In V3.5 and earlier CERES model versions, the extinction coefficients were different for these two processes: it was approximately 0.45 for ES0 but was equal to 1.00 for EP0.

Finally, the transpiration of the crop (EP), the water deficit factor on photosynthesis (SWFAC) and turgor factor (TURFAC) are calculated.

Kernel Number per Plant and Kernel Growth Rate in CERES-4.0

As in other cereals, maize grain yield is strongly related to kernel number m^{-2} at harvest and thus an accurate prediction of kernel number set per plant (GPP) is crucial for a maize crop model to correctly estimate production (Ritchie and Alagarswamy, 2003). Under rainfed conditions, a good simulation of the water deficit reduction on GPP will be needed. In CERES-4.0, GPP is a function of PSKER (average rate of photosynthesis during stage 4 (anthesis to effective grain filling period), Eq. [4] and [5]). The PSKER is directly related to the values of CARBO during stage 4 and therefore linearly influenced by the actual SWFAC effects on CARBO. Thus as SWFAC decreases from 1.00 to 0.00 (more water deficit), CARBO and GPP diminishes.

$$\text{GPP} = \text{G2} \times \text{PSKER}/7200.0 + 50.0 \quad [4]$$

$$\text{GPP} = \text{MIN}(\text{GPP},\text{G2}) \quad [5]$$

Table 1. Sowing date, harvest date, and observed plant density at harvest for the different rainfed treatments of 1998, 1999, 2000, 2001, and 2002 experiments.

Treatment	Sowing date†	Harvest date†	Plant density
			plants m^{-2}
1998-RF	14 May (134)	22 Sept. (265)	10.3
1999-RF-first	24 May (144)	30 Sept. (273)	9.4
1999-RF-second	7 June (158)	14 Oct. (287)	11.4
2000-RF-first	18 May (139)	25 Sept. (269)	9.5
2000-RF-second	8 June (160)	19 Oct. (293)	10.0
2001-RF	19May (139)	26 Sept. (269)	9.5
2002-RF	8 May (128)	1 Oct. (274)	8.0

† Day of year in parentheses.

where G2 is the genetic coefficient that defines the potential number of kernels per plant for a particular cultivar. Other than Eq. [4] and [5], many alternative functions to compute GPP have been proposed (Lizaso et al., 2001).

In CERES-4.0, grain growth rate per day (GROGRN) depends on temperature (RGFILL (relative rate of grain fill) is a temperature function), number of grains per plant, potential kernel growth rate per day (G3, mg kernel^{-1} d^{-1}) and soil water stress factor on photosynthesis:

$$\text{GROGRN} = \text{RGFILL} \times \text{GPP} \times \text{G3} \times 0.001 \times (0.45 + 0.55 \times \text{SWFAC}) \quad [6]$$

The objective of this research was to predict accurately maize biomass, grain yield and grain yield components under water-limiting conditions in northwest Spain, an environment where CERES-4.0 proved to be the most adequate of three tested CERES-Maize versions for good predictions of biomass at harvest and grain yield under nonlimiting water conditions (López-Cedrón et al., 2005). In the present paper, we observed that CERES-4.0 with default settings failed to simulate sufficiently high growth and yield under water-limited conditions. Thus we re-evaluated potential ET, energy partitioning to E0 and EP0, grain number, and grain growth rate aspects of model code responsible for poor performance under water-limited rainfed environment.

MATERIALS AND METHODS

Experiments

A common commercial cultivar of maize (*Zea mays* L.), 'Clarica', was grown under irrigated (IR; water and nutrients nonlimiting) and rainfed (RF; nutrients nonlimiting) management 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).

Experiments in 1999 and 2000 had two sowing dates (first and second), while in 1998, 2001, and 2002, only one sowing date was implemented (see Table 1). Before maize, during fall and winter, the experimental field was cultivated with Italian ryegrass (*Lolium multiflorum* L.) as a cover crop that was harvested approximately 2 wk before the maize sowing date. Soil was fertilized with ample amounts of N, P, and K (see López-Cedrón et al., 2005; irrigated and rainfed treatments were fertilized the same) to minimize limitation from these nutrients. Temperatures of the different growing seasons can be seen in Table 2 and were relatively cool when compared to the main world growing areas for maize. In all experiments, row spacing and sowing depth were 0.75 and 0.05 m, respectively. Plant density was close to 10 plants m^{-2} (Table 1 lists the actual field-sampled plant densities used for model simulations). Plot size was 12.0 by 7.0 m (16 rows of 7 m length) and had four replications. Drip irrigation was established for all irrigated plots and managed to avoid plant water stress.

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. Precipitation registered during the experimental period is shown in Table 3.

Table 2. Mean daily maximum (T_{max}) and minimum (T_{min}) temperature every 10–11 d between May and October in 1998, 1999, 2000, 2001, and 2002 in Lugo, Spain.

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

Table 3. Precipitation measured for 10 to 11 d intervals from May to October in 1998, 1999, 2000, 2001, and 2002.

	1998	1999	2000	2001	2002
	mm				
1–10 May	22.0	33.0	86.8	46.7	20.8
11–20 May	10.8	45.2	11.2	40.6	34.4
21–31 May	40.0	3.4	7.0	0.0	30.7
1–10 June	12.4	17.4	3.8	14.2	45.1
11–20 June	0.6	0.0	0.2	3.6	0.0
21–30 June	6.0	0.8	1.4	0.0	7.0
1–10 July	28.6	4.4	22.4	32.5	6.5
11–20 July	3.2	0.8	0.2	29.0	6.8
21–31 July	0.4	0.8	29.8	0.0	0.2
1–10 Aug.	0.2	57.0	4.6	12.0	9.3
11–20 Aug.	16.4	1.6	8.8	13.0	1.6
21–31 Aug.	0.2	6.6	12.8	51.0	3.9
1–10 Sept.	21.2	23.0	0.2	0.0	25.2
11–20 Sept.	3.0	117.0	14.4	1.0	33.7
21–30 Sept.	85.2	17.2	41.8	79.0	0.3
1–10 Oct.	12.4	3.3	9.4	53.4	36.1
11–20 Oct.	2.8	72.6	94.4	66.6	113.1
21–31 Oct.	7.4	91.2	37.0	50.6	61.7

Table 4. Characteristics of the different layers of the experimental soil profile used in the simulations.

Soil layer	Organic C	Bulk density	LL†	DUL†	SAT†	SRGF‡
cm	%	g cm^{-3}	% vol.			0–1
0–15	4.4	1.29	7.8	31.5	42.4	1.00
15–30	3.3	1.33	7.8	30.5	41.8	0.64
30–45	2.4	1.28	8.3	23.0	44.6	0.47
45–60	1.9	1.46	8.5	24.5	39.1	0.35
60–90	1.9	1.50	8.8	25.0	37.7	0.22
90–120	1.9	1.63	8.8	22.0	33.1	0.12
120–150	1.9	1.63	8.8	22.0	33.1	0.07

† DUL, LL and SAT: drained soil water limit, wilting point and soil water content at saturation, respectively.

‡ Soil rooting preferent function used by CERES-Maize model, normalized to 1.00 of the top soil layer.

Development Observation and Dry Matter Sampling

Development was observed three times per week in all experiments, using the growth staging method described by Jones and Kiniry (1986). Plant samples (0.5 m^2 area) were taken in each plot at 15-d intervals throughout the entire crop life cycle in the experiments done between 1998 and 2001, and dry matter production and partitioning between the different organs, as well as LAI were measured as described by López-Cedrón et al. (2005). Final harvests (see dates in Table 1) were performed on an area of 6 m^2 from the central rows of each plot in all experiments as described by López-Cedrón et al. (2005) to determine final biomass, grain yield, and yield components.

Soil Characteristics, Soil Water Measurements and Initial Conditions

The soil at the experimental site was a Typic Haplumbrept (USDA Soil Taxonomy) with a sandy-loam texture and had a pH in water of 5.6. The bulk density, texture, and carbon content of the different layers were measured for two sites within the experimental field. These data were included in the file (SOIL.SOL) that DSSAT model uses to define soil characteristics (Table 4).

Drained upper limit [DUL(L); % vol] and lower limit [LL(L); %vol] of each soil layer were estimated with four replications through the gravimetric method and soil bulk density was accounted for (Table 5). The DUL(L) of each soil layer was measured on 12 Apr. 1999, 7 d after a sufficient abundant irrigation to guarantee full recharge of the soil profile, where the soil surface was covered with a polyethylene mulch to avoid evaporation. The LL was measured in RF treatments at the end of the 1998 growing season (3 Sept. 1998) after the rainfed crop had extracted as much water as possible during a season that received 20.4 mm since 11 July and almost none during the last 18 d. As soil proved to be very homogenous below 60 cm depth, and roots were not sufficiently dense below 75 cm to extract all available water, LL of deeper soil layers were set to the values obtained for 60 to 75 cm depth. We recognize that the plant available water (DUL-LL) for this soil, at least for the 0 to 15 and 15 to 30 cm layers, is higher than that suggested by Ratliff et al. (1983), but high organic carbon content in those layers which could be part of the reason. For lower layers below 30 cm, the plant available values are within range of Ratliff et al. (1983).

To establish initial conditions of the different treatments for the simulations, we took gravimetric measurements to 90 cm depth at each sowing date except in 2001 where soil water data were collected 3 d after sowing (22 May). These data are the average of three replications. As *Lolium multiflorum* L. is a shallow rooted crop and northwest Spain winters are rainy and have low ET demand, we assumed that soil layers below 90 cm were at field capacity (DUL) at all sowing dates.

Table 5. Experimentally determined drained upper limit (DUL) and lower limit (LL) of the different soil layers. Each value is the average of four replications.

Soil layer	DUL†	LL‡
cm	% vol.	
0–15	31.68 (0.85)§	7.82 (0.56)§
15–30	30.87 (0.39)	7.83 (1.21)
30–45	22.69 (1.13)	8.30 (0.47)
45–60	24.01 (4.00)	8.48 (0.95)
60–75	23.85 (4.74)	8.85 (2.27)
75–90	24.49 (1.82)	–
90–105	21.42 (1.53)	–

† The DUL was determined on noncrop site on 12 Apr. 1999, 7 d after abundant irrigation when surface was covered with plastic film to prevent evaporation.

‡ The LL was determined on 3 Sept. 1998 after rainfed maize had extracted as much water as possible during a season that received 20.4 mm since 11 July.

§ Standard deviation in brackets.

Finally, to monitor water extraction during the 2001 growing season, soil water contents were determined gravimetrically to 150 cm depth with three replications at four dates, 22 June, 5 July, 31 July, and 26 September.

Volumetric Soil Water Content at Saturation and Soil Rooting Preference Function—Final Adjustment of Drained Upper Limit (L) for Simulations

Soil water content at saturation [SAT(L); % vol] and soil rooting preference function for each layer [SRGF(L)] (see Table 4) was calculated by the algorithm included in DSSAT-4.0 based on input of measured soil characteristics (layer thickness and depth, clay, silt, coarse, and organic fractions C). This same algorithm was used to set soil albedo (SALB; fraction) as 0.13, evaporation limit for stage 1 (SLU1; mm) as 6.0 mm, drainage rate (SLDR; fraction d^{-1}) as 0.60 d^{-1}, and soil run-off curve number (SLRO; Soil Conservation Service) as 73.

The LL(L) values placed in the file for the model runs were obtained through the method described previously (Table 5). Similarly, the DUL(L) values placed in the file for model runs came from data described previously in Table 5, although minor adjustments (<1%) to the experimentally-determined values were made to fit better simulated to observed water extraction dynamics of the 2001 treatment.

CERES-Maize Model Version

The CERES-Maize version (CERES-4.0) used in this work is the one included in DSSAT-4.0. The code and the model can be purchased through the International Consortium for Agricultural Systems Applications (ICASA-DSSAT) webpage (www.icasa.net/dssat/index.html; verified 3 Oct. 2007).

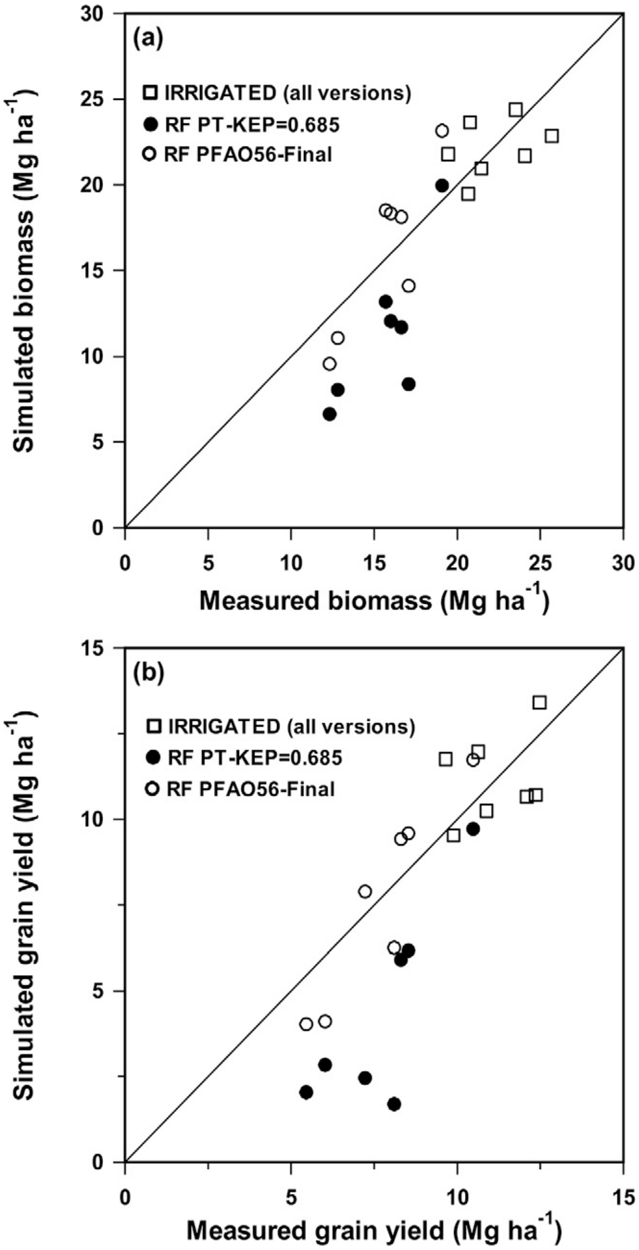


Fig. 1. Simulated vs. measured values of: (a) total biomass at harvest and (b) grain yield, for rainfed and irrigated treatments, using two different evapotranspiration (ET) options and modifications of the CERES-Maize V.4.0 model. 1. Default Priestley-Taylor (PT) ET option with KEP coefficient for partitioning between evaporation and transpiration equal to 0.685 (PT-KEP = 0.685); 2. Penman–Monteith FAO56 ET option with a KEP = 0.500, Kc = 1.00 and with Edmeades equation to compute grain number per plant with no direct soil water effect on grain growth (PFAO56-Final). Each point represents the mean of four replicates.

Model Options and Coefficients Based on Irrigated Treatments

Model runs with CERES-4.0 were performed, with water balance simulation switched "on," using (i) the PT ET as modified by Ritchie (PT; Ritchie, 1985) and (ii) the Penman–Monteith-FAO56 (PFAO56; Allen et al., 1998) method. Initial measured soil water content values were input at sowing date, except in 2001 when initial water content was adjusted to fit simulated water content to soil water content measurements made on 22 May 2001. As N supply proved to be nonlimiting, the model N balance was switched "off." The five genetic coefficients used to define the Clarica cultivar had been previously estimated in a low density experiment (see López-Cedrón et al. (2005)). Nevertheless, with these low density "inputs" CERES-4.0 slightly overpredicted biomass and grain yield of the seven irrigated treatments by approximately 1.9% and 9.4% (due to excessive simulated weight per average kernel (38%) and slightly underpredicted simulated seed number per land unit (21%)). Thus we calibrated G2 (potential kernel number per plant) and G3 (potential kernel growth rate) to optimize the model fit to grain number and weight of all high density irrigated treatments. After this change (now G2 = 1205.0 potential kernel number per plant instead of 936.0, and G3 = 5.75 mg seed^{-1} d^{-1} instead of 8.00) the average biomass, grain yield, harvest index (HI), kernel weight and number of kernels per unit land area of the seven irrigated treatments were accurately predicted. Average observed and simulated biomass, grain yield, kernel weight and kernel number per unit of land area of the seven irrigated treatments before evaluating rainfed treatments were respectively: 22,228 and 22,113 kg ha^{-1}; 11,138 and 11,184 kg ha^{-1}; 231 and 231 mg seed $^{-1}$; 4847 and 4832 kernel number m^{-2}. For these variables, the respective computed root mean square errors (RMSE) were: 2064 kg ha^{-1}, 1330 kg ha^{-1}, 24 mg seed $^{-1}$, and 418 kernel number m^{-2}.

Statistical and Graphical Procedures to Evaluate Evapotranspiration Options, Extinction Coefficients and Model Modifications

The following criteria were used to assess performance of the CERES-Maize model: (i) intercept (*a*) and slope (*b*) values of linear regression between simulated and observed biomass at harvest, grain yield at harvest, and grain harvest index using the seven treatments shown in Table 1; (ii) the RMSE of these variables; 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 follows:

$$\mathrm{RMSE} = \left[N^{-1} \sum_{i=1}^{n} (P_i - O_i)^2 \right]^{0.5} \qquad [7]$$

$$d = 1 - \left[\sum_{i=1}^{n} (P_i - O_i)^2 / \sum_{i=1}^{n} (|P_i'| + |O_i'|)^2 \right] \qquad [8]$$

where N is the number of observed values, O_i and P_i are observed and predicted values for the *i*th 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.

Because we wanted to test the ability of the model to simulate water deficit effect on reduction in biomass, grain yield, and yield components by comparison to irrigated predictions, we also calculated the same statistics above applied to (Predicted IR − Predicted RF) vs. (Observed IR − Observed RF).

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 vs. observed) were used for calculating *a*, *b*, RMSE, and *d*-index to compare the different model versions.

RESULTS AND DISCUSSION

Default Model Adequately Predicts Irrigated Treatments but Underpredicts Rainfed Maize

Once soil water holding characteristics and rooting preference function were set in the soil file and initial conditions set in the experimental files (*.MZX), we ran the model with the default ET option (PT) for irrigated (IR) and rainfed (RF) treatments. Despite obtaining correct estimation of biomass and grain yield for the irrigated treatments (Fig. 1), we observed that the model under predicted the mean biomass of the rainfed treatments by 4228 kg ha^{-1} (RMSE = 5027) and mean grain yield by 3323 kg ha^{-1} (RMSE = 3728) (Tables 6 and 7). Moreover, the model predictions of mean harvest index (HI) of rainfed treatments were always low (0.360 estimated vs. 0.490 measured; Table 8) due to underpredicted mean seed number (2479 estimated seeds m^{-2} vs. 3900 measured; Table 9). This trend to underpredict biomass and grain yield is confirmed by time series graphs (Fig. 2) where simulations predicted earlier water deficit effects on biomass accumulation and grain mass than were observed in all rainfed treatments except in 2001.

Phenology timing was not affected by water stress, neither in simulations nor in the field (except for the 2000-RF-first treatment, where harvest was accelerated from 4 October to 25 September due to extreme water deficit that caused an acceleration of crop death). With this exception, crop phases were correctly predicted in IR as in RF treatments.

Soil Characteristics, Initial Conditions, and Soil Water Extraction Dynamic

Because soil water holding characteristics (LL, DUL) (Tables 3 and 4), and initial conditions used in the simulations were established experimentally, uncertainty of water supply and water holding traits cannot be viewed as responsible for model failure to predict biomass and grain yield. Moreover, measured soil water holding capacity (DUL-LL) was high (e.g., 13.2–23.7% vol.; Table 4) for a soil of this texture and a soil pedotransfer function would actually have assigned lower values for many of the soil layers. In addition, time series data on soil water content during the 2001-RF experiment (a relatively rainy season) (Fig. 3), showed that the PT default option generally predicted too much water extraction in all layers below 15 cm. Likewise, the soil water data showed no observed extraction below 1.20 m and visual observation of the rooting profile made in the four rainfed plots at the end of 2002 growing sea-

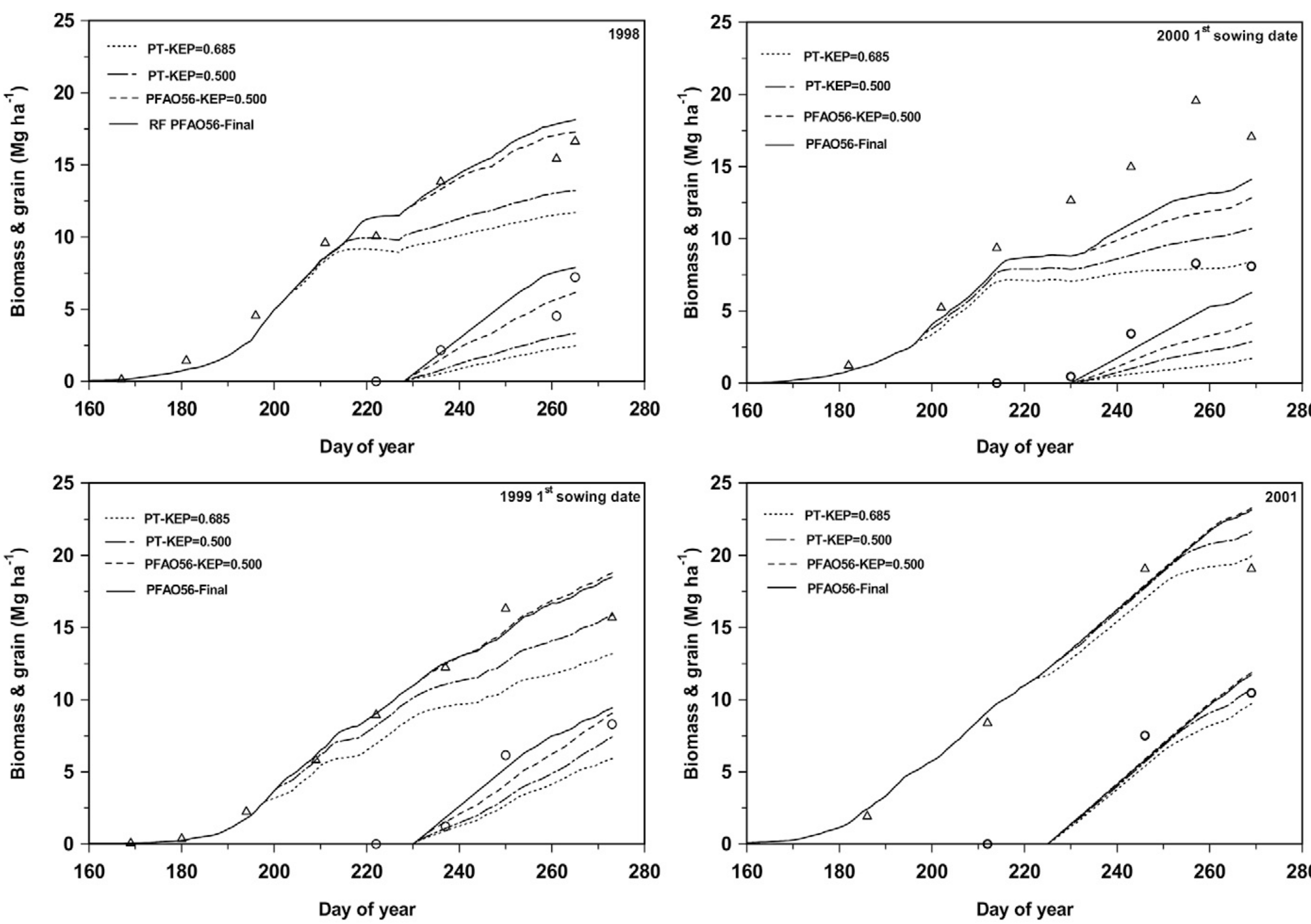


Fig. 2. Observed (points) and simulated (lines) dynamics of total biomass and grain yield of four rainfed treatments (1998; 1999-first, 2000-first and 2001) using different ET options and modifications of the CERES-Maize V.4.0 model. 1. Default Priestley-Taylor (PT) ET option with KEP coefficient for partitioning between evaporation and transpiration equal to 0.685 (PT-KEP = 0.685); 2. PT ET option with a KEP = 0.500; 3. Penman–Monteith FAO56 ET option with a KEP = 0.500 and Kc = 1.00 (PFAO56-KEP = 0.500); 4. Identical to (3) with Edmeades equation to compute grain number per plant with no direct soil water effect on grain growth (PFAO56-Final). Each point (triangle, biomass; circle, grain yield) represents the mean of four replicates.

Table 6. Measured and simulated biomass at harvest for rainfed treatments with the original default and different CERES-4.0 evapotranspiration options.†

Treatment	Measured	Simulated Priestley-Taylor		Simulated Penman-Monteith FAO56			
		KEP = 0.685	KEP = 0.500	KEP = 0.685 Kc = 1.00	KEP = 0.500 Kc = 1.00	KEP = 0.685 Kc = 1.10	KEP = 0.500 Kc = 1.10
		kg ha^{-1}					
1998-RF	16,630	11,694	13,236	15,333	17,283	13,169	15,158
1999-RF-first	15,693	13,117	15,870	15,738	18,780	14,928	17,732
1999-RF-second	16,000	12,053	15,504	15,364	18,349	14,441	17,339
2000-RF-first	17,067	8,393	10,686	9,871	12,830	9,047	11,477
2000-RF-second	12,795	8,060	9,397	9,803	11,090	9,392	10,428
2001-RF	19,080	19,964	21,662	23,008	23,286	22,086	23,076
2002-RF	12,315	6,640	7,823	7,693	8,843	7,397	8,436
Mean	15,654	11,426	13,454	13,830	15,780	12,923	14,807
RMSE	–	5,027	3,604	3,772	3,072	4,211	3,295
d	–	0.601	0.740	0.733	0.796	0.685	0.774
RMSE of diff.	–	5,029	3,520	3,801	3,303	4,132	3,294
d of diff.	–	0.546	0.698	0.666	0.739	0.638	0.743

† KEP is the LAI extinction coefficient for partitioning potential evapotranspiration between soil evaporation and plant transpiration; Kc is a crop coefficient that increases daily crop reference evapotranspiration linearly from 1.0 times ETo to Kc times ETo, as LAI increases from 0 to 6.

Table 7. Measured and simulated grain yield for rainfed treatments with the original default and different CERES-4.0 evapotranspiration options.†

Treatment	Measured	Simulated Priestley-Taylor		Simulated Penman-Monteith FAO56			
		KEP = 0.685	KEP = 0.500	Kc = 1.00 KEP = 0.685	Kc = 1.00 KEP = 0.500	Kc = 1.10 KEP = 0.685	Kc = 1.10 KEP = 0.500
		kg ha^{-1}					
1998-RF	7,224	2,460	3,336	4,732	6,128	3,236	4,594
1999-RF-first	8,303	5,908	7,419	7,390	9,060	7,053	8,321
1999-RF-second	8 528	6,172	7,887	8,123	9,609	7,623	9,035
2000-RF-first	8,098	1,695	2,853	2,412	4,158	2,029	3,334
2000-RF-second	6,019	2,840	3,391	3,555	4,067	3,415	3,844
2001-RF	10,474	9,722	10,746	11,598	11,880	10,931	11,670
2002-RF	5,451	2,038	2,382	2,504	2,804	2,357	2,649
Mean	7,728	4,405	5,431	5,759	6,821	5,235	6,207
RMSE	–	3,728	2,933	2,817	2,110	3,200	2,504
d	–	0.548	0.667	0.694	0.804	0.631	0.745
RMSE of diff.	–	3,885	3,044	2,974	2,322	3,317	2,609
d of diff.	–	0.529	0.638	0.655	0.750	0.611	0.715

† KEP is the LAI extinction coefficient for partitioning potential evapotranspiration between soil evaporation and plant transpiration; Kc is a crop coefficient that increases daily crop reference evapotranspiration linearly from 1.0 times ETo to Kc times ETo, as LAI increases from 0 to 6.

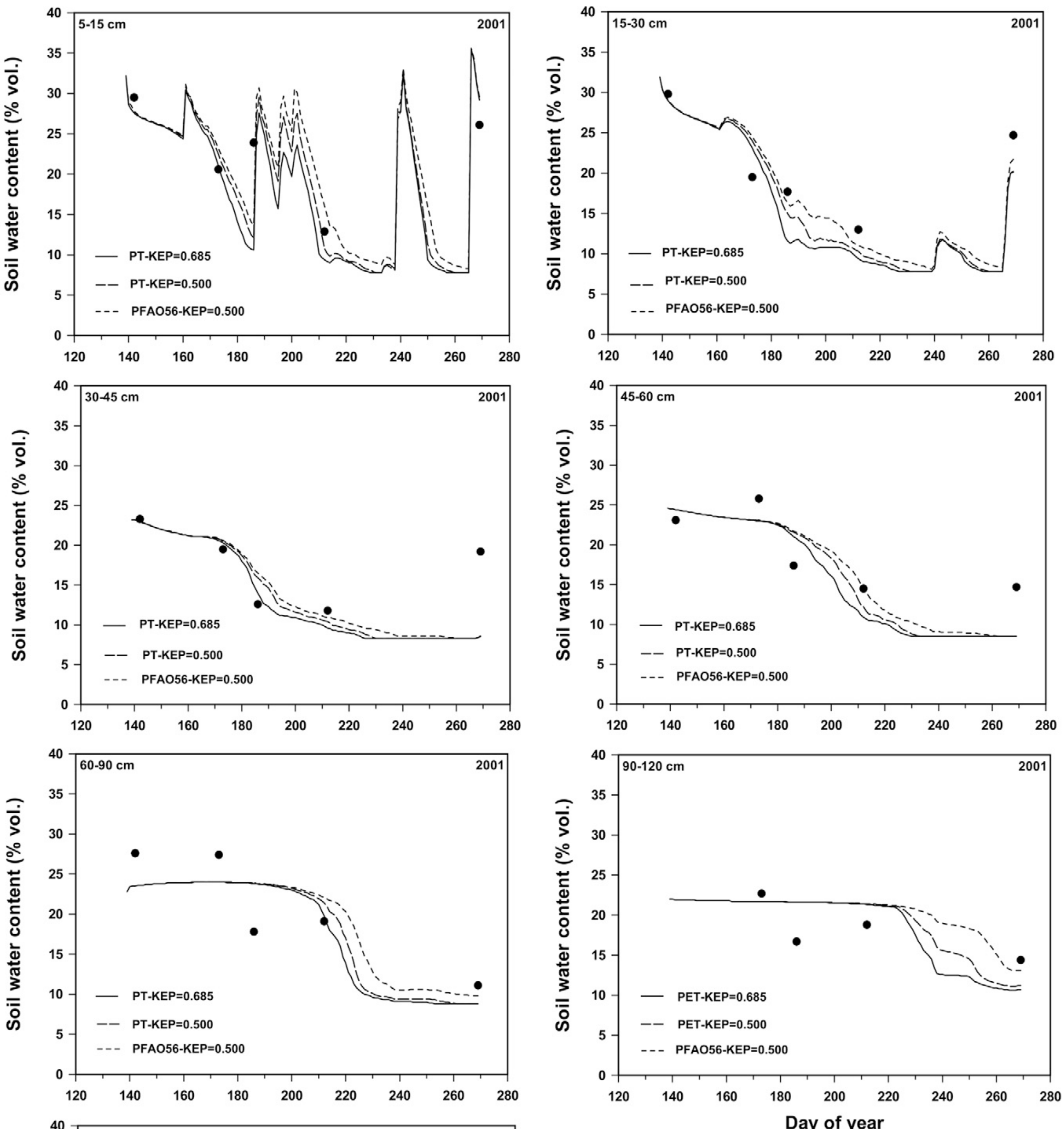
Table 8. Measured and simulated harvest index (fraction) for rainfed treatments with the original default and different CERES-4.0 evapotranspiration options.†

Treatment	Measured	Simulated Priestley-Taylor		Simulated Penman-Monteith FAO56			
		KEP = 0.685	KEP = 0.500	Kc = 1.00 KEP = 0.685	Kc = 1.00 KEP = 0.500	Kc = 1.10 KEP = 0.685	Kc = 1.10 KEP = 0.500
1998-RF	0.434	0.210	0.252	0.309	0.357	0.246	0.303
1999-RF-first	0.529	0.448	0.467	0.470	0.482	0.472	0.469
1999-RF-second	0.533	0.512	0.509	0.529	0.524	0.528	0.521
2000-RF-first	0.474	0.202	0.267	0.244	0.324	0.224	0.290
2000-RF-second	0.470	0.352	0.361	0.363	0.367	0.364	0.369
2001-RF	0.549	0.487	0.496	0.504	0.510	0.495	0.506
2002-RF	0.443	0.307	0.304	0.325	0.317	0.319	0.314
Mean	0.490	0.360	0.380	0.392	0.412	0.378	0.396
RMSE	–	0.155	0.128	0.119	0.092	0.137	0.109
d	–	0.439	0.507	0.520	0.614	0.482	0.561
RMSE of diff.	–	0.159	0.132	0.124	0.096	0.141	0.113
d of diff.	–	0.398	0.449	0.477	0.552	0.434	0.501

† KEP is the LAI extinction coefficient for partitioning potential evapotranspiration between soil evaporation and plant transpiration; Kc is a crop coefficient that increases daily crop reference evapotranspiration linearly from 1.0 times ETo to Kc times ETo, as LAI increases from 0 to 6.

son showed that very few roots reached this depth and none surpassed it. Furthermore, runoff was insignificant (averaged 5.4 mm over the seven rainfed treatments) because of a relatively moderate curve number, low rainfall and low intensity per day. Therefore, runoff, even if it could be reduced to zero, would have given less than a 0.5% yield increase, and was therefore not a significant cause for soil water depletion, reduced growth, and yield in this study. Thus it appears that the PT ET option overestimated the actual ET of the crop, and was therefore responsible for the generally too early and too severe predicted water deficit, which was the cause for the poor prediction of biomass and yield of CERES-4.0 under rainfed conditions.

Because Sau et al. (2004) previously documented that the PT default ET option of CROPGRO-Fababean overpredicted the actual crop ET under rainfed conditions in a Mediterranean environment, we decided to test other ET options, that proved to be more adequate for that environment, to see if they improved predictions of ET, biomass, and yield under this situation too. The interest in testing other equations to estimate crop ET was strengthened by the fact that prior research showed that CERES default models (with PT option)



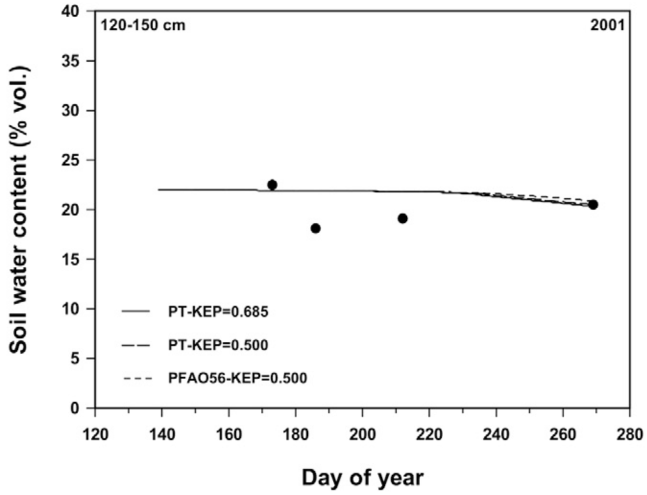


Fig. 3. Observed (points) and simulated (lines) dynamics of the soil water content of different soil layers during 2001 rainfed growing season, using different evapotranspiration (ET) options and modifications of the CERES-Maize V.4.0 model. 1. Default Priestley-Taylor (PT) ET option with KEP coefficient for partitioning between evaporation and transpiration equal to 0.685 (PT-KEP = 0.685); 2. PT ET option with a KEP equal to 0.500 (PT-KEP = 0.500); 3. Penman–Monteith FAO56 ET option with KEP = 0.500 and Kc = 1.00 (PFAO56-KEP = 0.500). Each point represents the mean of three replicates.

Table 9. Measured and simulated grain number per square meter for rainfed treatments with the original default and different CERES-4.0 evapotranspiration options.†

Treatment	Measured	Simulated Priestley-Taylor		Simulated Penman-Monteith FAO56			
		KEP = 0.685	KEP = 0.500	Kc = 1.00 KEP = 0.685	Kc = 1.00 KEP = 0.500	Kc = 1.10 KEP = 0.685	Kc = 1.10 KEP = 0.500
				no. m^{-2}			
1998-RF	3555	1414	1893	2709	3520	1868	2618
1999-RF-first	3937	3491	3887	3735	4346	3613	4086
1999-RF-second	4645	3752	4201	4373	4768	4209	4582
2000-RF-first	4215	1223	1579	1662	2273	1431	1812
2000-RF-second	3428	1695	1926	2048	2243	1973	2147
2001-RF	4543	4641	4896	4896	4896	4896	4896
2002-RF	2979	1137	1318	1390	1547	1308	1460
Mean	3900	2479	2814	2973	3370	2757	3086
RMSE	–	1729	1466	1304	1037	1508	1239
d	–	0.485	0.564	0.607	0.699	0.550	0.635
RMSE of diff.	–	1834	1583	1399	1140	1618	1363
d of diff.	–	0.403	0.462	0.509	0.594	0.454	0.523

† KEP is the LAI extinction coefficient for partitioning potential evapotranspiration between soil evaporation and plant transpiration; Kc is a crop coefficient that increases daily crop reference evapotranspiration linearly from 1.0 times ETo to Kc times ETo, as LAI increases from 0 to 6.

overpredicted water extraction, especially during the first part of the crop cycle in different environments (Jamieson et al., 1998; Jara and Stockle, 1999; Eitzinger et al., 2004).

Evaluation of Alternate Potential Evapotranspiration Equations

Penman–Monteith-FAO56 equation (PFAO56) with a crop coefficient (Kc) of 1.00 is available in CERES-4.0, and was one of the ET options that Sau et al. (2004) suggested to improve biomass and grain yield estimations. This is the equation presently recommended by the FAO to compute reference ET. Even with the default KEP coefficients (0.685), the PFAO56 option resulted in greater predictions of biomass, yield, and HI for rainfed treatments (Tables 6, 7, and 8). Average predicted biomass at harvest, grain yield, and HI increased from 11,426 to 13,830 kg ha^{-1}, 4405 to 5759 kg ha^{-1}, and 0.360 to 0.392, respectively, along with a clear reduction of RMSE and increase in *d* statistic closer to one. Under this cool environment for maize, the PFAO56 ET option predicted less accumulated E0 than PT. The average accumulated predicted E0 for the seven seasons was 534.8 and 468.4 mm with PT and PFAO56, respectively.

We also tried the PFAO56 option with a Kc value of 1.10, following the approach used by Sau et al. (2004) in which Kc allows E0 to increase from ETo of 1.00 to 1.10 × ETo as LAI increases from 0.00 to maximum LAI of 6.00). This option (PFAO56-Kc = 1.10) is not presently available in CERES-4.0 and would require a small FORTRAN code modification to be implemented. It provided a better fit than PT for biomass, yield, and HI but poorer predictions than PFAO56-Kc = 1.00. Thus, despite FAO recommendation to allow Kc to attain values above 1.00 for tall crops (Allen et al., 1998), for the present formulation and simulations this option proved to be too stressful.

Evaluation of Extinction Coefficient to Partition Potential Evapotranspiration to Potential Transpiration and Potential Evaporation

As Sau et al. (2004) showed that simulations could benefit using a KEP of 0.500 to partition ET between ES0 and EP0, and because this change is supported experimentally (Villalobos and Fereres, 1990) and by radiation extinction theory (Goudriaan, 1977; Goudriaan and van Laar, 1994), we tried a KEP of 0.500 in place of default CERES-4.0 KEP (0.685).

This reduction in KEP improved predictions with all three tested ET options (PT, PFAO56-Kc = 1.00) and PFAO56-Kc = 1.10) by systematically increasing average predicted biomass, grain yield, and HI of the rainfed treatments, reducing RMSE and increasing the *d* statistic (Tables 6, 7, and 8). In addition, reducing KEP from 0.685 to 0.500 improved the PT option predictions of soil water content for the different soil layers, reducing early simulated soil water extraction by the crop (Fig. 3) and improved the fit and the statistics of the time series simulations (Fig. 2), reducing RMSE for biomass from 3.870 to 3.002 t ha^{-1} and increasing *d* from 0.8950 to 0.9401, and reducing RMSE for grain yield from 5.580 to 2.954 t $ha^{-1}$and increasing *d* from 0.7292 to 0.8066. This KEP change allowed slopes (*b*) closer to one and intercepts (*a*) closer to zero for simulated vs. measured time series biomass and grain data. These results are consistent with those shown by Sau et al. (2004) for faba bean (*Vicia faba* L.) in a cool-season Mediterranean climate and with those obtained for wheat in New Zealand by Jamieson et al. (1998). Both papers showed that DSSAT models with PT option tended to overpredict water extraction under rainfed conditions, especially during early season. Sau et al. (2004) attributed this problem of the model to the use of an excessive KEP (1.00 in CERES-3.5, 0.85 in CROPGRO in DSSAT V3.5 release) and to a possible overestimation of E0 by PT option under cool and low VPD environments. Three wheat crop models, SIRIUS, SWHEAT and AFRCWHEAT2 (Jamieson et al., 1998) use a KEP of 0.45. All these examples suggest that the KEP used by CERES-4.0 is still high despite being reduced from 1.00 in CERES-3.5 to 0.685 in CERES-4.0. When CERES-4.0 with PT option for ET was run with the ET partitioning equations of CERES-3.5, all statistics were worse for prediction of biomass, yield, and HI. The RMSE increased from 5027 kg ha^{-1}, 3728 kg ha^{-1}, 0.155 to 6378; 4263; and 0.161 for biomass, yield and HI, respectively.

Evaluation of Alternative Functions to Estimate Daily Growth of the Grain and Grain Number per Plant

The PFAO-56 option with KEP = 0.500 was sufficient to accurately predict average biomass of the rainfed treatments at harvest (15,780 kg ha^{-1} predicted vs. 15,654 measured) but its simulations were still low for grain yield (6821 kg ha^{-1} predicted vs. 7728 measured) due to too small simulated kernel number per square meter (3370 seed m^{-2} estimated vs. 3900 measured). This failure to adequately predict drought effect on grain number (Table 9), led us to re-evaluate the grain number functions of the model. Literature review shows that CERES-Maize predictions of grain number per plant are generally less accurate than those for biomass and yield, despite good predictions of grain yield (Piper and Weiss, 1990; Jagtap et al., 1993; Lizaso et al., 2001). The existing function (Eq. [4]) was based on experiments done in Kenya by B.A. Keating and B.M. Wafula (unpublished data, 1992). It is a linear function of average rate of photosynthesis during stage 4 (PSKER) that establishes a minimum of 50 kernels per plant. On the other hand, the GPP version of the original CERES-Maize model (Jones and Kiniry, 1986) was the one proposed by Edmeades and Daynard (1979):

$$GPP = G2 \times (PSKER - 195)/[1213.2 + (PSKER - 195)] \qquad [9]$$

In Eq. [9], a minimum rate of photosynthesis during stage 4 of 195 mg $plant^{-1}$ d^{-1} is needed for the plant to set kernels. Upon comparison of the two equations where both were calibrated to the irrigated crop, it appeared that, under our experimental conditions (seven rainfed treatments), environmental factors that reduced PSKER via SWFAC had a much stronger reduction effect in Eq. [4] than in the Edmeades equation (Fig. 4). In addition, Ritchie and Alagarswamy (2003) in their paper recommended that CERES-Maize should be using a nonlinear function for kernel number vs. cumulative intercepted radiation.

Thus we replaced the default equation for GPP with Eq. [9], while continuing to run the model with the PFAO-56 option and KEP = 0.500. This equation change required a new calibration of the G2 genetic coefficient for the irrigated treatments, and G2 was set equal to 748 potential kernel number per plant instead of 1205. Then, the observed and simulated means (seven irrigated treatments) of weight per average kernel and seed number per surface unit, biomass, and grain yield were, respectively: 231 and 231 mg $kernel^{-1}$ (RMSE = 24); 4847 and 4853 number of kernels m^{-2} (RMSE = 299); 22,228 and 22,126 kg ha^{-1} (RMSE = 2020); 11,138 and 11,227 (RMSE = 1227). The Edmeades equation worked correctly for both irrigated and rainfed plants, increasing the predicted rainfed average of biomass, grain yield, and especially seed number per square meter and decreasing RMSE (Table 10 and Fig. 5). Under rainfed conditions, improvement was especially noticeable for average grain yield prediction that increased from 6821 kg ha^{-1} (RMSE = 2110) to 7397 (RMSE = 1530) due to a higher estimated average seed number per square meter.

Some researchers have suggested that grain growth is less sensitive to low plant water potential (SWFAC) than

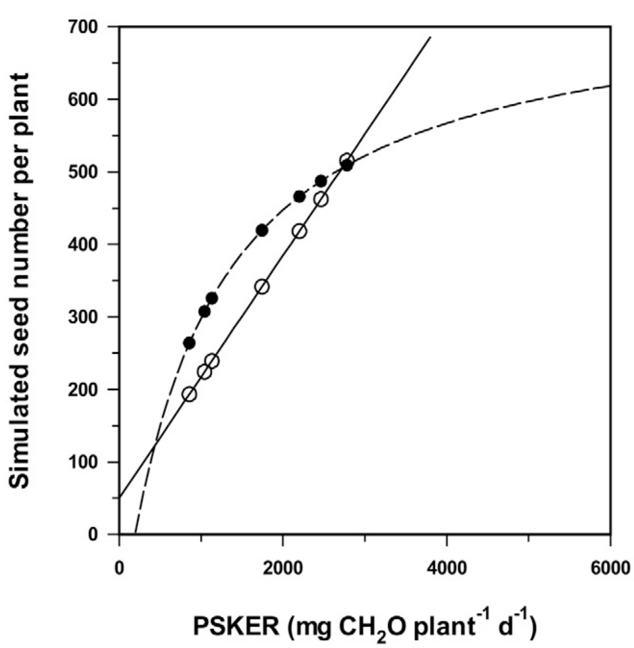


Fig. 4. The simulated seed number per plant (GPP) vs. average rate of photosynthesis per plant from anthesis to beginning effective grain-filling period (mg [CH_2O] $plant^{-1}$ d^{-1}) (PSKER) with current function (continuous line) and Edmeades function (discontinuous line). Symbols represent simulated GPP of the seven rainfed treatments with (open) current and (closed) Edmeades function. Model was run with the following option: Penman–Monteith FAO56 ET option with a KEP = 0.500 and Kc = 1.00 (PFAO56-KEP = 0.500).

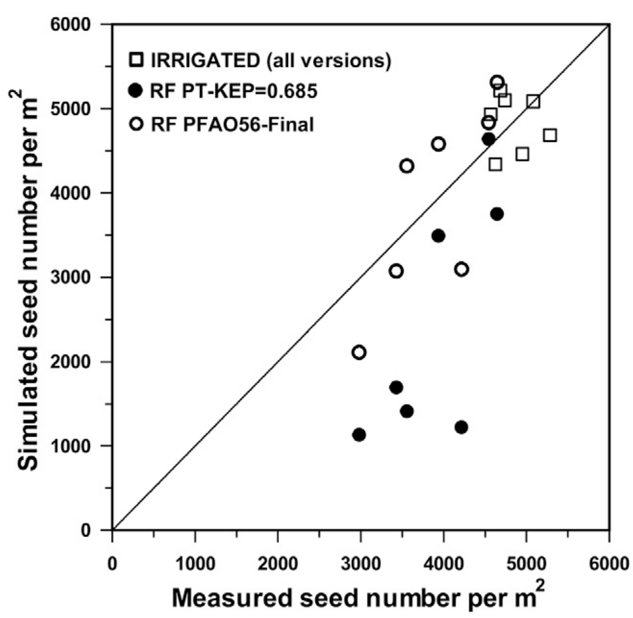


Fig. 5. Measured and simulated values of seed number per unit land area for rainfed and irrigated treatments using different evapotranspiration (ET) options and modifications of the CERES-Maize V.4.0 model. 1. Default Priestley-Taylor (PT) ET option with KEP coefficient for partitioning between evaporation and transpiration equal to 0.685 (PT-KEP = 0.685); 2. Penman–Monteith FAO56 ET option with a KEP = 0.500, Kc = 1.00 and Edmeades equation to compute grain number per plant with no direct soil water effect on grain growth (PFAO56-Final). Each point represents the mean of four replicates.

the whole plant because the xylem hydraulic connection from the embryos or endosperm is blocked in the pedicel of cereal grain or seed coats of legumes, thus minimizing water return flow in xylem and improving seed water status because there is also continuous phloem water flow to the seed (Fisher, 2000). Furthermore, the effect of SWFAC is already accounted for in the daily reduction of photosynthate production (CARBO). Therefore we removed SWFAC effect from the GROGRN equation (Eq. [6]) while keeping the Edmeades equation to compute GPP (PFAO56-Final run). This allowed simulated average grain weight to increase from 186 to 191 mg, reducing RMSE for this variable from 24 to 20 (Table 10). Now the fit to the 1:1 line is almost correct for biomass and grain yield (Fig. 1, PFAO56-Final) and is much better than it was with PT-KEP = 0.685, for seed number (Fig. 5). This final combination of modifications (PFAO56, KEP = 0.500, with Edmeades equation for computing grain number set, and no SWFAC effect on grain growth) also improved the fit and the statistics of the time series simulations (Fig. 2); reducing initial RMSE for biomass from 3.870 to 2.691 t ha^{-1} and increasing *d* from 0.895 to 0.967, and reducing initial RMSE for grain yield from 3.580 to 1.688 t ha^{-1} and increasing *d* from 0.729 to 0.929. All these changes allowed slopes (*b*) closer to one and intercepts (*a*) closer to zero for simulated vs. measured time-series biomass and grain data.

Table 10. Measured and simulated average biomass at harvest, grain yield, seed weight, and seed number per square meter for rainfed treatments with different CERES-4.0 options for kernel set.†

		Penman–Monteith FAO56 evapotranspiration equation		
Variable	Measured	Kc = 1.00 KEP = 0.500	Kc = 1.00 KEP = 0.500 Edmeades‡	Kc = 1.00 Edmeades & no SWFAC on GROGRN§
Biomass, kg ha^{-1}	15,654	15,780	16,079	16,126
RMSE		3,072	2,781	2,713
d		0.796	0.823	0.829
RMSE of diff.		3,303	3,074	2,984
d of diff.		0.739	0.760	0.772
Grain yield, kg ha^{-1}	7,728	6,821	7,397	7,577
RMSE		2,110	1,530	1,389
d		0.804	0.875	0.893
RMSE of diff.		2,322	1,867	1,755
d of diff.		0.750	0.796	0.812
Kernel wt., mg	201	196	186	191
RMSE		19	24	20
d		0.778	0.788	0.843
RMSE of diff.		15	29	27
d of diff.		0.829	0.648	0.633
Seed no. m^{-2}	3,900	3,370	3,905	3,905
RMSE		1,037	723	723
d		0.699	0.802	0.802
RMSE of diff.		1,140	784	784
d of diff.		0.594	0.714	0.714

† KEP is the LAI extinction coefficient for partitioning potential evapotranspiration between soil evaporation and plant transpiration; Kc is a crop coefficient that increases daily crop reference evapotranspiration linearly from 1.0 times ETo to Kc times ETo, as LAI increases from 0 to 6.

‡ Kc = 1.00, KEP = 0.500, plus Edmeades equation to compute grain number per plant.

§ Kc = 1.00, KEP = 0.500, plus Edmeades equation for grain number, plus no direct soil water factor (SWFAC) on grain growth (PFA056-Final).

CONCLUSIONS

We conclude from the tested ET options that, for this environment, both PT and PFAO56 predictions of biomass and grain yield benefit from use of 0.500 extinction coefficient instead of the default 0.685. In addition, the PFAO56 option, the less water demanding of the two tested ETo equations, gives the best predictions of the studied variables (biomass, grain yield, harvest index and grain number per square meter). These conclusions are similar to those obtained by Sau et al. (2004) for winter-spring crop (*Vicia faba* L.) in a rainfed Mediterranean environment. Finally the predicted grain number response to water deficit was poor with the default CERES-4.0 function for computing seed number per plant; but model performance was improved by using the function of Edmeades and Daynard (1979) which interestingly was the function used by the original model (Jones and Kiniry, 1986). Finally, model predictions were improved by removing the direct SWFAC effect on the function that calculates seed growth rate. All these changes make CERES-4.0 more reliable as a tool to design water efficient cropping strategies.

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APPENDIX

Summary of Abbreviations

CARBO: daily biomass accumulation per plant (g $plant^{-1}$ d^{-1})
d: index of agreement
DUL(L): drained upper limit of soil layer L (fraction in volume)
E0: potential daily evapotranspiration of the crop and soil (mm d^{-1})
EP: transpiration of the crop (mm d^{-1})
EP0: potential transpiration of the crop (mm d^{-1})
ES: soil evaporation (mm d^{-1})
ES0: potential soil evaporation (mm d^{-1})
ET: evapotranspiration
ETc: crop evapotranspiration under standard conditions (mm d^{-1})
ETo: crop reference evapotranspiration (mm d^{-1})
GROGRN: grain growth rate per plant per day (g $plant^{-1}$ d^{-1})
GPP: kernel number per plant
G2: genetic coefficient that defines the potential number of kernels per plant
G3: genetic coefficient that defines the potential kernel growth rate per day (mg $kenel^{-1}$ d^{-1})
HI: harvest index
IR: irrigated treatment
Kc: crop coefficient that increases daily crop reference evapotranspiration linearly from 1.0 times ETo to Kc times ETo, as LAI increases from 0 to 6

KEP: LAI extinction coefficient for partitioning potential evapotranspiration between soil evaporation and plant transpiration

LAI: leaf area index

LL(L): soil layer L water content at the lower limit or permanent wilt ing point (fraction in volume)

PSKER: average rate of photosynthesis per plant from anthesis to beginning effective grain filling period (mg (CH_2O) plant^{-1} d^{-1})

RGFILL: temperature function that describes relative rate of grain fill (0.00–1.00)

RF: rainfed treatment

RMSE: root mean square error

RWU: potential root water uptake of the crop (mm d^{-1})

RWU(L): potential root water uptake of the crop from soil layel L (mm d^{-1})

SALB: soil albedo (fraction)

SAT(L): soil layer L water content at saturation (fraction in volume)

SR: daily total solar radiation (MJ m^{-2} d^{-1})

SRGF(L): relative root length distribution factor (0.00–1.00)

SWFAC: soil water stress factor that affect photosynthesis (0.00–1.00)

T_{max}: mean daily maxium temperature

T_{min}: mean daily minimum temperature

TURFAC: turgor stress factor (0.00–1.00)

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