Simulating Planting Date Effects on Corn Production Using RZWQM and CERES-Maize Models

Saseendran S. Anapalli, L. Ma, D. C. Nielsen,* M. F. Vigil, and L. R. Ahuja

ABSTRACT

Corn (*Zea mays* L.) production in northeastern Colorado is constrained by a frost-free period averaging 11 May to 27 September. For optimization of yield, planting at the appropriate time to fit the hybrid maturity length and growing season is critical. Crop models could be used to determine optimum planting windows for a locality. We calibrated the plant parameters of the Root Zone Water Quality Model (RZWQM) and genetic coefficients for the CERES-Maize model and validated their performance against experimental data of three corn hybrids varying in days to maturity, planted on three planting dates in 2 yr at Akron, CO, under irrigation. Both models could be calibrated to predict leaf area index, soil water content, crop water use, and yield with similar levels of accuracy. Both models simulated the observed decline in yield with delayed planting date, but CERES-Maize simulated the yield from the latest planting date much more accurately for all three hybrids than did RZWQM (13% underpredicted by CERES-Maize; 50% overpredicted by RZWQM). Using the long-term Akron weather record, the latest planting dates for the short-, mid-, and long-season hybrids to have a 50% chance of achieving a break-even yield under irrigation were 13 May, 20 May, and 6 May, respectively. Long-term simulations also revealed that the longer maturity length hybrids lose yield faster than short maturity length hybrids with planting delay. The information generated by either RZWQM or CERES-Maize can be useful for making both planting and replanting decisions for corn hybrids of varying maturity length in northeastern Colorado.

SELECTION OF CORN planting date to ensure physiological maturity before fall frost is a management consideration for corn producers in eastern Colorado. As such, corn producers in these regions often need information on how planting date and hybrid selection affect grain yield and water use at a given location (Lauer et al., 1999). Corn planting dates in western Kansas, western Nebraska, and eastern Colorado are between 20 April and 7 June (Shoyer et al., 1996; Neild, 1981; Bauder et al., 2003). Optimum corn planting dates in the U.S. Corn Belt are reported to be between 20 April and 10 May (Benson, 1990). Advantages in crop yield performance due to planting corn before or after these dates (especially in the northern Corn Belt) have also been reported (Carter, 1984). Several multilocation, multiple-year experimental studies have reported the effects of planting dates on corn yield, water use, etc. (e.g., Nielsen et al., 2002b; Lauer et al., 1999; Swanson and Wilhelm, 1996). In general, all the reported studies for determining planting date recommendations for a locality made use of field experiments that have been done periodically with limited multiyear, multilocation replications, and conclusions are extrapolated statistically or otherwise. But planting date responses, depending on the weather variability at the location, vary a great deal among years and locations. Field experiments to capture all the multiyear, multilocation variability are nearly impossible. In this context, cropping system simulation models, well calibrated and validated against field experimental data, hold the promise for extrapolating the short-duration field experimental results to other years and other locations making use of long-term weather and soil information (Mathews et al., 2002). Accurate knowledge of the planting window of any particular hybrid at a particular location is critical when selecting hybrid seed for planting when normal planting is delayed or for replanting when crop stand is nonoptimal following hail or a late-season freeze (Benson, 1990).

Crop simulation models integrate the interdisciplinary knowledge gained through experimentation and technological innovations in the fields of biological, physical, and chemical sciences relating to agricultural production systems. Therefore, these models can increase understanding and management of agricultural systems in a holistic way. Due to the worldwide distribution of corn and its importance as a food cereal, various models have been developed for the prediction of corn development and grain yield in varied environments, e.g., CERES-Maize (Jones and Kiniry, 1986), SIMAIZ (Duncan, 1975), CORNF (Stapper and Arkin, 1980), RZWQM (Ahuja et al., 2000), ALMANAC (Kiniry et al., 1992), and APSIM (McCown et al., 1996).

In these contexts, objectives of the current study were to: (i) calibrate and assess the potentials of RZWQM (employing a generic crop growth model) and CERES-Maize (a dedicated corn model) for simulation of three corn hybrids (Pioneer 3902, 3732, and 3540) varying in maturity length from 91 to 109 d at three planting dates (from the end of April to the middle of June) during two growing seasons (1991, 1992) at Akron, CO, and (ii) apply the models to long-term weather records to determine probabilities of achieving break-even corn yields for these hybrids under irrigated (no water stress) conditions at various planting dates.

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Abbreviations: C_{LA}, leaf area conversion coefficient (defined as the biomass needed for unit leaf area index expansion); DSSAT, Decision Support System for Agrotechnology Transfer; ET, evapotranspiration; LAI, leaf area index; ME, mean error; RMSE, root mean square error; RZWQM, Root Zone Water Quality Model; TDR, time-domain reflectometry.

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Table 2. Calibrated plant growth parameters (regional and species specific) for simulation of irrigated corn hybrids PI 3902, PI 3732, and PI 3540 at Akron, CO, using the Root Zone Water Quality Model (RZWQM).

Parameter	PI 3902	PI 3732	PI 3540
Regional parameters			
1. Daily respiration as a function of photosynthate, fraction	0.130	0.090	0.100
2. Biomass to leaf area conversion coefficient, g leaf area^{-1}	11.50	11.50	12.50
3. Age effect for plants in the propagules development stage, fraction	0.650	0.750	0.900
4. Age effect for plants in the seed development stage, fraction	0.650	0.750	0.950
5. Maximum rooting depth, m	1.20	1.15	1.10
Species-specific parameters			
1. Minimum time needed for plant to germinate, d	4	5	5
2. Minimum time needed for plant to emerge, d	10	5	5
3. Minimum time needed for plant to grow to four-leaf stage, d	10	16	19
4. Minimum time needed for plant to complete vegetative growth, d	37	38	38
5. Minimum time needed for plant to complete reproductive growth, d	38	39	39

for simulating leaf area development throughout the growth period. Also in RZWQM, up to 50% of the aboveground biomass can senesce due to water and freezing stress and tissue aging. Dead aboveground biomass and dead root biomass are continuously sloughed into the soil organic pools, affecting the soil physical and hydraulic properties (Hanson, 2000). Soil organic matter in RZWQM is distributed over five computational pools and is decomposed by three types of microbial populations.

The Green–Ampt equation (Green and Ampt, 1911) is used for simulation of infiltration of rain or irrigation water into the soil matrix, and its subsequent redistribution is calculated by solving the Richards' equation. Soil hydraulic properties are estimated using the Brooks–Corey equation (Brooks and Corey, 1964). Additionally, processes such as preferential flow of soil water through macropores and the effect of tillage and crop residue on soil hydraulic properties are simulated (Ahuja et al., 2000).

Potential ET rate in RZWQM is estimated from a soil–canopy–residue system using a revised form of the Shuttleworth and Wallace (1985) double-layer model (Ahuja et al., 2000). Plant transpiration drives the passive uptake of N into the plant. Soil water and N are extracted by layer in proportion to the root biomass present and amount of N in the soil water. If passive uptake fails to supply the N demands, active uptake occurs using a process similar to the Michaelis–Menten substrate model if more N is available in the soil (Hanson, 2000).

The generic crop model of RZWQM has been parameterized to simulate corn and validated against measured data in various western and midwestern states (Hanson et al., 1999; Wu et al., 1999; Ghidey et al., 1999; Jaynes and Miller, 1999; Martin and Watts, 1999; Farahani et al., 1999; Landa et al., 1999). Major components of RZWQM have been validated by Ma et al. (2001). The model has not been tested and validated to assess its potential for simulation of planting date effects on corn production for development of crop management applications.

CERES-Maize [as implemented in DSSAT v3.5, available at http://www.icasa.net/dssat/ (verified 29 Sept. 2004); Jones and Kiniry, 1986; Ritchie et al., 1998] is also a process-oriented model that simulates phenological development of the crop (specifically corn); growth of leaves, stems, and roots; biomass accumulation based on light interception and environmental stresses; soil water balance; soil N transformations and uptake; and crop growth and development. This model is available as part of the DSSAT (Decision Support System for Agrotechnology Transfer) suite of crop models designed to estimate production, resource use, and risks associated with crop production practices (Tsuji et al., 1994; Jones et al., 1998). A complete description of the model is published elsewhere (Ritchie et al., 1998).

Four discrete functions of simulated leaf-tip number are used for predicting plant canopy leaf area in CERES-Maize (Lizaso et al., 2003). The calculated canopy leaf area is subjected to senescence coupled with plant development. Calculated senescence rate is modified to account for population and leaf-shading effects. Also deficits of N and water accelerate senescence. Final LAI is calculated from the canopy leaf area balance available each day as a function of plant population.

To facilitate use of a minimum data set that is widely available all over the world, CERES-Maize uses a simple water balance algorithm following a layered soil and a tipping-bucket approach to calculate yield reductions related to water stress (Ritchie, 1998). The USDA curve number technique (Williams, 1991) is used to calculate runoff and infiltration rates resulting from rain and irrigation. Potential ET calculations are based on the Ritchie (1972) adaptation of the Priestley–Taylor approach (Priestley and Taylor, 1972). This method

Table 3. Calibration results of the Root Zone Water Quality Model (RZWQM) and CERES-Maize for simulation of irrigated corn hybrids PI 3902, PI 3732, and PI 3540 at Akron, CO. (Calibration data set was from the first planting date in 1991.)

	Mean error = (predicted − measured)/measured					
	RZWQM			CERES-Maize		
Parameter	PI 3902	PI 3732	PI 3540	PI 3902	PI 3732	PI 3540
	%					
Grain yield	−0.8	−4.5	−3.4	0.5	1.3	−0.7
Anthesis date	†	†	†	−1.3	5.7	−1.1
Physiological maturity date	†	†	†	−0.7	4.1	−1.9
Maximum LAI	−1.1	27.3	−8.8	2.9	16.1	2.3
Crop ET‡	−4.9	−9.1	−5.3	8.8	−4.7	4.0
LAI progression§	0.78	0.98	1.30	0.42	0.72	0.78
Soil moisture§	0.057	0.098	0.064	0.063	0.070	0.068

† These parameters are not explicitly predicted by the model and hence not included here.
‡ Evapotranspiration (ET) from 22 May to 19 Sept. 1991.
§ Values for leaf area index (LAI) progression and soil moisture are root mean square error.

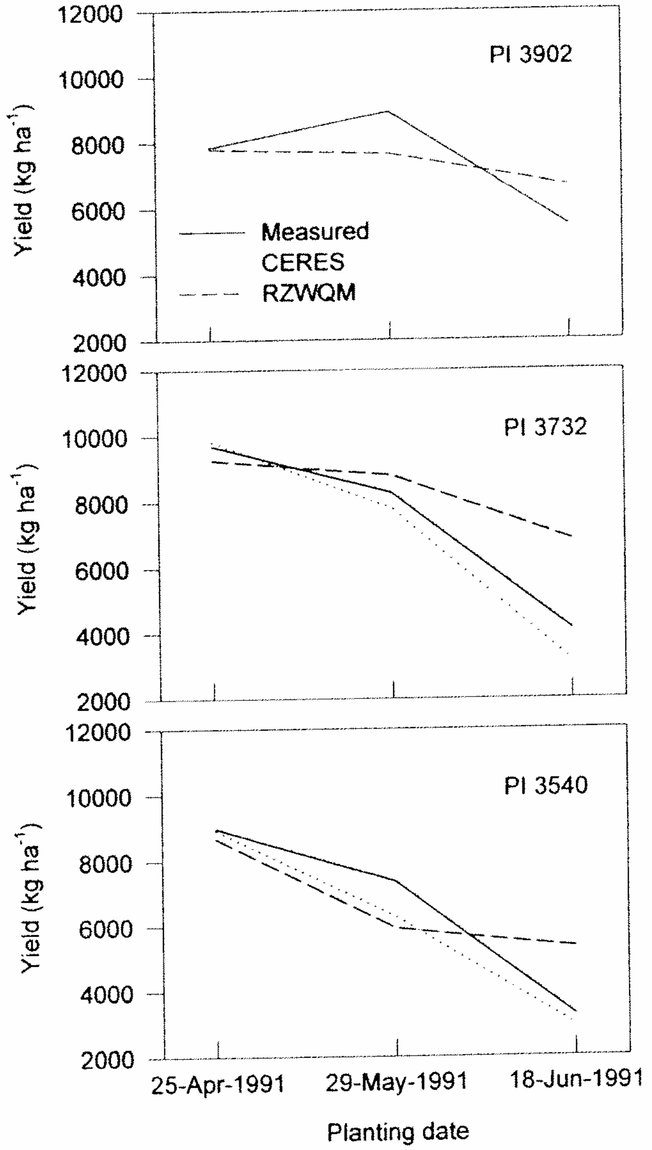

Fig. 6. Comparisons of measured reduction in corn grain yield with delay in planting of hybrids PI 3902, PI 3732 and PI 3540 with predictions by Root Zone Water Quality Model (RZWQM) and CERES-Maize at Akron, CO.

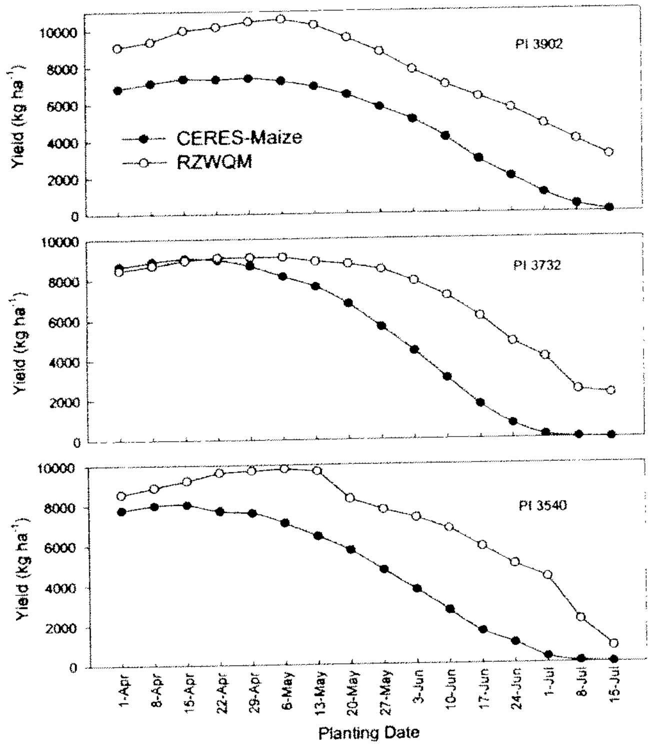

Fig. 7. Mean simulated irrigated corn yields (1912–1999, Akron, CO) for hybrids PI 3902, PI 2732, and PI 3540 planted at weekly intervals from 1 April through 15 July. Simulations from CERES-Maize and Root Zone Water Quality Model (RZWQM).

erage temperature to calculate a daily biomass value from which daily grain mass is partitioned, such that simulated grain yield is not influenced as much by low temperatures at the end of the growing season.

Based on the above yield predictions by RZWQM and CERES-Maize for plantings of the three corn hybrids from 1 April through 15 July, probabilities for achieving the break-even yield goal of 7000 kg ha^{-1} (P_{7000}) under irrigated conditions were developed (Fig. 8). RZWQM simulations showed P_{7000} above 0.5 from 1 April through 10 June for PI 3902 and PI 3732 and up to 3 June in the case of PI 3540. The CERES-Maize model showed P_{7000} above 0.5 from 1 April through 13 May in the case of PI 3902 and up to 20 May in the case of PI 3732. The probability of achieving the break-even yield goal was above 0.5 only up to 6 May in the case of the late-maturing hybrid, PI 3540. This result does not follow the generally accepted observation that longer-maturity hybrids cannot be planted as late as earlier-maturing hybrids. In this case, CERES-Maize predicts that the 101-d hybrid (PI 3732) could be planted a week later than the 91-d hybrid (PI 3902) and still have a 50% probability of achieving a yield of 7000 kg ha^{-1}. This may be a result of a combination of factors, such as a given hybrid's yield response to timing of high-temperature stresses that occur as planting date is changed, as well as potentially differing photoperiod responses between hybrids.

There exists a difference of about 3 to 4 wk in the end of the planting window simulated by the two models at the same probability level. This difference was mainly due to the failure of RZWQM to accurately simulate the yield decline associated with the latest planting date measured in the field experiments (Fig. 6). The RZWQM overpredicted grain yield in the third planting date experiment of 1991 by 21, 65, and 63%, respectively, for the three cultivars. However, RZWQM predictions also show a sharp decline in P_{7000} after 27 May planting though probabilities continue to be higher than with CERES-Maize.

CONCLUSIONS

Validation results of the calibrated RZWQM and CERES-Maize models showed reasonable accuracy in simulation of planting date effects on ET and grain yield of the three corn hybrids differing in maturity length grown under irrigated conditions in eastern Colorado.

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simulation were 0.057, 0.098, and 0.064 cm^3 cm^{-3} for the PI 3902, PI 3732, and PI 3540 hybrids, respectively (Table 3).

CERES-Maize

In CERES-Maize, genetic coefficients need to be calibrated separately for each of the three hybrids (Boote, 1999). In this study, we had information on (i) silking date, (ii) maturity date, (iii) grain yield, and (iv) LAI with which to calibrate the genetic coefficients. Godwin et al. (1989) suggested an iterative approach to reach reasonable estimates of the coefficients through trial-and-error adjustments to match the observed crop phenology and yield with those simulated by the model, if the data for calibration of the genetic coefficients are limited.

Following this method, based on the above data, we optimized the six genetic coefficients needed for simulation of each of the three corn hybrids (Table 4). For optimization of the coefficients, we developed a computer program to uniformly vary the six genetic coefficients over the range of values given in Table 4. The crop was simulated at each step, and the ME of simulated vs. observed values of the time to anthesis and physiological maturity, grain yield, and maximum measured LAI was calculated. The combination of genetic parameters that gave minimum error was selected separately for each hybrid and used in further calibration and validation of the model. Measured values of soil albedo, soil first-stage evaporation limit, drainage rate, and root growth factor for Rago silt loam soil were not available for input in the CERES-Maize model. As such, we started model simulations with default values available in the model for other silt loam soils. After initial calibration for genetic coefficients, we adjusted these soil parameters by matching measured and simulated soil water. The final values of genetic parameters for the three corn hybrids are given in Table 4.

As in the case of RZWQM parameters, these parameters also show substantial differences across the three hybrids. Evaluation of the calibration data set simulated with the CERES model also shows reasonable agreement between simulated and field-measured crop growth and development parameters of all three corn hybrids (Table 3). The calibrated model produced MEs of 0.5, 1.3, and −0.7% in grain yield predictions of the PI 3902, PI 3732 and PI 3540 hybrids, respectively. The MEs of silking and physiological maturity date simulations ranged between −1.9 and 5.7% (Table 3). The MEs of maximum LAI and ET simulations were between 2.3 and 16.1% and −4.7 and 8.8%, respectively (Table 3). The RMSEs of soil moisture simulations averaged across different soil layers and dates of measurement under the three hybrids were between 0.063 and 0.070 (Table 3). The RMSEs of LAI predictions of the model with time were 0.42, 0.72, and 0.78, respectively, for the three hybrids (Table 3).

RESULTS AND DISCUSSION

Weather

Weather conditions in 1991 in terms of temperature and solar radiation were normal to slightly above normal during the May through September period (Table 5). During June, July, and August 1992, temperatures and solar radiation were below normal, but above-normal temperature and solar radiation conditions existed during May and September 1992. Rainfall from 1 April to 31 October was 298 mm in 1991 and 324 mm in 1992.

Model Validation

Data from the two later planting dates in 1991 and all three planting dates in 1992 were used for validating the models. The validation data sets consisted of soil water content, time progression of LAI, crop ET, and grain yields of the three hybrids. Since the third crop of 1992 was harvested for silage due to delayed physiological maturity, the silage yield data were used in place of grain yield.

The RMSEs of soil water content predictions of RZWQM in the five planting date experiments of PI 3902, PI 3732, and PI 3540 varied between 0.057 and 0.112 cm^3 cm^{-3} (mean = 0. 081 cm^3 cm^{-3}), 0.064 and 0.113 cm^3 cm^{-3} (mean = 0.094 cm^3 cm^{-3}), and 0.064 and 0.111 cm^3 cm^{-3} (mean = 0.083 cm^3 cm^{-3}), respectively (Table 6). Soil water content predictions of CERES-

Table 6. Root mean square error (RMSE) of soil moisture predictions by Root Zone Water Quality Model (RZWQM) and CERES-Maize under irrigated corn hybrids PI 3902, PI 3732, and PI 3540 at Akron, CO. Probability level (*F* test) of significance in difference between the two model prediction variances also provided. (Lower values correspond to higher probabilities of observing significant differences. A value of 0.05 or less is considered significant.)

Corn hybrid	Planting date	RMSE of soil moisture predictions (cm^3 cm^{-3})		Significance of *F* test (*P*)
		RZWQM	CERES-Maize	
PI 3902	25 April 1991†	0.057	0.063	0.0677
	29 May 1991	0.064	0.065	0.4857
	18 June 1991	0.112	0.045	0.8999
	30 April 1992	0.071	0.068	0.8058
	19 May 1992	0.080	0.063	0.6552
	10 June 1992	0.106	0.079	0.8109
	Mean	*0.081*	*0.064*	
PI 3732	25 April 1991†	0.098	0.070	0.9976
	29 May 1991	0.064	0.055	0.9203
	18 June 1991	0.113	0.050	0.9999
	30 April 1992	0.101	0.075	0.9762
	19 May 1992	0.099	0.092	0.0622
	10 June 1992	0.089	0.093	0.1252
	Mean	*0.094*	*0.073*	
PI 3540	25 April 1991†	0.064	0.068	0.5629
	29 May 1991	0.075	0.062	0.9050
	18 June 1991	0.078	0.057	0.9999
	30 April 1992	0.065	0.061	0.1465
	19 May 1992	0.111	0.065	0.8966
	10 June 1992	0.076	0.087	0.1121
	Mean	*0.083*	*0.067*	

† Calibration data.

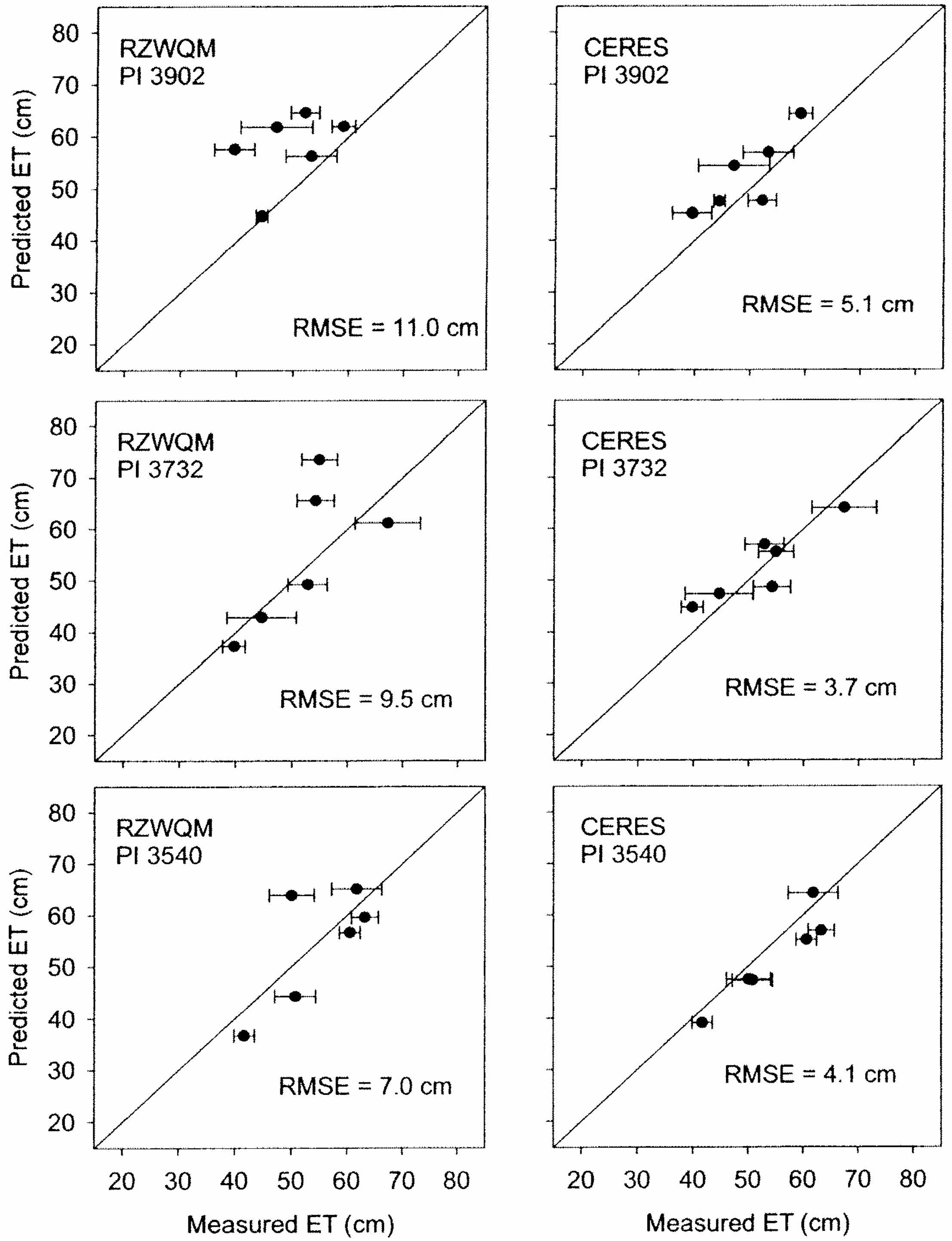

Fig. 4. Measured vs. predicted evapotranspiration (ET) for corn hybrids PI 3902, PI 3732, and PI 3540 at Akron, CO. Predicted values from simulations by the Root Zone Water Quality Model (RZWQM) and CERES-Maize. The six data points in each frame represent data from three planting dates in 2 yr (1991, 1992). Error bars represent one standard deviation about the means of the measured ET. The diagonal lines in the graphs are the 1:1 lines.

15 April for the three hybrids (Fig. 7). No appreciable difference in grain yield was simulated between 15 and 22 April plantings except in the case of hybrid PI 3540. For plantings after 22 April, CERES-Maize showed yield losses, and the rate of loss was much greater than plantings simulated by RZWQM after 6 May in the case of PI 3732 and PI 3540 (later-maturing hybrids). In the case of PI 3902 (early maturing hybrid), the decline in yield with delay in plantings was not appreciable until about 13 May. Average yield losses per day of delay in planting from 22 April through 15 July plantings for the PI 3902, PI 3732, and PI 3540 hybrids were 87, 109, and 93 kg ha^{-1}, respectively. Compared with RZWQM simulation results, the CERES-Maize model better pre-

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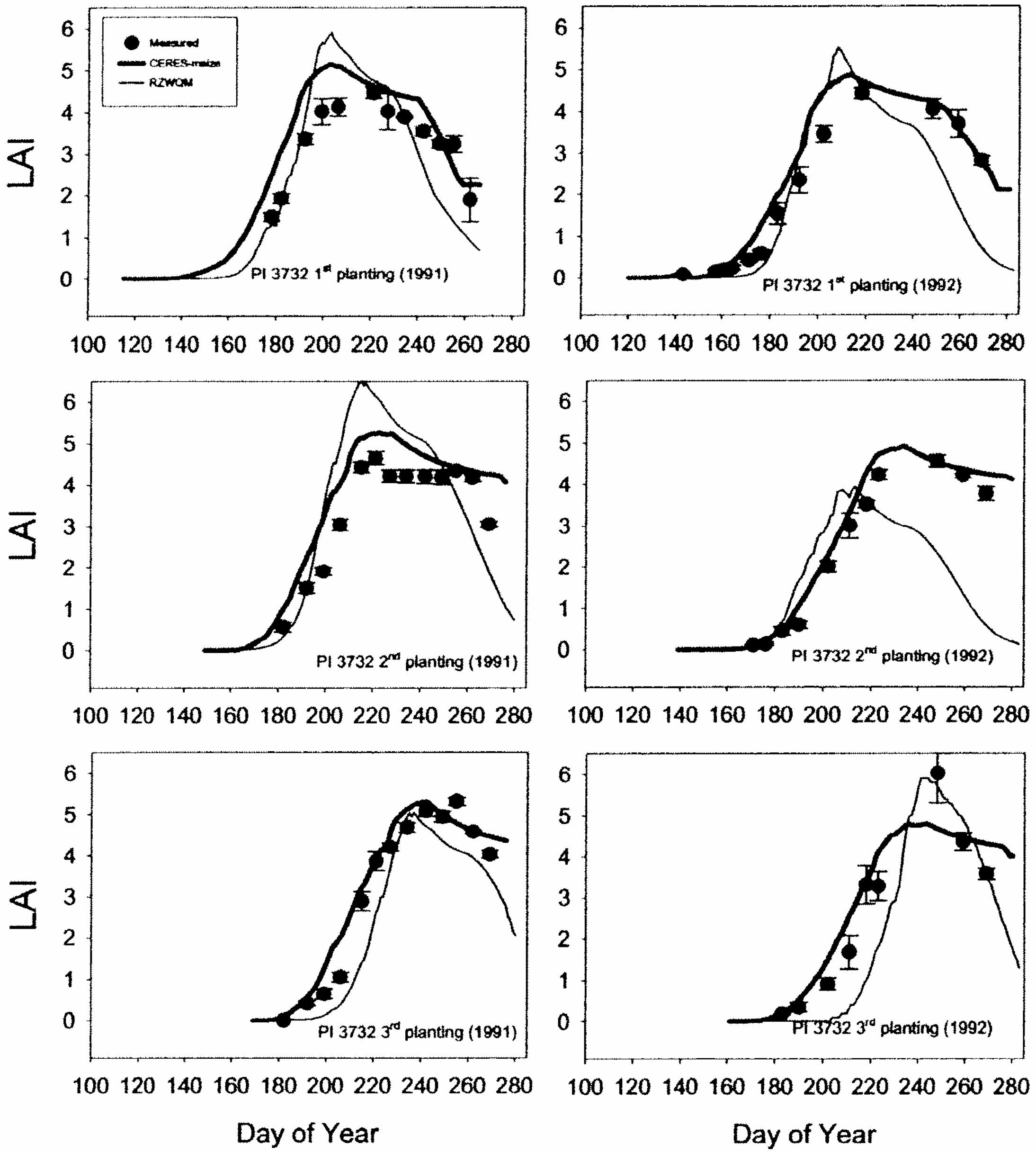

Fig. 2. Comparisons of measured leaf area index (LAI) progressions of PI 3732 corn hybrid at three planting dates in 1991 and 1992 with simulations by Root Zone Water Quality Model (RZWQM) and CERES-Maize. The first planting of 1991 was used to calibrate the models. Error bars represent one standard deviation about the means of measured LAI.

of C_{LA}, which is assumed to remain constant with growth stages (a user input parameter intended for calibration). Hence, changes in specific leaf weight and leaf area with different crop growth stages in RZWQM are not accounted for, leading to inaccurate simulations of time progressions of LAI. CERES-Maize calculates LAI using functions based on leaf-tip number (leaf number increases with development of the crop), resulting in better simulation of the time progression of LAI than simulations produced by RZWQM. The sometimes large differences in LAI simulations by RZWQM compared with LAI observed in the field indicate a need for improvement of the crop development part of the generic crop model for better simulation of planting date effects on crop growth and development.

The ET simulations of both RZWQM and CERES-Maize models showed reasonable correspondence with measured values of all three corn hybrids at all three planting dates (Fig. 4). The RMSEs of ET simulations by RZWQM were 11.0, 9.5, and 7.0 cm, respectively, for the PI 3902, PI 3732, and PI 3540 corn hybrids. The CERES-Maize model simulated ET more accurately with RMSEs of 5.1, 3.7, and 4.1 cm, respectively. Higher RMSEs with RZWQM simulations were due to the comparatively larger errors in LAI predictions, as discussed earlier.

To validate the grain or silage yield predictions of the model, we used grain yield data for the two planting date experiments of 1991 (first planting was used for calibration of the models) and the first two planting date experiments of 1992. The third planting of 1992 was harvested for silage, resulting in no grain yield data