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Application of the CSM-CERES-Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment

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Abstract

In recent years, maize has become one of the main alternative crops for the Autumn–Winter growing season (off-season) in several regions of Brazil. Water deficits, sub-optimum temperatures and low solar radiation levels are some of the more common problems that are experienced during this growing season. However, the impact of variable weather conditions on crop production can be analyzed with crop simulation models. The objectives of this study were to evaluate the Cropping System Model (CSM)-CERES-Maize for its ability to simulate growth, development, grain yield for four different maturity maize hybrids grown off-season in a subtropical region of Brazil, to study the impact of different planting dates on maize performance under rainfed and irrigated conditions, and for yield forecasting for the most common off-season production system. The CSM-CERES-Maize model was evaluated with experimental data collected during three field experiments conducted in Piracicaba, SP, Brazil. The experiments were completely randomized with three replications for the 2001 experiment and four replications for the 2002 experiments. For the yield forecasting application, daily weather data for 2002 were used until the forecast date, complemented with 25 years of historical daily weather data for the remainder of the growing season. Six planting dates were simulated, starting on February 1 and repeated every 15 days until April 15. The evaluation of the CSM-CERES-Maize showed that the model was able to simulate phenology and grain yield for the four hybrids accurately, with normalized RMSE (expressed in percentage) less than 15%. The planting date analysis showed that a delayed planting date from February 1 to April 15 caused a decrease in average yield of 55% for the rainfed and 21% for the irrigated conditions for all hybrids. The yield forecasting analysis demonstrated that an accurate yield forecast could be provided at approximately 45 days prior to the harvest date for all four maize hybrids. These results are promising for farmers and decision makers, as they could have access to accurate yield forecasts prior to final harvest. However, to be able to make practical decisions for stock management of maize grains, it is necessary to develop this methodology for different locations. Future model evaluations might also be needed due to the release of new cultivars by breeders.

Keywords: Crop simulation; Corn; DSSAT; Decision support system; Irrigation management

1. Introduction

During the last decade maize, (*Zea mais* L.) has become one of the most important alternative crops for the Fall–Winter growing season (off-season) in several regions of Brazil. This is mainly due to technological advancements, such as improved crop rotations, better use of human resources and agricultural equipment, and higher prices for maize at harvest. In the central–western and southeastern regions of Brazil, the area that has been planted with maize has increased by 119% from 1995 to 2005, while the total production has increased by 66% (IEA, 2005; Tsunechiro and Tavares Ferreira, 2005). In these vast regions, the weather is characterized by abundant precipitation from October to February and insufficient and variable precipitation from March to September. Due to the varying weather conditions, maize is a high-risk crop. Water deficits, sub-optimum temperatures and solar radiation are common during the Fall–Winter growing season, causing a reduction in potential yield, e.g., 88% on average for several hybrids

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(Farinelli et al., 2003). Planting can be delayed when available soil water is insufficient to establish a crop or due to a previously late-harvested crop. However, a delayed planting date increases the risk of damage due to frosts during anthesis and grain filling for maize grown off-season (Caramori et al., 1999). Although some research has been conducted for maize grown off-season, there is a lack of technical information on the impact of variable weather conditions on yield (Oliveira and Fornasieri, 1999).

Crop simulation models have been used for many different applications in various countries around the world. The Decision Support System for Agrotechnology Transfer (DSSAT v4.0) is a comprehensive decision support system (Tsuji et al., 1994; Hoogenboom et al., 2004) that includes the Cropping System Model (CSM)-CERES-Maize model (Ritchie et al., 1998; Jones et al., 2003). Crop growth and development are simulated by the CSM-CERES-Maize model with a daily time step from planting to maturity and are based on physiological processes that describe the response of maize to soil and aerial environmental conditions. Potential growth is dependent on photosynthetically active radiation and its interception, whereas actual biomass production on any day is constrained by suboptimal temperatures, soil water deficits, and nitrogen deficiencies. The input data required to run the DSSAT models include daily weather data (maximum and minimum temperature, rainfall, and solar radiation); soil characterization data (physical, chemical, and morphological properties for each layer); a set of cultivar coefficients characterizing the cultivar being grown in terms of plant development and grain biomass; and crop management information, such as the established plant population, row spacing, seeding depth, and application of fertilizer and irrigation. The soil water balance is simulated to evaluate potential yield reduction caused by soil water deficits. The soil water balance is determined on a daily basis as a function of precipitation, irrigation, transpiration, soil evaporation, runoff, and drainage from the bottom of the profile. The soil water is distributed in several layers with depth increments specified by the user (Ritchie and Godwin, 1989; Ritchie, 1998). A detailed description of the CSM-CERES-Maize model can be found in Jones and Kiniry (1986), Ritchie et al. (1998), Garrison et al. (1999), Lizaso et al. (2001, 2003), and Ritchie and Alagarswamy (2003). The CSM-CERES-Maize has been tested extensively for different soil types and for a range of climatic conditions and with various maize hybrids (Hodges et al., 1987; Carberry et al., 1989; Jagtap et al., 1993; Jones et al., 2003).

Many of the decision support applications include assessing the long-term impact of climate and associated environmental risks and to evaluate alternative crop management practices for alleviating and mitigating these risks (Muchow et al., 1991; Thornton et al., 1995; Faria et al., 1997; Chipanshi et al., 1997; Cavero et al., 2000). One of the applications of the crop models has been to determine optimum planting dates. Kumar et al. (2002) and Mall et al. (2004) determined optimum planting dates for soybean in India and Ruiz-Nogueira et al. (2001) for soybean in Spain. Studies involving the evaluation of different planting dates using CSM have also been conducted for rice in India (Saseendran et al., 1998) and Cuba (Rivero Vega et al., 2005) and for canola in Western Australia (Farre et al., 2002).

The DSSAT crop models have also been used for yield forecasting in simulation studies (Duchon, 1986; Thornton et al., 1997; Bannayan et al., 2003; Yun, 2003). These forecasts can be conducted prior to planting or during the actual growing season. In both cases, the information obtained can be used by the farmers for management of expected crop production, or by governments for agricultural planning (Hoogenboom, 2000). The simulations that are conducted during the growing season for yield forecasting normally use the most-recently recorded weather data and for future weather use the daily weather of past years (Duchon, 1986; Thornton et al., 1997). The change in distribution of the projected outcome as more and more "unknown" weather is replaced with observed weather from the current growing season is especially of interest to farmers and decision makers. The predicted yield variability usually decrease until the variance approaches zero, once all unknown weather data have been replaced by observed weather data from the current growing season (Thornton et al., 1997). In Brazil crop harvest forecasting is usually made through annual estimates, using questionnaires that are answered directly by farmers or entities involved in the agricultural production. This is an expensive methodology with a considerable degree of subjectivity (Fontana et al., 2000).

The objectives of this study were (1) to evaluate the performance of the CSM-CERES-Maize model for simulating growth, development, and yield for four maize hybrids of different maturity grown off-season in a subtropical environment in Brazil; (2) to apply the CSM-CERES-Maize to evaluate the impact of different planting dates on off-season maize yield under irrigated and rainfed conditions and (3) to conduct yield forecasts for the most common maize system grown off-season, under rainfed conditions using different maturity hybrids.

2. Material and methods

2.1. Field experiments

Three field experiments with four maize hybrids were conducted at the "Escola Superior de Agricultura Luiz de Queiroz" of the University of São Paulo, in Piracicaba (−22.7° latitude, −47.4° longitude, 580 m elevation above sea level), São Paulo State, Brazil, during 2001 and 2002. The climate of the region, according to the Koppen classification, is Cwa: subtropical with rainy summers (December to March) and dry winters (June to September). One experiment was conducted in 2001 under irrigated conditions, and two experiments were conducted in 2002, one under rainfed and one under irrigated conditions. The irrigation system was a center pivot and soil moisture was maintained near field capacity in the entire profile. All experiments had a randomized complete block design with three replications for 2001 and four replications for 2002. Each plot was 20 m in length, with four rows spaced at 0.8 m. The maize hybrids used in this study were: AG9010, a very short season hybrid [904 growing degree days, (GDD) from planting to silking, base temperature of 8 °C)], DAS CO32 and Exceler, two short season hybrids (995 GDD), and DKB 333B, a normal season hybrid (1037 GDD) (Soler et al., 2005). The planting dates were March 15 for the 2001 experiment and March 13 for the two experiments conducted in 2002. Additional details on crop management are reported in Soler et al. (2005).

2.2. Plant measurements

For the vegetative phase, phenology was recorded by counting the leaves' collar appearance on a daily basis for all experiments. Silking was recorded when silks were visible outside the husks on 50% of the plants of each plot. Physiological maturity was determined by regularly sampling two cobs per plot to assess the presence of black layers at the base of the grains. Destructive methods were used to obtain leaf area and above ground biomass by sampling 1 m of row from the central rows of the plots approximately every 18 days. The sampling areas were spaced to avoid the effects of previous samplings. Plant height of the three plants was also measured at the same time. The length and width of each leaf were measured manually and the area of each individual leaf was estimated based on the product of the length and maximum width multiplied by 0.75 as described by McKee (1964). The LAI was calculated by dividing the total leaf area of each plant by the soil surface available for each plant; this was estimated as total meter square per hectare divided by the number of actual plants per hectare. The samples were separated into stems, leaves, ears, and husks; oven dried (with air circulating at 70 °C) to constant weight, and weighed.

The final harvest was conducted manually for the two central rows by harvesting 8 m of the row. Plants were separated into different parts similarly to the samplings during the growing season and then dried. For kernel moisture determination, the collected samples were weighted, dried in an oven, and weighted again. Yield was corrected to 0% of moisture. The number of grain per ear was counted in 12 ears per replication. Grain weight was obtained from the average of the weight of 8 groups of 100 grains, then corrected to 0% of moisture, and converted to 1 grain weight.

2.3. Weather and soil data

Daily maximum and minimum air temperature, rainfall, and incoming solar radiation data were obtained from an automatic weather station (Campbell Scientific, Logan, UT) of the University of São Paulo, situated adjacent to the field experiments. During the off-season period of the year, a decrease in solar radiation, a decrease in the number of rainy days as well as total amount of rainfall, and a decrease in temperature are common in this region (Fig. 1). The average daily total solar radiation for June is only 62% of the average daily solar radiation for January and the average monthly total precipitation for June is only 19% of that of January.

The soil of the experimental site was classified as a Typic Eutrudox, characterized by its high clay content (Table 1). The parameters that were determined include soil texture, bulk density, and soil chemistry. To analyze the individual soils of the three field experiments, 12 soil samples were collected at depths of 0–20, 20–40, 40–60, and 60–100 cm. For the experiments conducted in 2002, 12 samples of soil at 0–20 and 20–50 cm depths were analyzed to determine the soil water retention capacity at 10 different tension values, ranging from 0 kPa (saturation) to 15 kPa (permanent wilting point). This information was used to convert tensiometer readings to soil water content. For the experiments conducted in 2002, three sets of tensiometers were installed at four depths (20, 40, 55, and 70 cm), and were monitored every 2 days. In addition, the soil water content was obtained by gravimetric method three times during the growing season, including one sample prior to planting at the start of the experiment and two during the vegetative period. To summarize the results, the soil water content that was measured with the gravimetric method and tensiometers and simulated with CSM-CERES-Maize was analyzed for the hybrid AG9010 only.

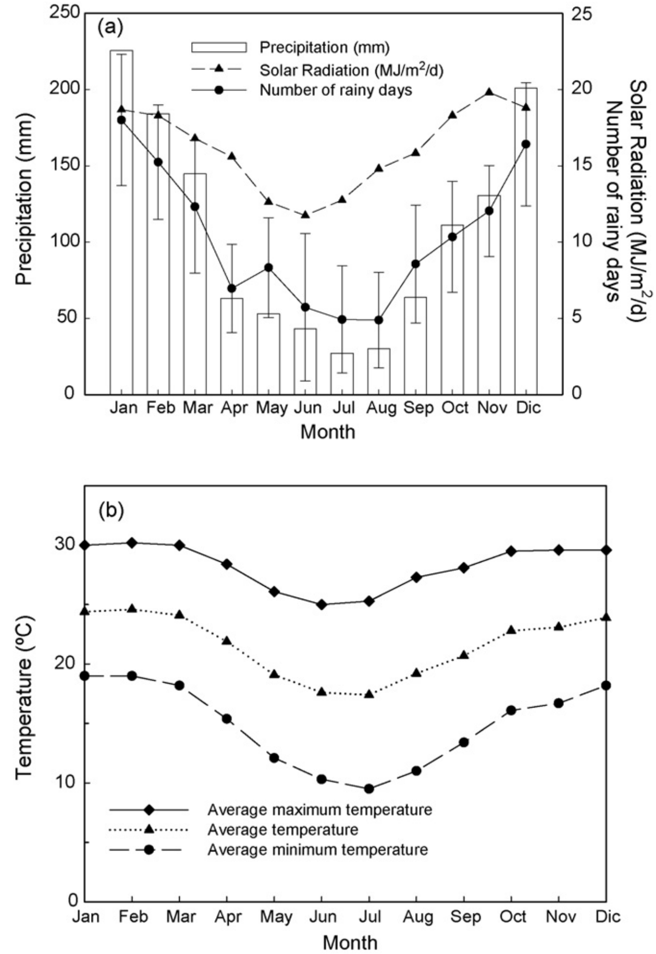

Fig. 1. Average weather conditions for Piracicaba, São Paulo State, Brazil: (a) average daily total solar radiation, average monthly total precipitation, and average and standard deviation of the monthly total number of rainy days; (b) maximum, average and minimum air temperature.

The saturated soil water content for the upper layer of the soil (0–20 cm) of the irrigated experiments conducted during 2001 and 2002 was 0.53 $cm^3\,cm^{-3}$, the field capacity was 0.34 $cm^3\,cm^{-3}$ and the wilting point was 0.28 $cm^3\,cm^{-3}$ (Table 1). The 2002 rainfed experiment was located in an area not far from the irrigated experiment, but with some differences in soil texture that affected the soil physical and hydraulic prop-

Table 1
Soil properties for the experiments conducted in Piracicaba, SP, Brazil

Depth (cm)	Clay (%)	Silt (%)	Bulk density ($g\,cm^{-3}$)	Field capacity ($cm^3\,cm^{-3}$)	Wilting point ($cm^3\,cm^{-3}$)	Saturated water content ($cm^3\,cm^{-3}$)	Organic carbon (%)
Irrigated experiments (2001 and 2002)							
0–20	65.0	15.0	1.23	0.34	0.28	0.53	1.47
20–40	65.0	17.0	1.13	0.33	0.27	0.53	1.11
Rainfed experiment (2002)							
0–20	60.0	15.0	0.90	0.28	0.17	0.45	1.40
20–40	61.0	18.0	0.91	0.29	0.18	0.45	1.10

erties. There was a 5% difference in clay content between the soil of the rainfed experiment (60%) and the soil of the irrigated experiments (65%) in the upper layer (0–20 cm). The saturated soil water content for the upper layer of the soil of the rainfed experiment was $0.45\,cm^3\,cm^{-3}$, the field capacity was $0.28\,cm^3\,cm^{-3}$, and the wilting point was $0.17\,cm^3\,cm^{-3}$ (Table 1).

2.4. Evaluation of the CSM-CERES-Maize model

The CSM-CERES-Maize model was calibrated with the data obtained from the 2001 irrigated experiment and evaluated with data obtained from the two field experiments conducted in 2002. For calibration, the cultivar coefficients were obtained sequentially, starting with the phenological development parameters related to flowering and maturity dates, followed by the crop growth parameters related with kernel filling rate and kernels number per plant (Hunt and Boote, 1998). An iterative procedure (Hunt et al., 1993) was used to select the most appropriate value for each phenological and developmental parameter. A detailed description of the cultivar coefficients used by the CSM-CERES-Maize is presented in Table 2. For calibration and evaluation, the simulated dates of emergence, flowering, and maturity as well as yield and yield components were compared with the observed values. Different statistics indexes were determined, including the normalized root mean square error (RMSE) expressed in percent, calculated according to Loague and Green (1991) with Eq. (1).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \times \frac{100}{M} \quad (1)$$

where P_i and O_i refer to predicted and observed values for the studied variables, respectively, e.g., days from planting to silking, days from silking to physiological maturity, LAI, biomass, yield and yield components. M is the mean of the observed variable. Normalized RMSE gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent with a normalized RMSE less than 10%, good if the normalized RMSE is greater than 10 and less than 20%, fair if the normalized RMSE is greater than 20% and less than 30%, and poor if the normalized RMSE is greater than 30% (Jamieson et al., 1991).

For the yield and yield components, the mean square error (MSE) was calculated and separated into a systematic (MSEs) and unsystematic (MSEu) component according to the procedure described by Willmott (1981). The Index of Agreement (d) proposed by Willmott et al. (1985) was estimated (Eq. (2)). According to the d-statistic, the closer the index value is to one, the better the agreement between the two variables that are being compared and vice versa.

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

where n is the number of observations, P_i the predicted observation, O_i is a measured observation, $P'_i = P_i - M$ and $O'_i = O_i - M$ (M is the mean of the observed variable).

In addition, the percentage prediction deviations (PD) were also computed. A negative deviation indicates an underprediction, while a positive deviation indicates an overprediction. For the days from planting to silking and days from planting to physiological maturity, a regression analysis was conducted between

Table 2
Cultivar coefficients used with the CSM-CERES-Maize model

Genotype	$P1$ (°C day)	$P2$ (days)	$P5$ (°C day)	$G2$ (Nr)	$G3$ (mg day^{-1})	PHINT (°C day)
AG9010	196.0	0.5	758.0	990	5.20	46.6
DKB 333B	263.0	0.5	842.0	940	4.40	44.1
DAS CO32	240.0	0.5	747.8	990	5.00	43.4
EXCELER	232.0	0.5	766.0	990	5.15	42.3

$P1$: Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days, °C day, above a base temperature of 8 °C) during which the plant is not responsive to changes in photoperiod. $P2$: Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h). $P5$: Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C). $G2$: Maximum possible number of kernels per plant. $G3$: Kernel filling rate during the linear grain filling stage and under optimum conditions (mg day^{-1}). PHINT: Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances (Hoogenboom et al., 1994).

observed and simulated values using PROC REG routine with the software SAS (SAS Inst., 2001).

2.5. Planting date analysis

An analysis of the effect of different planting dates on yield of maize grown off-season was conducted using 25 years of historical weather data from Piracicaba, São Paulo, Brazil that were obtained from the weather station of the University of São Paulo, situated adjacent to the field experiments. Six different planting dates were simulated using the seasonal analysis tool of DSSAT Version 4.0 under both rainfed and irrigated conditions. The off-season planting dates started on February 1 and were repeated every 15 days until April 15. The results are presented in box plots, in which the box itself contains the middle 50% of the data, the upper edge (hinge) of the box indicates the 75th percentile of the data set and the lower hinge indicates the 25th percentile. The median yield value is indicated by a horizontal line in the box. The upper and bottom lines of the diagram represent the yield between the 10th and 90th percentiles. In addition, the percentage of yield reduction was estimated for each planting date with the following equation:

$$Y_{\mathrm{r}} = \left[1 - \left(\frac{Y_{\mathrm{rainfed}}}{Y_{\mathrm{irrig}}}\right)\right] \times 100 \qquad (3)$$

where Y_{r} is the yield reduction, Y_{rainfed} the yield under rainfed conditions, and Y_{irrig} is yield under irrigated conditions.

2.6. Yield forecasting

The CSM-CERES-Maize model was used for yield forecasting for the four hybrids that were studied. The daily historical weather data for Piracicaba for 25 years were combined with the daily weather data recorded for 2002. Biweekly yield forecasts were conducted, starting on March 31, 2002 until July 31. For these forecasts, the antecedent daily weather data for 2002 were used until the forecast date, complemented with 25 years of historical weather data for the remainder of the growing season. Crop management was based on the local agronomic practices, and included rainfed conditions and low levels of nitrogen fertilizer. For each forecast date, the mean and standard deviations for the forecasted yield were determined.

3. Results and discussion

3.1. Evaluation of the CSM-CERES-Maize model

3.1.1. Cultivar coefficients

The CSM-CERES-Maize model includes six cultivar coefficients that define phenology and growth (Table 2). The very short season hybrid AG9010 had the lowest value for $P1$ (thermal time from seedling emergence to the end of the juvenile phase), e.g., 196 °C day, while the normal season hybrid, DKB 333B had the highest value, e.g., 263 °C day. The coefficient $P2$ (extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate) was set equal to 0.5 for all four hybrids, because no response to photoperiod was simulated since the daylength during the growing season was less than the critical photoperiod, i.e., 12.5 h, and decreased during the cropping season. The values for $P5$ (thermal time from silking to physiological maturity) ranged from 747.8 °C day for the hybrid DAS CO32 to 842 °C day for the hybrid DKB 333B. The values for $G2$ (the maximum possible number of kernels per plant) ranged from 940 to 990 (number per plant) for the four hybrids and did not show much variation. The $G3$ (kernel filling rate) ranged from 4.4 mg day^{-1} for the hybrid DKB 333B to 5.2 mg day^{-1} for the hybrid AG9010. The phyllochron interval (PHINT) was set as the average observed value for each hybrid for all three experiments and ranged from 42.3 °C day for the hybrid Exceler to 46.6 °C day for the hybrid AG9010 (Soler et al., 2005).

3.1.2. Soil water content

The soil water content for the irrigated experiment of 2002 was maintained near field capacity for the entire profile, in order for the crop to have an adequate water supply throughout the growing season (Fig. 2). There was good agreement between simulated and observed soil water content for all four measurement depths (normalized RMSE < 15%).

The seasonal variation in soil water content for the rainfed experiment showed several differences when compared to the irrigated experiment. The temporal variation of the observed (gravimetric) and simulated soil water content decreased from March 1 to April 15 (Fig. 2). The tensiometers installed in the 20 cm layer hydraulically ceased to function first because they reached the low limit of operation, followed by those installed at the 40, 55, and 70 cm depths. Therefore, the tensiometers' readings were not included in the rainfed graphs of Fig. 2.

3.1.3. Phenology

The evaluation of the CSM-CERES-Maize model for simulating the duration from planting to silking with data from 2002 experiments revealed similar average values for the four hybrids between observed and predicted values, e.g., 58 days for observed and 59 days for simulated for irrigated conditions and 59 days for both observed and simulated for the rainfed conditions. The coefficient of determination (r^2) between the simulated and observed duration from planting to anthesis for the four hybrids in the three experiments was 0.96, with the slope of the regression equation not statistically different from one and the intercept not different from zero ($P = 0.05$). In addition, the normalized RMSE was low (1.6%).

The evaluation of the CSM-CERES-Maize model for simulating the duration from planting to physiological maturity, showed identical average values for the four hydrids between observed and simulated values, 129 days for irrigated conditions and 128 days for rainfed conditions. For the four hybrids, the normalized RMSE was low, e.g., 0.7%. Furthermore, the r^2 was high, e.g., 0.99, with a slope of the regression equation that was not statistically different from one and the intercept was not different from zero ($P = 0.05$), confirming the ability of the CSM-CERES-Maize model for simulating the duration from

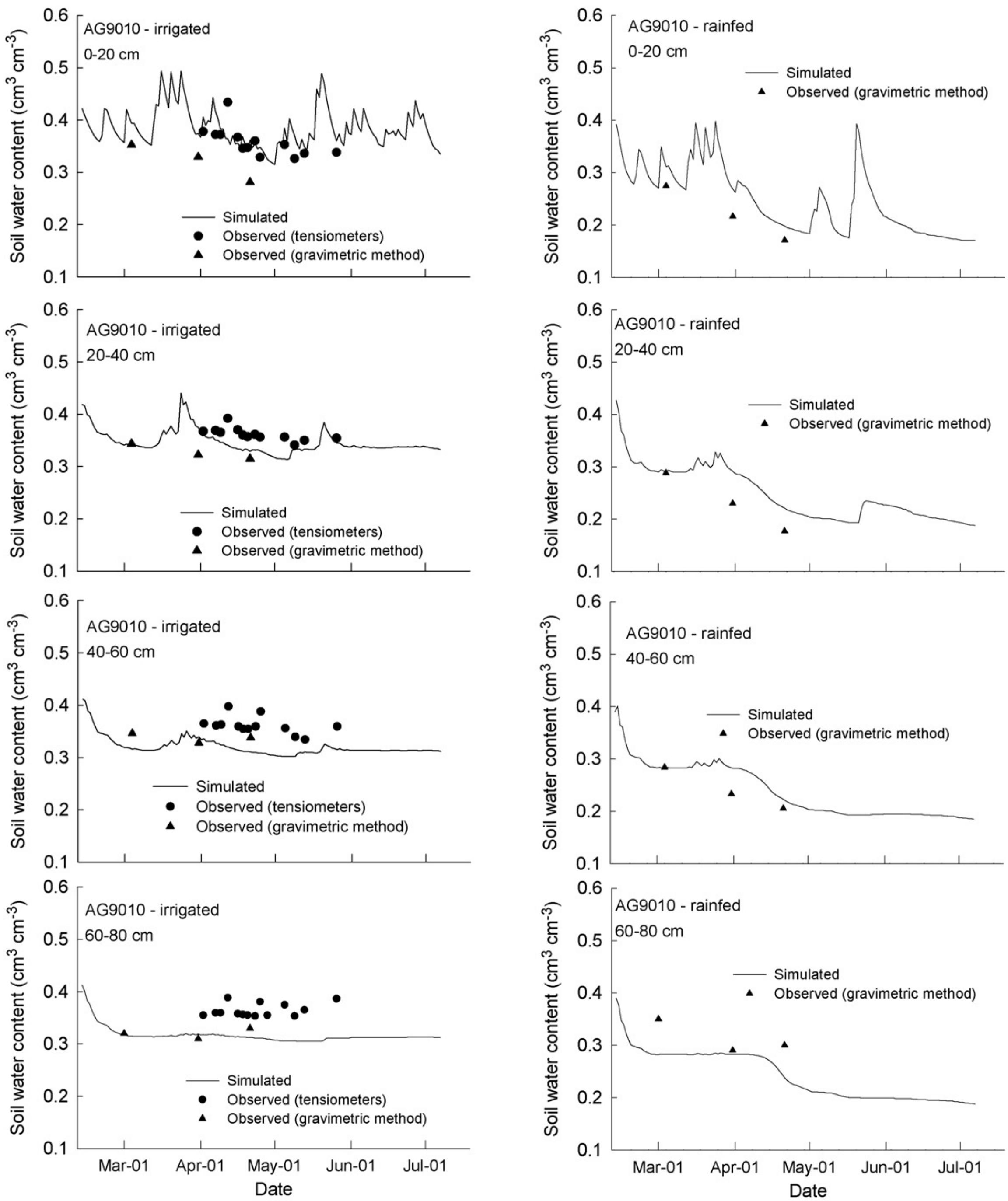

Fig. 2. Observed and simulated soil water content for hybrid AG9010 grown under irrigated and rainfed conditions in 2002.

planting to physiological maturity of maize grown off-season in a subtropical environment.

3.1.4. Leaf area index and biomass

The evaluation of the LAI with the CSM-CERES-Maize model using the data from the 2002 irrigated experiment, showed that the best prediction was for the hybrid DKB 333B with a normalized RMSE of 10.4%, while the highest normalized RSME was obtained for the hybrid AG9010 (24.2%) (Fig. 3). For the 2002 rainfed experiment, LAI was very well simulated for the hybrids DKB 333B, DAS CO32, and Exceler, with a normalized RMSE that ranged from 10% to 20% (Fig. 4). However, there was an underestimation of LAI for the hybrid AG9010, with a value of 24.4% for normalized RMSE. The results agree in part with previous works conducted using CSM-CERES-Maize model, which suggest that the functions that describe leaf growth and senescence could be modified to improve the simulation of LAI for specific environments (Ben Nouna et al., 2000).

The CSM-CERES-Maize model simulated biomass fairly well for the 2002 irrigated experiment. Normalized RMSE

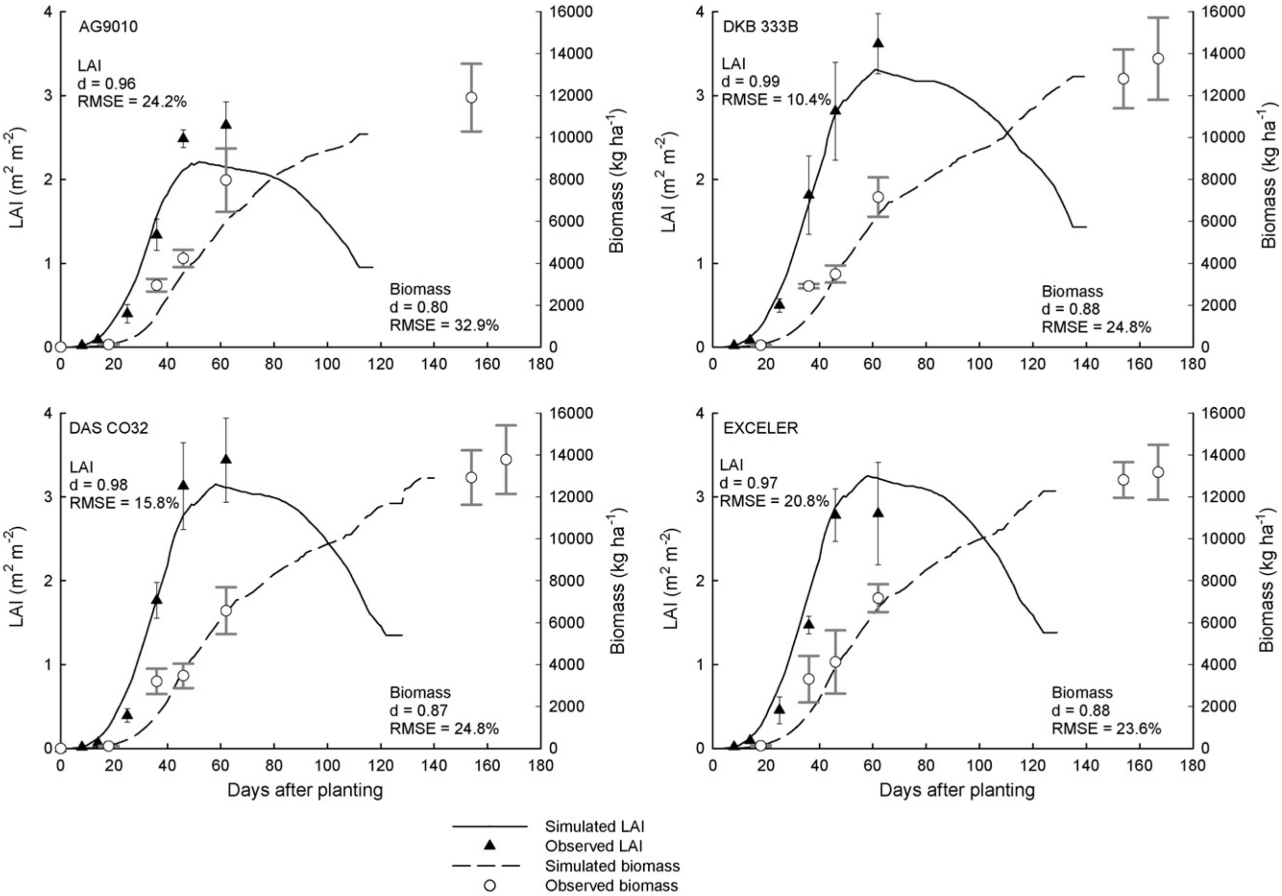

Fig. 3. Observed and simulated leaf area index and biomass for four maize hybrids grown under irrigated conditions in 2002.

ranged from 23.6% to 32.9% for the four hybrids, with the most accurate prediction for the hybrid Exceler (Fig. 3). A good estimation of biomass between simulated and observed values was obtained for the 2002 rainfed conditions for the hybrids AG9010, DKB 333B and Exceler, with a normalized RMSE that ranged from 10% to 20%. For the hybrid DAS CO32, biomass was only fairly well predicted, with a normalized RMSE of 24.7% (Fig. 4). Some disagreements between observed and simulated biomass have previously been reported by Ben Nouna et al. (2000).

3.1.5. *Yield and yield components*

Yield was very well simulated for the four hybrids and low values were obtained for the percentage prediction deviation (PD). The hybrids DKB 333B and DAS CO32, had the lowest values of PD for the two experiments conducted during 2002, ranging from 1.1% to 6.0% (Table 3). In addition, for the four hybrids the normalized RMSE was smaller than 10%. The simulated yields ranged from 3895 kg ha^{-1} for the hybrids DKB 333B to 5504 kg ha^{-1} for the hybrid Exceler and the observed yields ranged from 3823 kg ha^{-1} for the hybrid DKB 333B to 5306 kg ha^{-1} for the hybrid Exceler. The RMSE was low for the four hybrids grown under irrigated conditions (193 kg ha^{-1}) and under rainfed conditions (348 kg ha^{-1}), while the systematic term of the MSE (MSEs) was an important component of the MSE (Table 3).

The PD for kernel number was small for hybrids DKB 333B and DAS CO32 for two experiments conducted in 2002 ranging from −7.8% to 6.5%. However, for the hybrid AG9010, the PD ranged from 0.9% for the irrigated experiment to 21.2% for the rainfed experiment (Table 4). For the four hybrids the normalized RMSE values (%) for kernel number was less than 15%. The RMSE expressed as # m^{-2} was 102 and 257 for the four hybrids grown under irrigated and rainfed conditions, respectively. The MSEs was an important component of the MSE. These results agree with previous studies that have shown that the CSM-CERES-Maize can predict yield accurately for a wide range of environmental conditions, while the predictions for the number of kernels per plant have been less accurate (Piper and Weiss, 1990; Jagtap et al., 1993; Ritchie and Alagarswamy, 2003).

Kernel weight, in general, was accurately simulated for the four hybrids in the two experiments (Table 5). The hybrids DAS CO32 and Exceler had the lowest PD values, ranging from −1.3% to 3.4%, while the PD for the hybrid AG9010 varied from −10.3% to −9.1%. The RMSE was 11 and 14 mg $kernel^{-1}$ for the four hybrids grown under irrigated and rainfed conditions, respectively. For the four hybrids grown under irrigated conditions the unsystematic term of the MSE (MSEu) was important, indicating the capability of the CSM-CERES-Maize model for simulating kernel weight. In some cases the CSM-

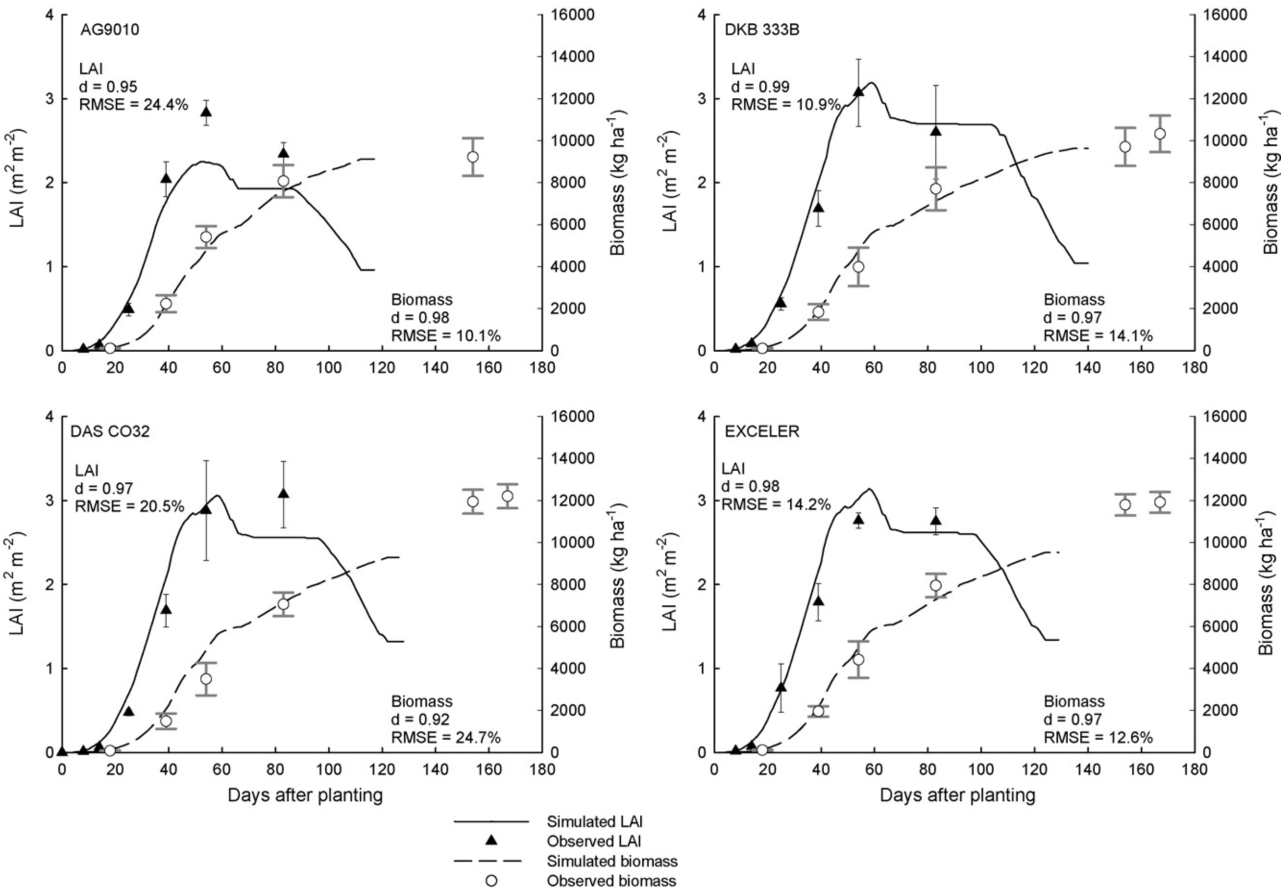

Fig. 4. Observed and simulated leaf area index and biomass for four maize hybrids grown under rainfed conditions in 2002.

CERES-Maize model showed a trend to compensate between kernel number and kernel weight, which could explain the good yield prediction. Similarly, Sadler et al. (2000) reported large variations in maize yield in field experiments; sometimes compensatory effects, e.g., kernel number and mass, explained similar final yields.

3.2. *Evaluation of optimum planting dates*

3.2.1. *Rainfed conditions*

The average yield decreased by 55% when the planting date was delayed from February 1 to April 15 for all four hybrids. For the first planting date, i.e., February, 1 for the very

Table 3
Observed and simulated average yield for four different hybrids under rainfed and irrigated conditions

Experiment	Hybrid	Simulated ($kg\,ha^{-1}$)	Observed ($kg\,ha^{-1}$)	PD[a] (%)	d[b]	Normalized RMSE (%)[c]	RMSE ($kg\,ha^{-1}$)	MSE[d]	MSEs[e]	MSEu[f]
Irrigated 2002	AG9010	4924	4986	−1.2						
	DKB 333B	5446	5139	6.0						
	DAS CO32	5159	5047	2.2						
	Exceler	5504	5306	3.7						
Statistics					0.73	3.78	193	37,460	27,212	10,246
Rainfed 2002	AG9010	4499	4044	11.3						
	DKB 333B	3895	3823	1.9						
	DAS CO32	4153	4109	1.1						
	Exceler	4337	4859	−10.7						
Statistics					0.63	8.29	348	121,657	82,048	39,607

[a] Percentage prediction deviation.
[b] Index of agreement.
[c] Root mean square error.
[d] Mean square error.
[e] Systematic MSE.
[f] Unsystematic MSE.

Table 4
Observed and simulated average kernel number for four different hybrids under rainfed and irrigated conditions

Experiment	Number of kernels		PD[a] (%)	d[b]	Normalized RMSE (%)[c]	RMSE #	MSE[d]	MSEs[e]	MSEu[f]
	Simulated	Observed							
Irrigated 2002									
AG9010	2339	2318	0.9						
DKB 333B	2213	2078	6.5						
DAS CO32	2165	2308	−6.2						
Exceler	2233	2286	−2.3						
Statistics									
				0.54	4.56	102	10,481	6,729	3752
Rainfed 2002									
AG9010	2183	1801	21.2						
DKB 333B	1869	2028	−7.8						
DAS CO32	1916	2011	−4.7						
Exceler	1862	2152	−13.5						
Statistics									
				0.01	12.87	257	66,082	63,973	2111

[a] Percentage prediction deviation.
[b] Index of agreement.
[c] Root mean square error.
[d] Mean square error.
[e] Systematic MSE.
[f] Unsystematic MSE.

short season maturity hybrid AG9010 the yields were lower than 3621 kg ha^{-1} for 25% of the years, while the yields were higher than 7482 kg ha^{-1} for 25% of the years. The median yield value for normal season maturity hybrid DKB 333B decreased from 4822 kg ha^{-1} to 1817 kg ha^{-1} for the planting dates from March 1 to April 15. For all hybrids, the simulated yield between the 10th and 90th percentiles decreased. An example is presented in Fig. 5a for hybrid DAS CO32, showing that there was an increase in the risk of obtaining very low yields for the late planting dates. The results suggested that there was a large impact of the weather conditions, such as a low amount of precipitation, low temperatures, and low levels of solar radiation (Fig. 1), when planting was delayed.

Table 5
Observed and simulated average kernel weight for four different hybrids under rainfed and irrigated conditions

Experiment	Simulated (mg kernel^{-1})	Observed (mg kernel^{-1})	PD[a] (%)	d[b]	Normalized RMSE (%)[c]	RMSE (mg kernel^{-1})	MSE[d]	MSEs[e]	MSEu[f]
Irrigated 2002									
AG9010	210	231	−9.1						
DKB 333B	252	251	0.4						
DAS CO32	233	228	2.2						
Exceler	246	238	3.4						
Statistics									
				0.76	4.80	11	132	11	121
Rainfed 2002									
AG9010	208	232	−10.3						
DKB 333B	211	225	−6.2						
DAS CO32	225	228	−1.3						
Exceler	236	238	−0.8						
Statistics									
				0.46	6.07	14	196	121	75

[a] Percentage prediction deviation.
[b] Index of agreement.
[c] Root mean square error.
[d] Mean square error.
[e] Systematic MSE.
[f] Unsystematic MSE.

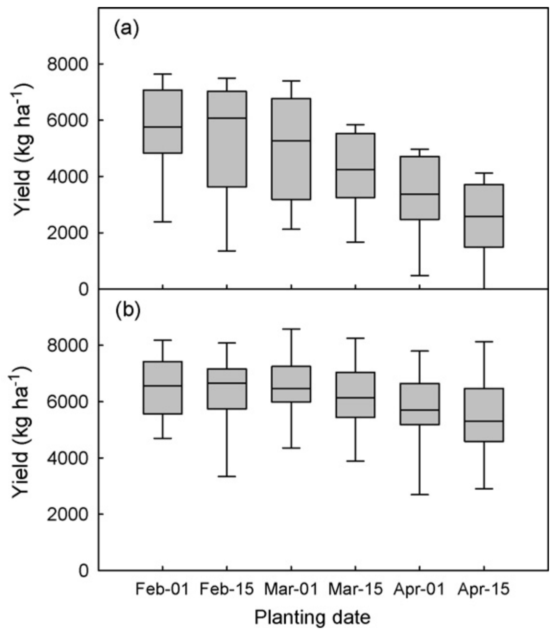

Fig. 5. Simulated yield for different planting dates under rainfed conditions for the hybrid DAS CO32 under rainfed (a) and irrigated (b) conditions.

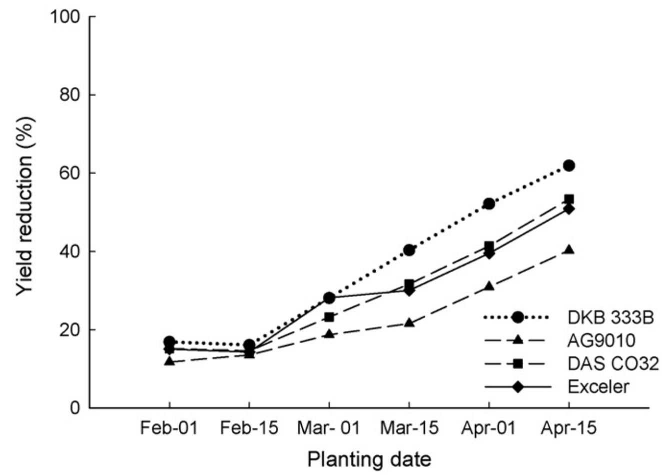

Fig. 6. Simulated yield reduction (%) due to water deficiency for the four maize hybrids grown off-season in 2002.

3.2.2. Irrigated conditions

For irrigated conditions, the decrease in yield was less evident than under rainfed conditions, as there was only a 21% difference in the average yield between the earliest and latest planting date, compared to 55% for the rainfed conditions. For the very short season hybrid, AG9010, the average yield was 6454 kg ha^{-1} for the earliest planting date, i.e., February 1, and 5039 kg ha^{-1} for the latest planting date, i.e., April 15. There was a decrease in the median yield values for the planting dates after March 1 for all four hybrids. The simulated yield for the 10th percentiles also decreased (bottom lines of the diagram in Fig. 5b) for late planting dates, but the simulated yield was always greater than 2000 kg ha^{-1} for all four hybrids. The decrease for the irrigated conditions was not as evident as it was for the rainfed conditions (Fig. 5b).

The yield reductions expressed as the yield decrease between irrigated and rainfed conditions ranged from 10% to 18% for the hybrids AG9010 and DKB 333B, respectively, for the earliest planting date, February 1 (Fig. 6). Similar values were found for the second planting date, i.e., February 15. For the March 1 to April 15 planting dates, a sustainable increase in risk of obtaining low yields was simulated. For the final planting date, i.e., April 15, the yield reductions ranged from 38% to 60% for the hybrids AG9010 and DKB 333B, respectively. For the short-season hybrids, e.g., DAS CO32 and Exceler, in between values were found (50–53%). These results are in agreement with previous studies that showed that short-season hybrids are more adapted for maize grown off-season compared to normal hybrids (Oliveira et al., 1994; Duarte et al., 1994).

3.3. Yield forecasts

There was a high variability in yield for the early yield forecasts conducted during April and May, depicted by the large standard deviation associated with each forecast (Fig. 7). This high yield variability shown at the start of the growing season confirmed the high risk associated with growing maize off-season under rainfed conditions.

When the simulations were conducted considering an extensive period with actual weather records for 2002, the standard deviation of simulated yield decreased for all four hybrids as the growing season progressed, reaching low values approximately 20 days prior to physiological maturity (Fig. 7). For the hybrids AG9010, DAS CO32, and Exceler, the estimated yield had a standard deviation that was close to 0 on July 15 (Fig. 7a, c, and d), while for the hybrid DKB 333B, with a normal growing season maturity, the standard deviation reached almost 0 two weeks later on July 31 (Fig. 7b). The yield forecast conducted at the end of the growing season resulted in a similar value to the observed yield under rainfed conditions (triangle points in Fig. 7) for the four hybrids grown in 2002. These similarities between simulated and observed yields were expected to occur, because the CSM-CERES-Maize model was evaluated using the observed yield values for the rainfed experiment of 2002. Using the actual weather data for 2002, an accurate yield forecast could be obtained at least 45 days prior to harvest for all four hybrids, which is a somewhat promising result. Similar results have been reported using this methodology in other crops like millet (Thornton et al., 1997) and peanut Garcia y Garcia et al. (2003), in which accurate yield forecasts during the growing season were shown. Discussions about the importance of early yield predictions for agricultural planning and food security issues have also been presented (Thornton et al., 1997). There appears to be much potential in using crop models for yield forecasts. However, the models need to be calibrated and evaluated because of the common replacement of hybrids used by the farmers and in order to obtain accurate simulations for local conditions. Furthermore, there is also a requirement for fairly detailed input data to run the crop models. The potential benefits offered by crop models can only be achieved if they are used appropriately, with an understanding of their capabilities as well as their limitations.

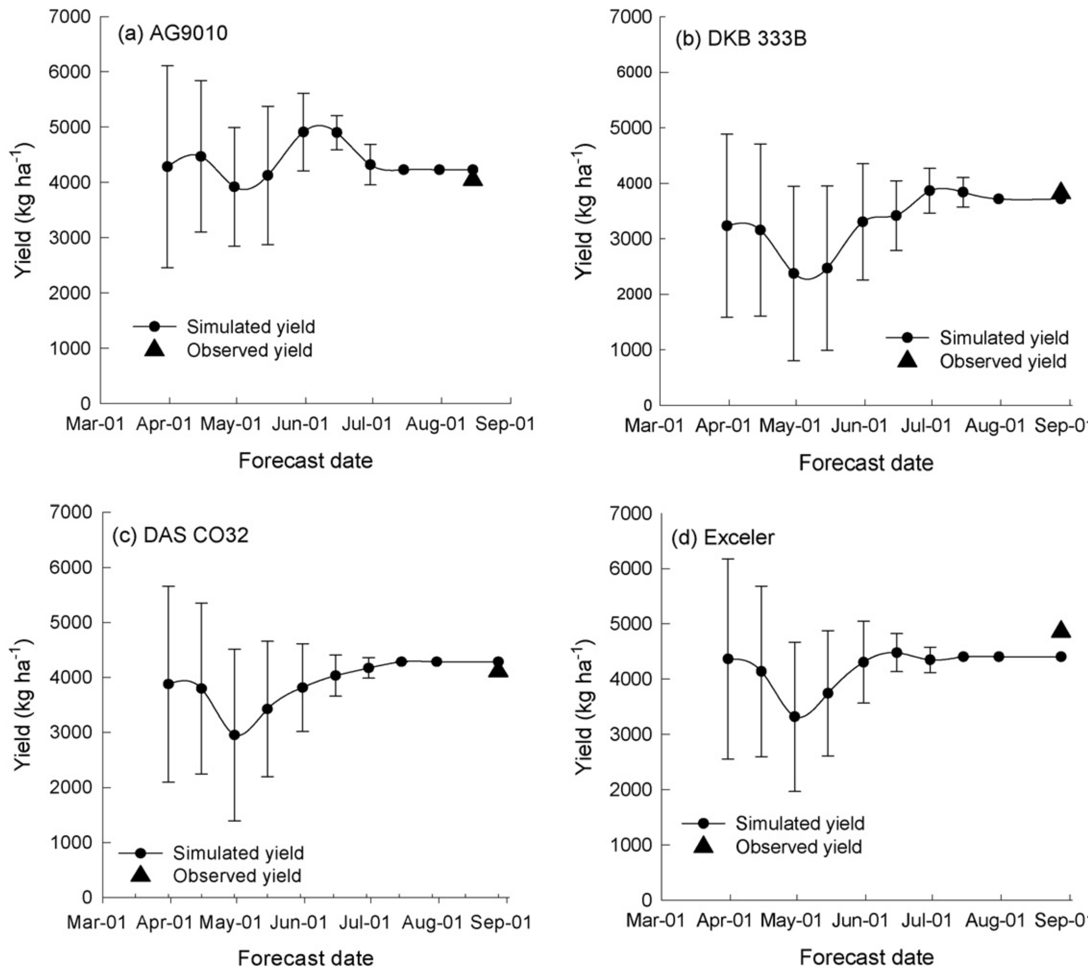

Fig. 7. Average forecasted yield and standard deviation for 2002 as a function of the forecast date and observed yield (kg ha^{-1}) for hybrids AG9010 (a), DKB 333B (b), DAS CO32 (c), and Exceler (d).

4. Conclusions

The CSM-CERES-Maize model was able to accurately simulate phenology and yield for four hybrids grown off-season in a subtropical environment in Brazil. In general, total biomass and LAI were also reasonably well simulated, especially for the hybrids Exceler, DAS CO32, and DKB 333B. For both rainfed and irrigated cropping systems, average yield decreased with later planting dates. For normal and late planting dates the very short and short seasons hybrids performed best compared to the normal season hybrid DKB 333B.

This study also showed that the CSM-CERES-Maize model can be a promising tool for yield forecasting for maize hybrids, grown off-season in Piracicaba, SP, Brazil, as an accurate yield forecast was obtained at approximately 45 days prior to harvest. This information is considered to be timely and useful for farmers and decision makers.

Further research is needed to apply this methodology to different locations in order to be able to make practical decisions with respect to grain stock management. Additional model calibration and evaluation might also be needed because of regular changes in the varieties used by farmers.

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