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.

Saseendran S.A., L. Ma, and L.R. Ahuja, Great Plains Syst. Res., 2150 Centre Ave., Bldg. D, Suite 200, Fort Collins, CO 80526; and D.C. Nielsen and M.F. Vigil, USDA-ARS, Central Great Plains Res. Stn., 40335 County Rd. GG, Akron, CO 80720. Received 9 Jan. 2004. *Corresponding author (David.Nielsen@ars.usda.gov).

Published in Agron. J. 97:58–71 (2005).

677 S. Segoe Rd., Madison, WI 53711 USA

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.

MATERIALS AND METHODS

Field Experiment

Corn growth and development data collected in field experiments at the Central Great Plains Research Station (40°9′ N, 103°9′ W; 1384 m above mean sea level) 6.4 km east of Akron, CO (Nielsen and Hinkle, 1996), were used in this study for calibration and validation of RZWQM and CERES-Maize. In this experiment, three Pioneer corn hybrids [(i) Pioneer Hybrid 3902 (PI 3902), (ii) Pioneer Hybrid 3732 (PI 3732), and (iii) Pioneer Hybrid 3540 (PI 3540)] with maturity ratings of 91, 101, and 109 d were planted on 25 April, 29 May, and 18 June in 1991 and on 30 April, 19 May, and 10 June in 1992. Each hybrid/planting date area was 24 by 120 m, divided into four replicate plots with dimensions of 24 by 30 m. The plots were disc-tilled and fertilized at planting with ammonium nitrate at 168 kg ha^{-1} to minimize N stress. Therefore, the model simulations in the present study were made assuming no N stress. Final plant populations in all the experiments were 73910 plants ha^{-1} in rows spaced 0.76 cm apart. Soil type at the location is a Rago silt loam (fine montmorillonitic mesic Pachic Arguistoll).

All the plots were irrigated weekly with solid-set overhead sprinklers, with applications bringing the 0- to 90-cm soil layer back to field capacity to ensure a near non-water-stressed crop condition. Irrigation amounts were measured at the center of each plot. Irrigation amounts ranged from 35 to 68 cm in 1991 and from 12 to 26 cm in 1992; amounts varied due to precipitation received, length of growing season, and time of maximum leaf area development.

Measurements of leaf area index (LAI) were made nondestructively using a plant canopy analyzer (LAI-2000, LI-COR, Inc., Lincoln, NE) in the center of each plot (eight measurements averaged to give one LAI value per plot) at approximately weekly intervals. Grain yields were measured in all the experiments except the third planting date in 1992, as this crop was harvested for silage due to delayed physiological maturity. However, total aboveground biomass was recorded for this planting date experiment. Average LAI and yield were calculated from the four replicate measurements for each planting date–hybrid combination, as well as standard deviation as a measure of experimental error.

Weather and Soil Data and Calculation of Crop Evapotranspiration

Daily rainfall, maximum and minimum air temperature, solar radiation, wind speed, and relative humidity were recorded by an automated weather station located about 300 m east of the experimental plots. Since no runoff was observed following precipitation, we assumed that daily rainfall records were made up of single storms of 2-h duration, as a surrogate for break-point (storm intensity) rainfall data input in the RZWQM model. The 2-h storm duration is long enough to ensure that no runoff was simulated as observed in the field under Colorado conditions (Ma et al., 1998). Measured soil physical properties and estimated hydraulic properties (Rawls et al., 1982) for Rago silt loam soil were adopted from Nielsen et al. (2002a) for use in the models (Table 1).

Soil water measurements were taken weekly with a neutron probe (Troxler Model 3321 Depth Moisture Gauge, Troxler Electronic Lab., Inc., Research Triangle Park, NC) at depths of 0.45, 0.75, 1.05, 1.35, and 1.65 m. The neutron probe was calibrated against water content from soil samples collected at the time of access tube installation. Soil water in the 0.00- to 0.30-m layer was measured by time-domain reflectometry (TDR) using a TRASE System 1 Model 6050X1 TDR system (SoilMoisture Equip. Corp., Santa Barbara, CA). The manufacturer-supplied calibration was used to convert dielectric constant values to volumetric soil water. Neutron probe access tubes and TDR waveguides were located in the interrow space between corn rows in the center of each of the four replicate plots in each of the hybrid–planting date combinations. Measured corn evapotranspiration (ET) was calculated by the water balance method (Rosenberg et al., 1983) from changes in soil water content plus measured rain and irrigation. We assumed runoff and deep percolation were negligible. The plots were located on level ground but were furrow-diked on every row to minimize runoff potential. Measurements of soil water content at 1.65 m indicated no movement of water into lower soil depths. The four calculated ET values for each hybrid–planting date combination were averaged together to give one value to compare with ET simulated by each model. Standard deviations of ET were calculated as a measure of experimental error

Model Description

The RZWQM [ver. RZWQM98, available at http://gpsr.ars.usda.gov/ (verifed 29 Sept. 2004); Ahuja et al., 2000] has a generic crop growth model (Hanson, 2000) that can be parameterized to simulate a specific crop. Phenological development, while not explicitly simulated, is handled through seven growth stages. These include (i) dormant seeds, (ii) germinating seeds, (iii) emerged plants, (iv) established plants, (v) plants in vegetative growth, (vi) reproductive plants, and (vii) senescent plants. Plants advance from one growth stage to another after meeting a predefined minimum days modified by an environmental fitness function representing water, N, and temperature stresses. Detailed descriptions of the different components of RZWQM are available elsewhere (Ahuja et al., 2000; Hanson et al., 1998).

RZWQM calculates LAI by dividing the biomass partitioned to the leaves each day by a leaf area conversion coefficient (C_{LA}), a calibration parameter. The C_{LA} is defined as the biomass needed for unit LAI expansion. A single C_{LA} is used

Table 1. Physical and hydraulic properties of the Rago soil used in Root Zone Water Quality Model (RZWQM) simulations (Nielsen et al., 2002a).

Soil depth	Soil bulk density	Sand	Silt	Clay	Water content 33 kPa	Water content 1500 kPa	Saturated hydraulic conductivity
m	Mg m^{-3}	%			m^3 m^{-3}		mm h^{-1}
0.0–0.15	1.33	39.0	41.7	19.3	0.224	0.092	96.7
0.15–0.3	1.33	32.3	44.3	23.4	0.236	0.104	96.7
0.3–0.6	1.32	37.0	40.7	22.3	0.230	0.098	96.7
0.6–0.9	1.36	45.7	36.7	17.6	0.221	0.089	140.8
0.9–1.2	1.40	45.7	42.3	12.0	0.215	0.084	118.7
1.2–1.5	1.42	48.3	41.7	10.0	0.212	0.081	108.0
1.5–1.8	1.42	48.3	41.7	10.0	0.212	0.081	108.0

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.

Table 4. Genetic coefficients for CERES-Maize developed for the PI 3902, PI 3732, and PI 3540 corn hybrids calibrated against irrigated corn grown at Akron, CO. Values given in parentheses are the range used in calibration of each specific parameter.

No.	Parameter	PI 3902	PI 3732	PI 3540
1	Thermal time from seedling emergence to the end of juvenile phase during which the plants are not responsive to changes in photoperiod (200–500 degree days).	237	293	277
2	Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 h (0–1 d)	0.3	0.8	0.6
3	Thermal time from silking to physiological maturity (500–900 degree days).	810	745	870
4	Maximum possible number of kernels per plant (500–900 kernels).	700	600	700
5	Kernel filling rate during the linear grain filling stage and under optimum conditions (4–12 mg/d).	6.0	9.5	6.3
6	Phylochron interval (35–55 degree days).	49	49	50

avoids the use of wind and vapor pressure data that are not widely available for potential ET calculations.

In CERES–Maize, crop development rates are calculated based only on temperature and photoperiod (Ritchie et al., 1998). Biomass partitioned to grain in CERES-Maize is modified by daily minimum temperature (Singh, 1985). Soil organic matter in CERES-Maize consists of fast-decaying "fresh organic matter" and slowly decaying "soil humus fraction." Volatilization loss of N is not simulated for dryland conditions in CERES-Maize (Godwin and Singh, 1998). In CERES-Maize, N uptake is simulated based on the crop N demand and potential N uptake rate as described by Godwin and Singh (1998).

The CERES-Maize model has been extensively used worldwide for development of crop management applications. Paz et al. (1999) used the model to develop a technique to characterize yield variability across a corn field for site-specific crop management applications. Wafula (1995) developed crop management strategies to improve marginal rainfed corn yields in Kenya using CMKEN, a locally adapted version of CERES-Maize. Kovacs et al. (1995) determined strategies to control N leaching from corn and wheat (*Triticum aestivum* L.) fields in Hungary using CERES-Maize and CERES-Wheat models. Many studies have compared CERES-Maize performance with other crop simulation models (Kiniry and Bockholt, 1998; Kiniry et al., 1997; Otegui et al., 1996; Xie et al., 2001). No study for testing and validation of the model for simulation of planting date effects on corn has been reported.

Model Calibration

Both RZWQM and CERES-Maize models were calibrated for all three corn hybrids separately with data collected from the first planting date (25 April) in 1991. Calibration of the models was based on field-measured values of LAI, grain yield, measured crop ET, and soil water measurements. The models were validated against the remaining five experimental data sets (the two remaining planting dates in 1991 and the three planting dates in 1992). All three hybrids planted on the third planting date of 1992 (10 June) were harvested for silage due to the crop not reaching physiological maturity. Therefore, silage yield was used in place of grain yield for validation of the models at this planting date.

To accurately simulate crop growth and development of a particular corn hybrid at a particular location, process-oriented models like CERES-Maize and RZWQM need calibration of their crop-specific parameters that are not easy to quantify in the field (Hanson et al., 1999; Ahuja and Ma, 2002). As stated previously, N was applied at the rate of 168 kg ha^{-1} (adequate to keep plants free of N stress). When CERES-Maize was run with N simulation at an N rate of 168 kg ha^{-1}, no N stress was observed in the model simulations (data not shown). Hence, both the RZWQM and CERES-Maize models were run without simulation of N stress during calibration and validation comparisons.

Root Zone Water Quality Model

The RZWQM developers recommended users calibrate for soil water content, then the N component, and finally the plant production component (Hanson et al., 1999; Ma et al., 2003). The generic crop growth model of RZWQM was previously calibrated for corn simulation at several locations (Farahani et al., 1999; Hanson et al., 1999; Wu et al., 1999; Ghidey et al., 1999; Jaynes and Miller, 1999; Martin and Watts, 1999; Landa et al., 1999). Farahani et al. (1999) developed plant growth parameters for RZWQM simulations of corn in Colorado. These parameters were shown to be cultivar sensitive and thus calibrated in this study (Ma et al., 2003). There were appreciable differences in the calibration parameters among the three corn hybrids (Table 2). The RZWQM calibration data show that mean errors [ME = 100 × (predicted − measured)/measured] of grain yields were −0.8, −4.5, and −3.4% for PI 3902, PI 3732, and PI 3540, respectively (Table 3). Maximum LAI, ET, and soil moisture calibration results of RZWQM are also shown in Table 3. The RZWQM did not predict explicit phenology of the crop but did simulate LAI progression with time. The root mean square errors (RMSEs) of LAI predictions with time were 0.78, 0.98, and 1.30 for the respective three hybrids, and RMSEs of soil water content

Table 5. Monthly average maximum and minimum temperatures and daily solar radiation at Akron, CO, during 1991, 1992, and averaged from 1987 to 2003.

	Maximum temperature			Minimum temperature			Solar radiation		
	1991	1992	1987–2003	1991	1992	1987–2003	1991	1992	1987–2003
	°C						MJ m^{-2} d^{-1}		
May	22.4	23.8	22.1	7.9	6.3	6.3	23.2	24.7	22.7
June	29.2	25.7	28.3	13.5	11.0	11.9	26.4	25.8	26.0
July	31.4	28.6	31.9	14.4	14.0	14.9	27.2	24.4	25.6
Aug.	30.6	27.8	30.6	13.7	12.7	14.1	22.9	21.3	22.3
Sept.	26.4	27.6	25.9	8.9	8.9	8.9	20.3	20.7	18.6

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 ($cm^3\ cm^{-3}$) RZWQM	CERES-Maize	Significance of *F* test (*P*)
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.

Maize showed RMSEs between 0.045 and 0.079 cm^3 cm^{-3} (mean = 0.064 cm^3 cm^{-3}), 0.050 and 0.093 cm^3 cm^{-3} (mean = 0.073 cm^3 cm^{-3}), and 0.057 and 0.087 cm^3 cm^{-3} (mean = 0.067 cm^3 cm^{-3}) under the respective corn hybrids (Table 6). In general, RMSEs of soil water content predictions of CERES-Maize showed better correspondence with the field-measured values than the RZWQM results. However, the *F* test showed that the difference in the variances in the soil water predictions by the two models were not statistically significant (Table 6).

Progression of LAI development simulated by the CERES-Maize model showed better correspondence with measured values than RZWQM (Fig. 1–3). The RMSEs of LAI simulated by CERES-Maize were between 0.33 and 0.78 across all planting dates and the three corn hybrids (Table 7). The LAIs of all the three hybrids simulated showed more or less similar levels of accuracy. These results show that both the growth and phenology components of this model are adequate to capture the planting date effects on crop development with reasonable accuracy. The RZWQM showed larger errors in simulations of LAI development with time (Fig. 1–3). The RMSEs of first planting date (calibration data) of 1991 ranged between 0.78 and 1.30 across the cultivars. The first planting date of 1992 (validation) exhibited RMSEs between 0.87 and 1.95. The second planting dates of 1991 and 1992 were more poorly simulated with RMSEs of 1.02 and 1.47 and 1.45 and 1.55, respectively, across the three cultivars. Through different growth stages of the crop, RZWQM calculates LAI from biomass partitioned to the leaf and a single value

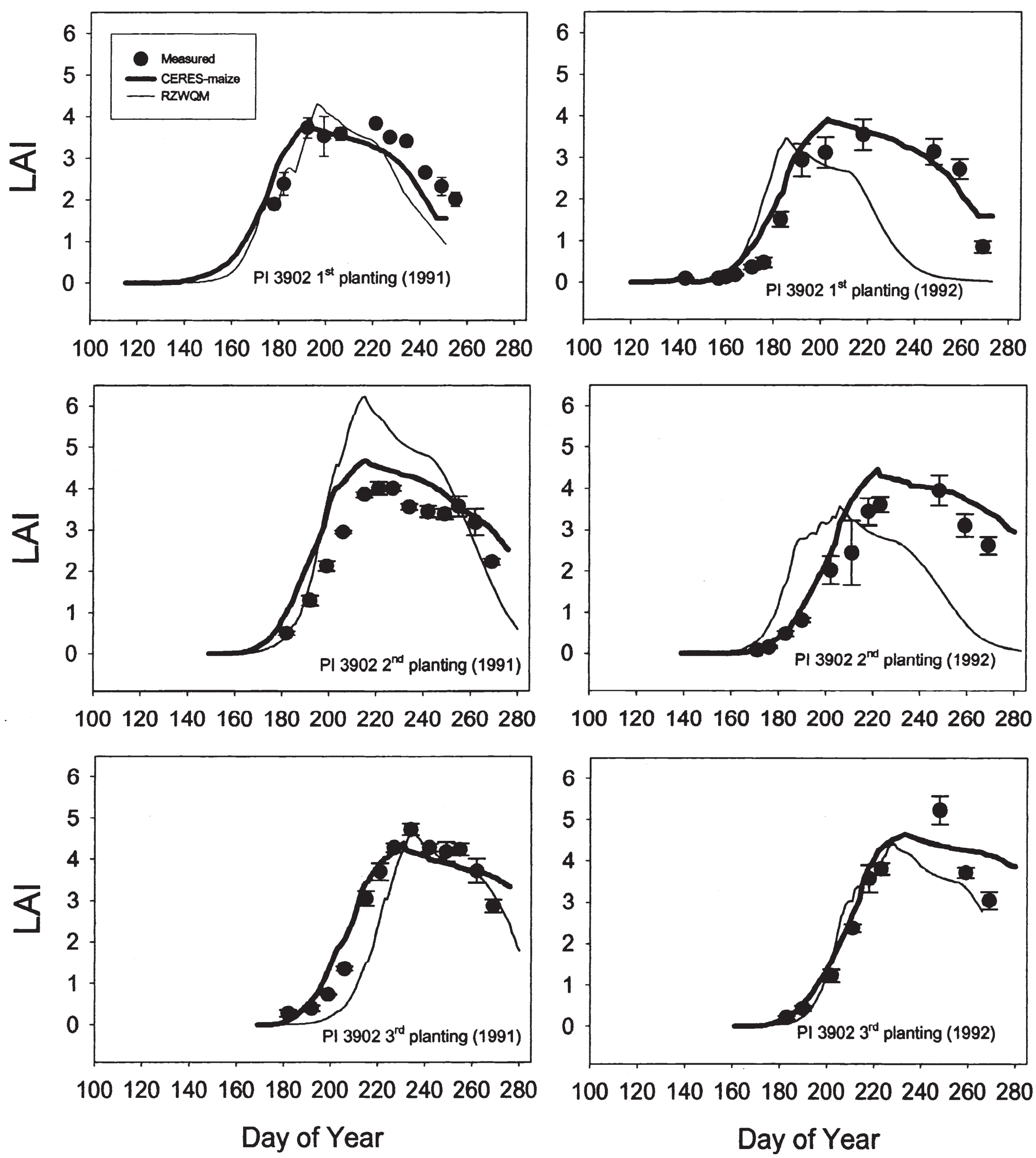

Fig. 1. Comparisons of measured leaf area index (LAI) progressions of PI 3902 corn hybrid at three planting dates in 1991 and 1992 with simulations by Root Zone Water Quality Model (RZWQM) and CERES-Maize. The first planting of 1991 was used to calibrate the models. Error bars represent one standard deviation about the means of measured LAI.

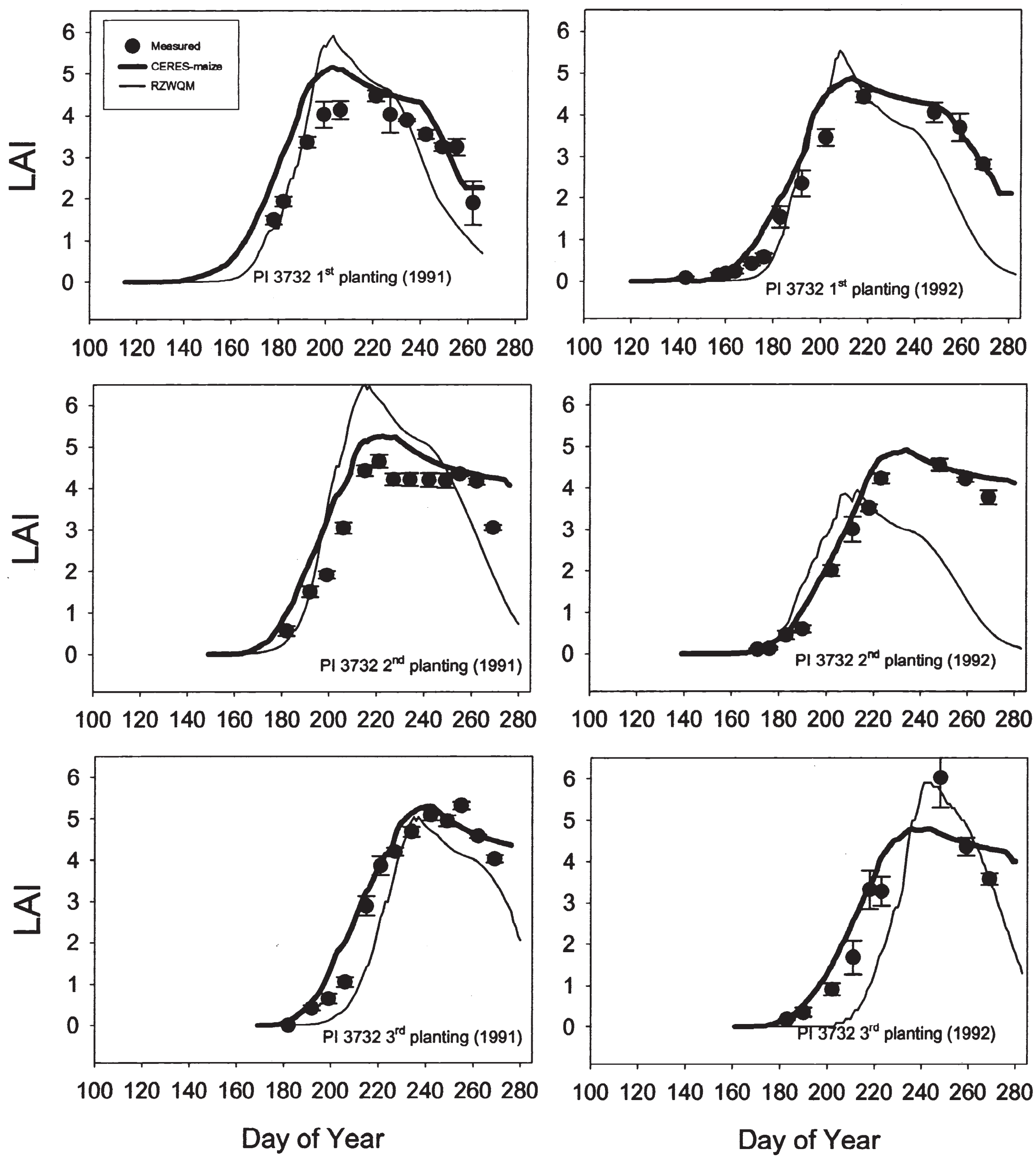

Fig. 2. Comparisons of measured leaf area index (LAI) progressions of PI 3732 corn hybrid at three planting dates in 1991 and 1992 with simulations by Root Zone Water Quality Model (RZWQM) and CERES-Maize. The first planting of 1991 was used to calibrate the models. Error bars represent one standard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

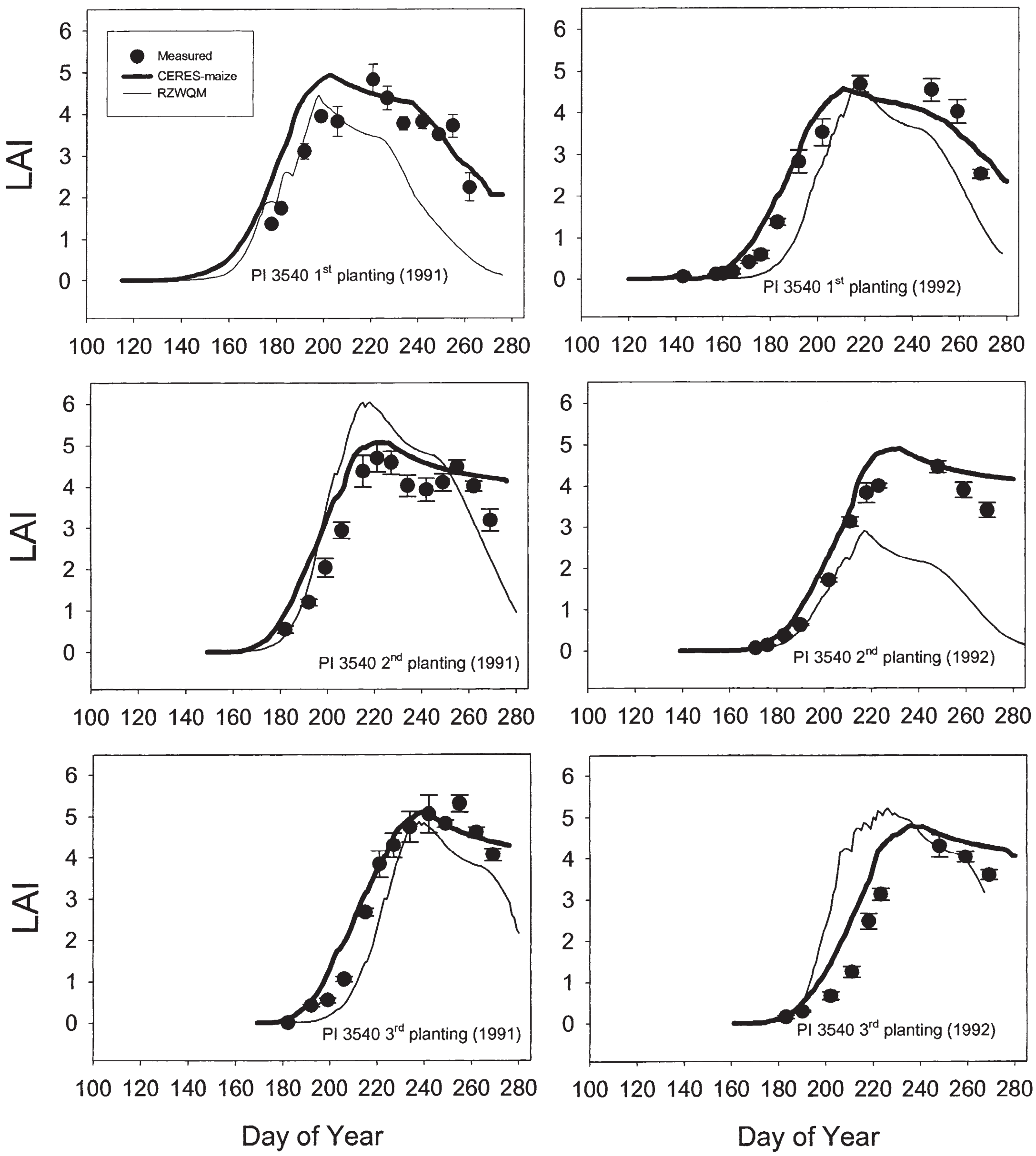

Fig. 3. Comparisons of measured leaf area index (LAI) progressions of PI 3540 corn hybrid at three plantings dates in 1991 and 1992 with simulations by Root Zone Water Quality Model (RZWQM) and CERES-Maize. The first planting of 1991 was used to calibrate the models. Error bars represent one standard deviation about the means of measured LAI.

for this experiment. Therefore, the silage yields were compared with the aboveground biomass simulations of the models. The validation data showed good correspondence between measured and predicted grain yields by both RZWQM and CERES-Maize for all three corn hybrids across all the planting dates (Fig. 5). Reduction in grain yield with delay in planting date as measured in the field was well reflected in the simulations by both models (Fig. 6). However, CERES-Maize was able to capture the relative decrease in grain yield between the first and third planting dates with a better level of accuracy than RZWQM. The major factor limiting crop growth with delayed planting in the corn-growing areas of USA is the onset of cold air temperatures and associated fall killing frosts in the September–October months (Nielsen et al., 2002b). To account for this effect, the biomass partitioned to grain in CERES-Maize is modified by the daily minimum temperature (Singh, 1985). Low-temperature–dependent grain yield reductions are not accounted for in RZWQM. Hence, the relative decreases in grain yields with planting dates were better reflected in CERES-Maize than in RZWQM simulations. Coefficients of determination (r^2) between measured and simulated grain yields were 0.96, 0.97, and 0.96 by CERES-Maize and 0.94, 0.85, and 0.92 by RZWQM, respectively, for the PI 3902, PI 3732, and PI 3540 corn hybrids. The RMSEs for RZWQM grain yield predictions were 894, 1546, and 1280 kg ha^{-1} for PI 3902, PI 3732, and PI 3540 corn hybrids, respectively (Table 7). Corresponding RMSEs of CERES-Maize model predictions were 1125, 1285, and 1005 kg ha^{-1} for the respective hybrids (Table 7). RZWQM simulations of the third

Table 7. Summary of root mean square errors (RMSEs) of leaf area index (LAI) and grain yield simulations of irrigated corn hybrids PI 3902, PI 3732, and PI 3540 at Akron, CO, by the Root Zone Water Quality Model (RZWQM) and CERES-Maize. The mean errors (ME) of silage predictions by the models from the third planting date in 1992 are also included.

	RMSE					
	RZWQM			CERES-Maize		
Planting date	PI 3902	PI 3732	PI 3540	PI 3902	PI 3732	PI 3540
LAI						
1991						
First planting†	0.78	0.98	1.30	0.42	0.72	0.78
Second planting	1.47	1.23	1.02	0.69	0.65	0.68
Third planting	0.76	0.76	0.75	0.33	0.40	0.39
1992						
First planting	1.95	0.94	0.87	0.39	0.42	0.42
Second planting	1.50	1.55	1.45	0.52	0.37	0.47
Third planting	1.15	1.07	1.97	0.55	0.68	0.76
Grain yield	894	1546	1280	1125	1285	1005
	ME, %					
Silage yield‡	7	−5	−5	6	17	8

† Calibration data.
‡ Third planting of 1992 was harvested for silage.

planting date of 1992 (crop harvested for silage) underpredicted silage yield for PI 3732 and PI 3540 by 5% and overpredicted by 7% for PI 3902. The CERES-Maize model overpredicted silage yield by 6, 17, and 8% for PI 3902, PI 3732, and PI 3540, respectively. The fact that the generic crop model of RZWQM simulated yields nearly as well as the dedicated corn model, CERES-Maize, is noteworthy.

Model Application: Determining Optimum Planting Window

If the calibrated models stand the test of validation with independent data sets, they can be potentially used as tools for operational, tactical, and strategic decision support in on-farm crop management (Mathews et al., 2002). Saseendran et al. (1998) used the CERES-Rice simulation model to determine optimum planting windows for rice (*Oryza sativa* L.) cultivation in a tropical climate. As an example of applications of the models calibrated and validated in this study, we made an attempt to use them for derivation of optimum planting windows for the three corn hybrids under irrigated (no water stress, no N stress) conditions at Akron, CO. CERES-Maize was run under the no-water-stress option (water balance module turned off). The RZWQM was forced to run without water stress by scheduling irrigations based on root water depletion and irrigating to field capacity at least once in every 4 d. Simulated planting of the hybrids was done at weekly intervals from 1 April through 15 July of every year for 88 yr making use of the long-term weather data from 1912 through 1999 collected at Akron. All model simulations were started on 1 January of the corresponding crop year and run until physiological maturity was simulated. Using the 88 yr of simulated grain yield data at every planting date, the probability of achieving an economic break-even corn grain yield was calculated. The dates with higher probability of achieving the break-even yield were selected as the optimum planting window. For the analysis, the break-even yield was fixed at 7000 kg ha^{-1} after consultation with area farmers. Because solar radiation and wind speed data were available only from 1983 through 1999, the solar radiation data records were extended backward through 1912 using the Weatherman utility in DSSAT (Hansen et al., 1994), and the wind speed data records were extended backward using the CLIGEN90 weather generator utility available in RZWQM.

The RZWQM simulated a gradual gain in grain yield with delay in planting dates from 1 April through 6 May (Fig. 7). The gain in grain yield during this period averaged about 42, 20, and 35 kg ha^{-1}, respectively, with each day of delay in planting for the PI 3902, PI 3732, and PI 3540 hybrids. In the case of PI 3732, the increasing trend in yield and subsequent decrease in yield with planting delay from 1 April was very gradual compared with the other two hybrids. Nafziger (1994) reported on corn yield response to planting dates from a 4-yr field study conducted at Monmouth and DeKalb, IL. He observed that corn yields increased from mid-April to late April planting dates and then declined with delay in planting toward late May. In our simulation study, planting after 6 May generally resulted in gradual yield losses. Yield losses per day of delay in planting from 6 May through 27 May averaged about 86, 29, and 98 kg ha^{-1}, respectively, for the three hybrids (Fig. 7). From 3 June planting onwards, the yield loss per day delay in planting was simulated to occur at a faster rate, averaging about 116, 128, and 141 kg ha^{-1}, respectively, for each day of delay in planting for the three hybrids. These results show that the yield loss with delay in planting date increases with increasing maturity length of a cultivar. This was basically due to the increasing number of days of below-optimum temperatures encountered by the long-season cultivars toward the end of the growing season. These findings agree with literature reports that corn hybrids responded differently to planting dates (Darby and Lauer, 2002; Lauer et al., 1999). Hybrids with longer maturity periods were reported to benefit from an early planting date and to suffer from a delayed planting date (Hicks et al., 1970).

The CERES-Maize model simulated gain in grain yield of about 37, 37, and 21 kg ha^{-1}, respectively, with each day of delay in plantings from 1 April through

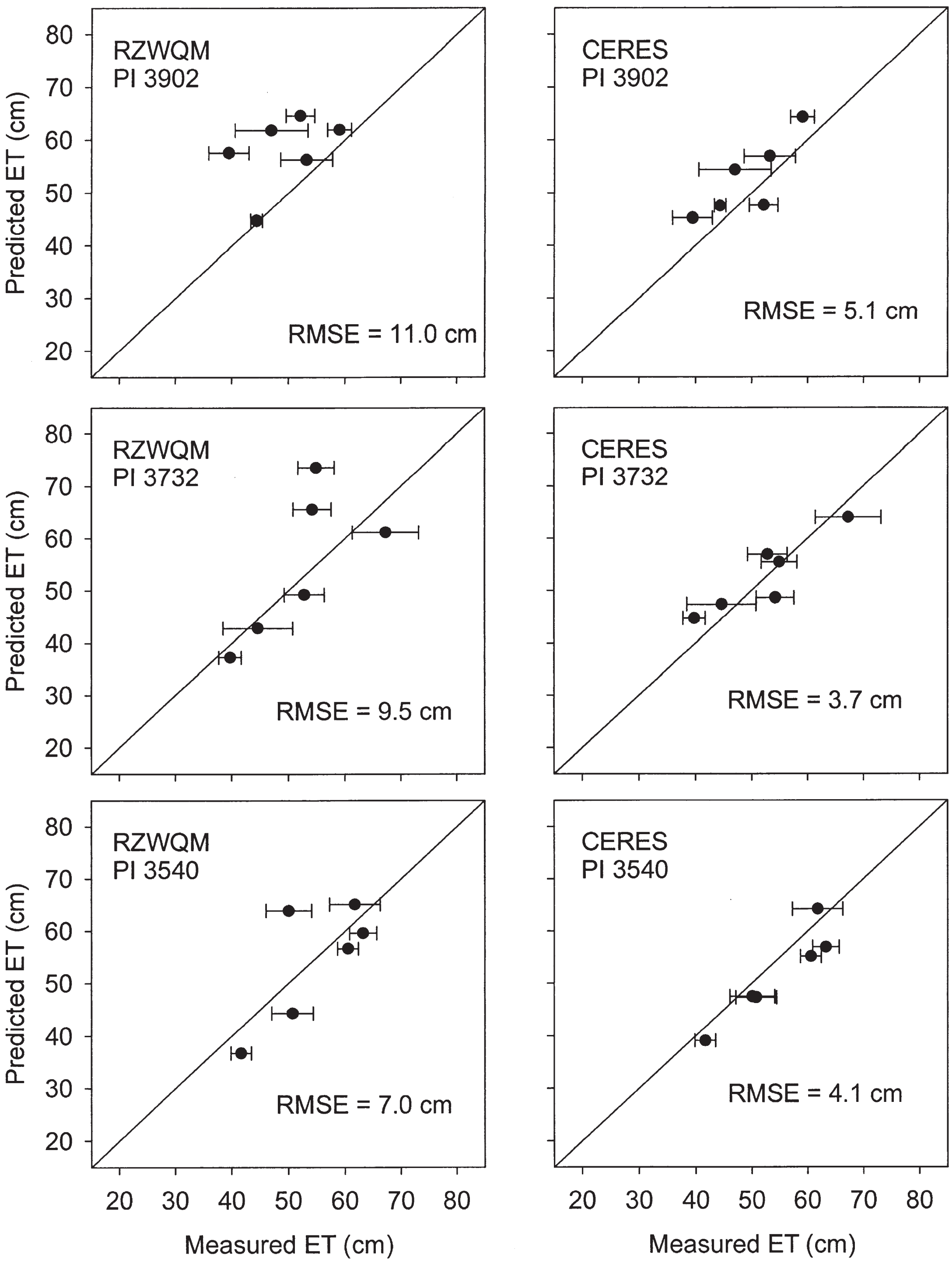

Fig. 4. Measured vs. predicted evapotranspiration (ET) for corn hybrids PI 3902, PI 3732, and PI 3540 at Akron, CO. Predicted values from simulations by the Root Zone Water Quality Model (RZWQM) and CERES-Maize. The six data points in each frame represent data from three planting dates in 2 yr (1991, 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-

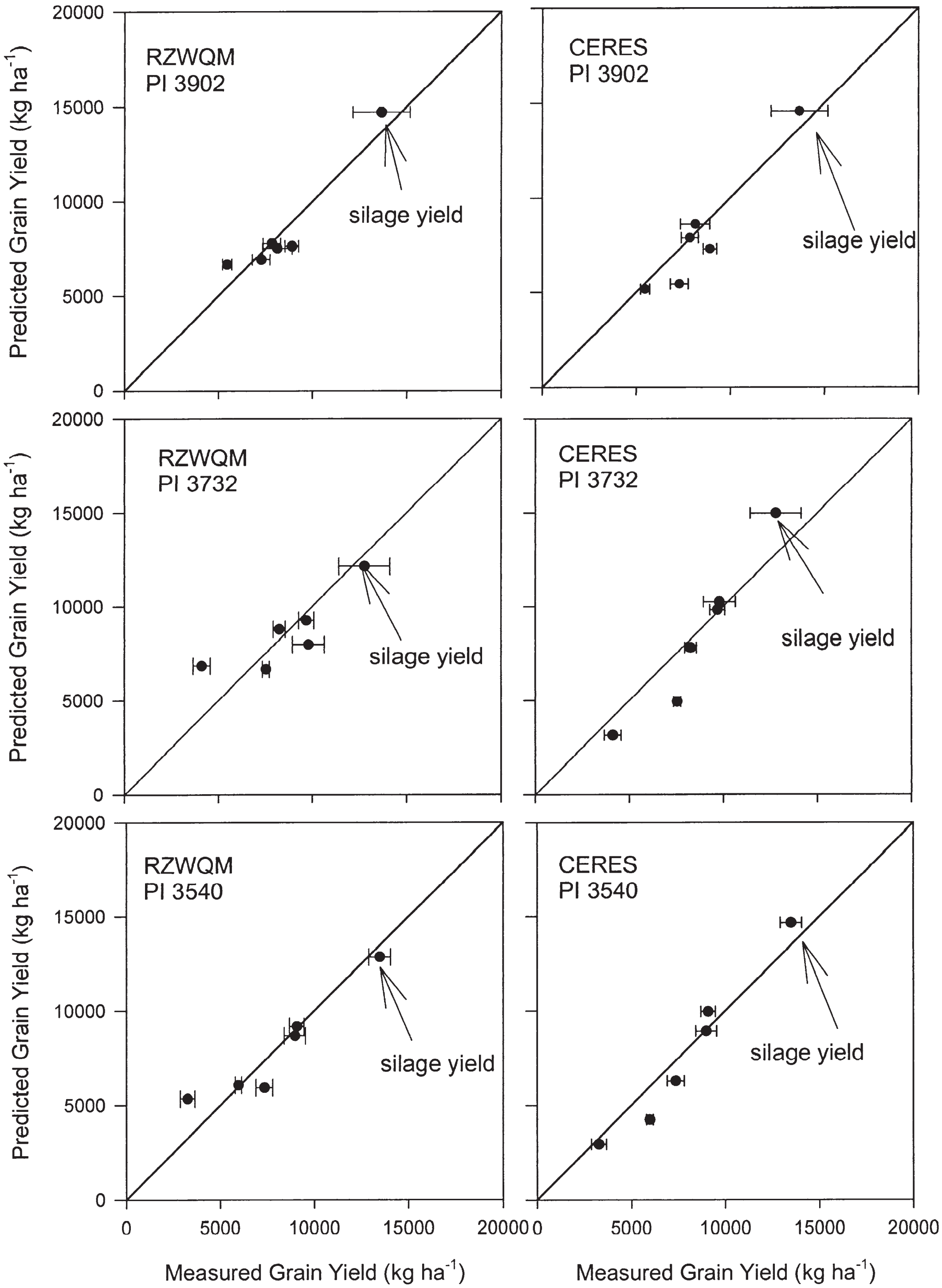

Fig. 5. Measured vs. predicted grain (or silage) yield for corn hybrids PI 3902, PI 3732, and PI 3540 at Akron, CO. Predicted values from simulations by the Root Zone Water Quality Model (RZWQM) and CERES-Maize. The six data points in each frame represent data from three planting dates in 2 yr (1991, 1992). Error bars represent one standard deviation about the means of the measured yields. The diagonal lines in the graphs are the 1:1 lines.

dicted the sharper decline in yield with planting delay, which may be due to the better prediction of phenological development and LAI of the crop (Fig. 1–3).

The average long-term corn yields simulated by CERES-Maize were generally lower than those simulated by RZWQM. This may be a reflection of the more frequent lower yields simulated by CERES-Maize as the model stopped due to slow grain-filling rate. Grain growth rate in CERES-Maize is controlled in part by daily minimum temperature (Singh, 1985). Because of the high elevation and low atmospheric humidity conditions observed at Akron, CO, there are frequent instances when low or zero corn grain yields are simulated by CERES-Maize. In contrast, RZWQM uses daily av-

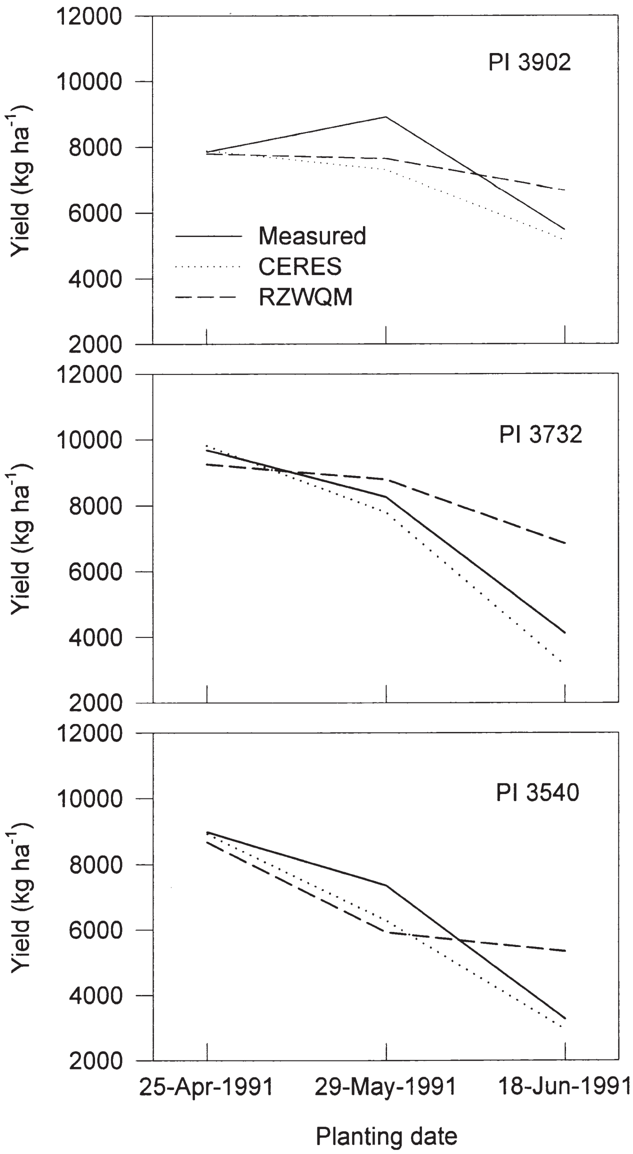

Fig. 6. Comparisons of measured reduction in corn grain yield with delay in planting of hybrids PI 3902, PI 3732 and PI 3540 with predictions by Root Zone Water Quality Model (RZWQM) and CERES-Maize at Akron, CO.

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

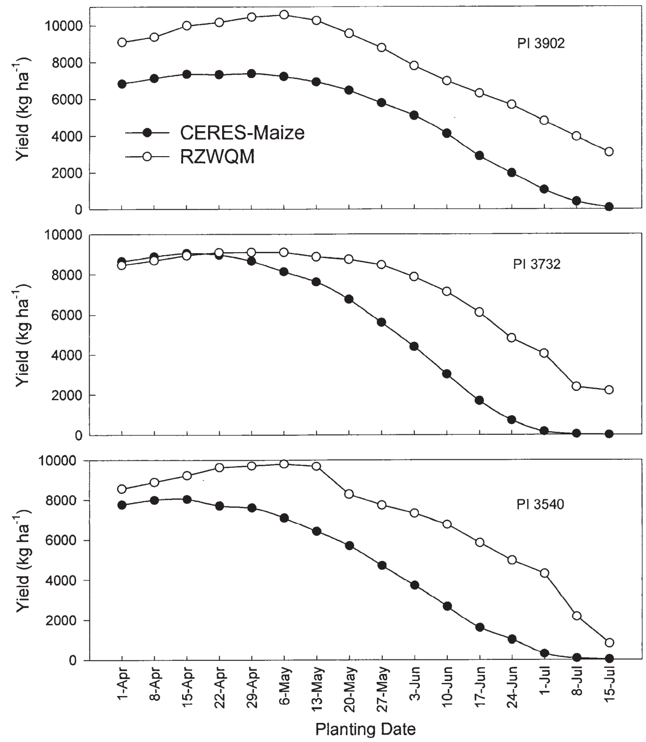

Fig. 7. Mean simulated irrigated corn yields (1912–1999, Akron, CO) for hybrids PI 3902, PI 2732, and PI 3540 planted at weekly intervals from 1 April through 15 July. Simulations from CERES-Maize and Root Zone Water Quality Model (RZWQM).

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.

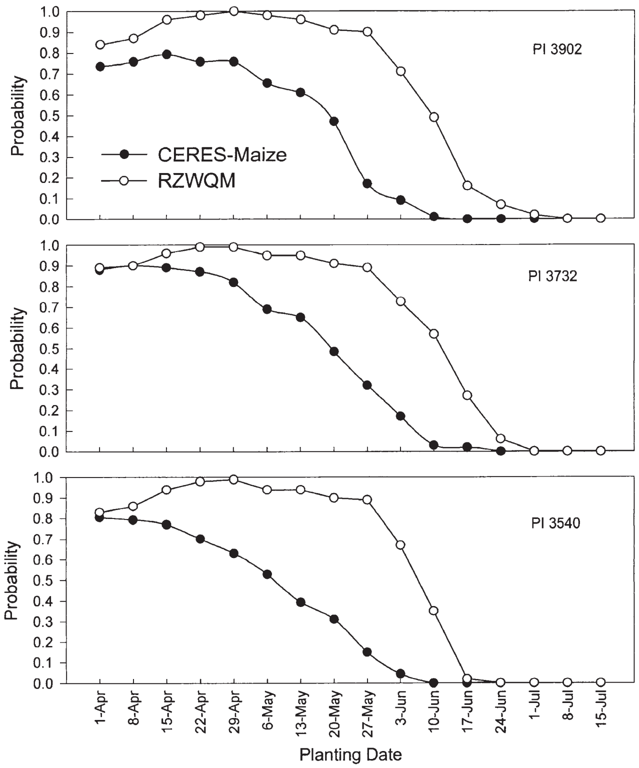

Fig. 8. Probabilities of achieving break-even corn yield goal (7000 kg ha^{-1}) under irrigated conditions for plantings from 1 April through 15 July, derived from the long-term (1912–1999) simulations of hybrids PI 3902, PI 3732 and PI 3540 by CERES-Maize and Root Zone Water Quality Model (RZWQM).

The LAI simulations by CERES-Maize were in better agreement with measurements than those of RZWQM, whereas the soil moisture simulations by CERES-Maize were not significantly better than from RZWQM. The validated models can be used to make many strategic and tactical decisions in corn cultivation. As an example of these applications, we used the validated models to define optimum planting windows for corn hybrids in eastern Colorado under irrigated conditions. Both models predicted small increases in yield as planting date was delayed from April to early May, with declining corn grain yield associated with delay in planting into mid-May and June. This agrees with locally developed recommendations for corn production in northeastern Colorado (Bauder et al., 2003) which give optimum corn planting dates ranging from 20 April to 15 May and a 2 to 5% drop in yield as planting date is moved 12 d before or after the optimum planting date. Due to the difference in the accuracy of yield loss with delayed planting simulated by both RZWQM and CERES-Maize, the simulated planting window with the same probability level of achieving a break-even yield differed by about 3 to 4 wk between the two models. Using the simulation results from CERES-Maize (which better predicted the yield decline for the latest planting date), a recommended latest planting date that would have a 50% chance of achieving the break-even yield under irrigated conditions at Akron, CO, would be 13 May, 20 May, and 6 May for PI 3902, PI 3732, and PI 3540, respectively. Results of the study will be useful for both planting and replanting decision support of these corn hybrids in this region. These results are for conditions with no N and water stress, typical of irrigated corn production in eastern Colorado and western Nebraska. Modeling of planting date effects on corn development and yield should be further tested under conditions of varying water and N availability.

REFERENCES

Ahuja, L.R., J.D. Hanson, K.W. Rojas, and M.J. Shaffer. 2000. Model overview. p. 1–12. *In* L.R. Ahuja, K.W. Rojas, J.D. Hanson, M.J. Shafer, and L. Ma (ed.) Root Zone Water Quality Model. Modeling management effects on water quality and crop production. Water Resour. Publ., LLC, Highlands Ranch, CO.

Ahuja, L.R., and L. Ma. 2002. Parameterization of agricultural system models: Current approaches and future needs. p. 273–316. *In* L.R. Ahuja, L. Ma., and T. A. Howell (ed.) Agricultural system models in field research and technology transfer. Lewis Publ., CRC Press, Boca Raton, FL.

Bauder, T., R. Waskom, J. Schneekloth, and J. Alldredge. 2003. Best management practices for Colorado corn. Bull. XCM574A. Colorado State Univ. Coop. Ext., Fort Collins.

Benson, G.O. 1990. Corn replant decisions: A review. J. Prod. Agric. 3:180–184.

Boote, K.J. 1999. Concepts for calibrating crop growth models. p. 179–199. *In* G. Hoogenboom, P.W. Wilkens, and G.Y. Tsuji (ed.) DSSAT version 3, Vol. 4. Univ. of Hawaii, Honolulu.

Brooks, R.H., and A.T. Corey. 1964. Hydraulic properties of porous media. Hydrol. Paper 3. Colorado State Univ., Fort Collins.

Carter, P.R. 1984. Optimum corn planting practices. Selecting corn hybrids. A3264. Univ. of Wisconsin Coop. Ext., Madison.

Darby, H.M., and J.G. Lauer. 2002. Planting date and hybrid influence on corn forage yield and quality. Agron. J. 94:281–289.

Duncan, W.G. 1975. SIMAIZ: A model simulating growth and yield in corn. *In* D.N. Baker, P.G. Creech, and F.G. Maxwell (ed.) An application of system methods to crop production. Mississippi Agric. and Forestry Exp. Stn., Mississippi State.

Farahani, H.J., G.W. Buchleiter, L.R. Ahuja, G.A. Peterson, and L.A. Sherrod. 1999. Seasonal evaluation of the Root Zone Water Quality Model in Colorado. Agron. J. 91:212–219.

Ghidey, F., E.E. Alberts, and N.R. Kitchen. 1999. Evaluation of the Root Zone Water Quality Model using field measured data from the Missouri MSEA. Agron. J. 91:183–192.

Godwin, D.C., J.T. Ritchie, U. Singh, and L.A. Hunt. 1989. A user's guide to CERES-wheat—v2.10. Int. Fert. Dev. Center, Muscle Shoals.

Godwin, D.C., and U. Singh. 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. p. 157–177. *In* G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton (ed.) Understanding options for agricultural production. Kluwer Academic Publ., Dordrecht, the Netherlands.

Green, W.H., and G.A. Ampt. 1911. Studies on soil physics: 1. Flow of air and water through soils. J. Agric. Sci. 4:1–24.

Hansen, J.W., N.B. Pickering, J.W. Jones, C. Wells, H. Chan, and D.C. Godwin. 1994. Weatherman. p. 137–200. *In* G.Y. Tsuji, G. Uehara, and S. Balas (ed.) DSSAT version 3. Vol. 3. Univ. of Hawaii, Honolulu.

Hanson, J.D. 2000. Generic plant production. p. 81–118. *In* L.R. Ahuja, K.W. Rojas, J.D. Hanson, M.J. Shafer, and L. Ma (ed.) Root Zone Water Quality Model. Modeling management effects on water quality and crop production. Water Resour. Publ., LLC, Highlands Ranch, CO.

Hanson, J.D., L.R. Ahuja, M.D. Shaffer, K.W. Rojas, D.G. DeCoursey, H. Farahani, and K. Johnson. 1998. RZWQM: Simulating the effects of management on water quality and crop production. Agric. Syst. 57:161–195.

Hanson, J.D., K.W. Rojas, and M.J. Shaffer. 1999. Calibrating the Root Zone Water Quality Model. Agron. J. 91:171–177.

Hicks, E.R., S.D. Evans, R.D. Frazier, W.E. Luschen, W.W. Nelson, H.J. Otto, C.J. Overdahl, and R.H. Peterson. 1970. Corn manage-

ment studies in Minnesota 1967–68–69. Misc. Rep. 96. Minnesota Agric. Exp. Stn., St. Paul.
Jaynes, D.B., and J.G. Miller. 1999. Evaluation of the Root Zone Water Quality Model using data from the Iowa MSEA. Agron. J. 91:192–200.
Jones, C.A., and J.R. Kiniry. 1986. CERES-Maize: A simulation model of maize growth and development. Texas A&M Univ. Press, College Station.
Jones, J.W., G.Y. Tsuji, G. Hoogenboom, L.A. Hunt, P.K. Thornton, P.W. Wilkens, D.T. Imamura, W.T. Bowen, and U. Singh. 1998. Decision Support System for Agrotechnology Transfer: DSSAT v3. p. 157–177. *In* G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton (ed.) Understanding options for agricultural production. Kluwer Academic Publ., Dordrecht, the Netherlands.
Kiniry, J.R., and A.J. Bockholt. 1998. Maize and sorghum simulation in diverse Texas environments. Agron. J. 90:682–687.
Kiniry, J.R., J.R. Williams, P.W. Gassman, and P. Debaeke. 1992. A general process-oriented model for two competing plant species. Trans. ASAE 35:801–810.
Kiniry, J.R., J.R. Williams, R.L. Vanderlip, J.D. Atwood, D.C. Reicosky, J. Mulliken, W.J. Cox, H.J. Mascagni, Jr., S.E. Hollinger, and W.J. Wiebold. 1997. Evaluation of two maize models for nine U.S. locations. Agron. J. 89:421–426.
Kovacs, G.J., T. Nemeth, and J.T. Ritchie. 1995. Testing simulation models for the assessment of crop production and nitrate leaching in Hungary. Agric. Syst. 49:385–397.
Landa, F.M., N.R. Fausey, S.E. Nokes, and J.D. Hanson. 1999. Plant production model evaluation for the Root Zone Water Quality Model (RZWQM). Agron. J. 91:220–227.
Lauer, J.G., P.R. Carter, T.M. Wood, G. Diezel, D.W. Wiersma, P.E. Rand, and M.J. Mlynarek. 1999. Corn hybrid response to planting date in the northern corn belt. Agron. J. 91:834–839.
Lizaso, J.I., W.D. Batchelor, and M.E. Westgate. 2003. A leaf model to simulate cultivar-specific expansion and senescence of maize leaves. Field Crops Res. 80:1–17.
Ma, L., D.C. Nielsen, L.R. Ahuja, R.W. Malone, S.A. Saseendran, K.W. Rojas, J.D. Hanson, and J.G. Benjamin. 2003. Evaluation of RZWQM under varying irrigation levels in eastern Colorado. Trans. ASAE 46:39–49.
Ma, L., M.J. Shaffer, and L.R. Ahuja. 2001. Application of RZWQM for soil nitrogen management. p. 265–301. *In* L.R. Ahuja, L. Ma., and T. A. Howell (ed.) Agricultural system models in field research and technology transfer. Lewis Publ., CRC Press, Boca Raton, FL.
Ma, L., M.J. Shaffer, J.K. Boyd, R. Waskom, L.R. Ahuja, K.W. Rojas, and C. Xu. 1998. Manure management in an irrigated silage corn field: Experiment and modeling. Soil Sci. Soc. Am. J. 62:1006–1017.
Martin, D.L., and D.G. Watts. 1999. Evaluation of the Root Zone Water Quality Model for conditions in central Nebraska. Agron. J. 91:201–211.
Mathews, R., W. Stephens, T. Hess, T. Middleton, and A. Graves. 2002. Applications of crop/soil simulation models in tropical agricultural systems. Adv. Agron. 76:31–124.
McCown, R.L., G.L. Hammer, J.N.G. Hargreaves, D.P. Holzworth, and D.M. Freebairn. 1996. APSIM: A novel software system for model development, model testing and simulation in agricultural system research. Agric. Syst. 50:255–271.
Nafziger, E.D. 1994. Corn planting date and plant population. J. Prod. Agric. 7:59–62.
Neild, R.E. 1981. Effects of weather on corn planting and seedling establishment. NebGuide G552. IANR, Univ. of Nebraska, Lincoln.
Nielsen, D.C., and S.E. Hinkle. 1996. Field evaluation of basal crop coefficients for corn based on growing degree days, growth stage, or time. Trans. ASAE 39:97–103.
Nielsen, D.C., L. Ma, L.R. Ahuja, and G. Hoogenboom. 2002a. Simulating soybean water stress effects with RZWQM and CROPGRO models. Agron. J. 94:1234–1243.
Nielsen, R.L., P.R. Thomison, G.A. Brown, A.L. Halter, J. Wells, and K.L. Wuethrich. 2002b. Delayed planting effects on flowering and grain maturation of dent corn. Agron. J. 94:549–558.
Otegui, M.E., R.A. Ruiz, and D. Petruzzi. 1996. Modeling hybrid and sowing date effects on potential grain yield of maize in a humid temperate region. Field Crops Res. 47:167–174.
Paz, J.O., W.D. Batchelor, B.A. Babcock, T.S. Colvin, S.D. Logsdon, T.C. Kaspar, and D.L. Karlen. 1999. Model-based technique to determine variable rate nitrogen for corn. Agric. Syst. 61:69–75.
Priestley, C.H.B., and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81–92.
Rawls, W.J., D.L. Brakensiek, and K.E. Saxton. 1982. Estimation of soil water properties. Trans. ASAE 25:1316–1320, 1328.
Ritchie, J.T. 1972. Model for predicting evapotranspiration from the soil-plant-atmosphere. Plant Soil 58:81–96.
Ritchie, J.T. 1998. Soil water balance and plant water stress. p. 41–54. *In* G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton (ed.) Understanding options for agricultural production. Kluwer Academic Publ., Dordrecht, the Netherlands.
Ritchie, J.T., U. Singh, D.C. Godwin, and W.T. Bowen. 1998. Cereal growth, development and yield. p. 79–98. *In* G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton (ed.) Understanding options for agricultural production. Kluwer Academic Publ., Dordrecht, the Netherlands.
Rosenberg, N.J., B.L. Blad, and S.B. Verma. 1983. Microclimate: The biological environment. 2nd ed. John Wiley & Sons, New York.
Saseendran, S.A., K.G. Hubbard, K.K. Singh, N. Mendiratta, L.S. Rathore, and S.V. Singh. 1998. Transplanting dates for rice in Kerala, India using both CERES and ClimProb. Agron. J. 90: 185–190.
Shoyer, J.P., C. Thompson, R. Brown, P.D. Ohlenbusch, D.L. Fjell, S. Staggenborg, S. Duncan, and G.L. Kilgore. 1996. Kansas crop planting guide. Agric. Exp. Stn. Bull. L-818. Kansas State Univ., Manhattan.
Shuttleworth, W.J., and J.S. Wallace. 1985. Evaporation from sparse crops—an energy combination theory. Q. J. R. Meteorol. Soc. 111: 839–855.
Singh, U. 1985. A crop growth model for predicting corn (*Zea mays* L.) performance in the tropics. Ph.D. diss. Univ. of Hawaii, Honolulu.
Stapper, M., and G.F. Arkin. 1980. CORNF: A dynamic growth and development model for maize (*Zea mays* L.). Res. Cent. Progr. and Model Documentation 80–2. Backland Res. Cent., Texas Agric. Exp. Stn., Temple.
Swanson, S.P., and W.W. Wilhelm. 1996. Planting date and residue effects on growth, partitioning, and yield of corn. Agron. J. 88: 205–210.
Tsuji, G.Y., G. Uehara, and S. Balas. (ed.) 1994. DSSAT Version 3. Vol. 2., Univ. of Hawaii, Honolulu.
Wafula, B.M. 1995. Applications of crop simulation in agricultural extension and research in Kenya. Agric. Syst. 49:399–412.
Williams, J.R. 1991. Runoff and water erosion. p. 439–455. *In* R.J. Hanks and J.T. Ritchie (ed.) Modeling plant and soil systems. Agron. Monogr. 31. ASA, CSSA, and SSSA, Madison, WI.
Wu, L., W. Chen, J.M. Baker, and J.A. Lamb. 1999. Evaluation of the Root Zone Water Quality Model using field-measured data from a sandy soil. Agron. J. 91:177–182.
Xie, Y., J.R. Kiniry, V. Nedbalek, and W.D. Rosenthal. 2001. Maize and sorghum simulations with CERES-Maize, SORKAM, and ALMANAC under water-limiting conditions. Agron. J. 93:1148–1155.