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Simulating Inbred-Maize Yields with CERES-IM

Daniel P. Rasse, Joe T. Ritchie,* Wallace W. Wilhelm, Jun Wei, and Edward C. Martin

ABSTRACT

CERES-Maize, which was designed for simulation of hybrid maize (*Zea mays* L.), cannot be applied directly to seed-producing inbred maize because of specific field operations and physiological traits of inbred maize plants. We developed CERES-IM, a modified version of CERES-Maize 3.0 that accommodates these inbred-specific operations and traits, using a set of phenological measurements conducted in Nebraska (NE), and further tested this model with a set of field data from Michigan (MI). Detasseling (i.e., removal of the tassels from the female plants) was conducted prior to silking. Male rows were removed approximately 10 d following 75% silking. The thermal time from emergence to the end of the juvenile phase (P1) and the potential number of kernels per plant (G2) were assessed from field data, and were the only two coefficients allowed to vary according to the inbred line. Rate of leaf appearance of the inbreds was accurately simulated using a measured phyllochron interval of 54 degree-days (°Cd). Simulation of detasseling and male-row removal improved grain yield simulation for inbreds. For a set of 35 inbred-site-year simulations, the model simulated grain yield with satisfactory accuracy (RMSE = 429 kg ha^{-1}). Average grain yields were 4556 and 4721 kg ha^{-1} for the measured and simulated values, respectively. CERES-IM simulations suggest that the effect of male-row removal on grain yield is extremely sensitive to the precise date at which this operation is conducted. This would explain the inconsistent effect of male-row removal on female grain yields reported in the literature.

THE VAST MAJORITY OF MAIZE marketed in the USA and Canada comes from single-cross hybrids produced from crosses between two inbred lines (Wych, 1988). The pollen-supplying inbred line is referred to as *male*, while the seed-bearing line is referred to as *female*. Uniform distribution of pollen to the female plants requires that alternate male and female rows are planted in a pattern that optimizes marketable kernel yields (Culy et al., 1991). The row pattern is designed to provide sufficient pollination of all female rows while minimizing the surface allocated to nonproductive male rows (Culy et al., 1991). Male plants are mechanically destroyed following complete pollen shedding. This operation is conducted to prevent ears from the self-pollinated male plants from being harvested together with the female ears. Male-row removal is supposed to increase seed yields by leaving more nutrients and water available to the remaining female plants. Nevertheless, this effect has not been clearly demonstrated (Wych, 1988).

Detasseling is the operation that consists of removing the tassels of the female plants prior to silk emergence and pollen shed to prevent self-pollination. During this operation, several leaves are generally removed from the plants. Though male-sterile inbreds have also been used to avoid detasseling of seed-bearing female plants, most maize inbreds planted in the USA are not male-sterile and require mechanical detasseling (Wych, 1988; J. Wei, personal communication, 1999). Detasseling is an important field operation that modifies the plant canopy. The number of leaves removed by detasseling depends on plant morphology, the time of detasseling relative to the time of tassel emergence, pollen shed and silk emergence, and the settings of the mechanical detasseling machines (Wilhelm et al., 1995b). Removal of the tassel alone was reported to augment maize grain yields by increasing the amount of light available to the top leaves (Duncan et al., 1967; Hunter et al., 1969). Leaf removal associated with detasseling induces a linear decline in grain and stover yields proportional to the number of leaves removed (Wilhelm et al., 1995b). Stover biomass was reduced by 4 to 18% when one to three leaves were removed with the tassel (Wilhelm et al., 1995b).

Inbred maize plants differ from grain-producing hybrids in size and potential grain yield. The canopy of inbred-maize fields varies greatly depending on the inbred, but is generally much reduced compared with that of hybrid maize (Orr et al., 1997). Grain yields are lower for inbreds than for hybrids (Peterson and Corak, 1993). In the Platte River Valley of Nebraska, grain yields of inbred maize averaged only 3.5 Mg ha^{-1} (Wilhelm et al., 1995b). Published data suggest that total numbers of kernels per plant are substantially lower for inbreds than for hybrid maize plants (Wilhelm et al., 1995b).

The seed industry has a great interest in predicting grain yield responses to environmental conditions. Irrigation scheduling and N fertilization can be better managed through a decision support system. Grain yield and growth duration of inbred maize can be estimated with an accurate crop model to determine optimum areas for seed production in regions of the world where there is no history of growing inbred maize but where potential markets exist for hybrid maize seeds. Predicting maize seed production in North America a couple of months prior to harvest can help companies better plan for the seed production campaign in tropical regions during the wintertime. Inbred maize, used for the production of hybrid-maize seeds, represents a specific

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Abbreviations: CRM, coefficient of residual mass; G2, maximum possible number of kernels per plant; G3, kernel filling rate; GPP, grain per plant; LAI, leaf area index; MI, Michigan; NE, Nebraska; P1, thermal time from emergence to end of juvenile phase; P2, photoperiodism coefficient; P5, thermal time from silking to physiological maturity; PHINT, phyllochron interval; RMSE, root mean square error.

production system that has not yet benefited from the efforts invested in models used for simulating grain production of hybrid maize, such as CERES-Maize. The CERES-Maize model has been used to investigate irrigation strategies (Algozin et al., 1988; Boggess and Ritchie, 1988; Martin et al., 1996), planting strategies (Hodges and Evans, 1990; Otegui et al., 1996; Wafula, 1995), cultivar adaptation to the environment (Otegui et al., 1996; Wafula, 1995), nitrate leaching (Bowen et al., 1993; Pang et al., 1998), and crop response to climate change (Kovács, 1998; Magrin et al., 1997). CERES-Maize has been modified for specific maize production systems, such as semiarid tropical environments (Carberry et al., 1989). CERES-Maize cannot be applied directly to inbred-maize systems because of the specific field operations associated with the production of maize seeds (i.e., male-row removal and detasseling) as well as differences in plant growth and development between inbred and hybrid maize. Our objective was to develop an inbred-maize simulation model (i.e., CERES-IM) from the existing CERES-Maize.

METHODOLOGY

Field Data

Field data used for development and testing of CERES-IM were collected at two experimental sites. The first field experiments were conducted from 1995 to 1997 on a Butler-Hastings silt loam (fine, smectitic, mesic Abruptic Argiaquolls) near Doniphan, NE. Inbred lines were FR1075 (Illinois Foundation Seeds, Champaign, IL), P38 (Pioneer Hi-Bred International, Johnston, IA), and RO3 (Pioneer) in 1995, and FR1064 (Illinois Foundation Seeds), P38, and RO3 in 1996 and 1997. Each year, inbred maize was planted at 7.4 plants per m^2 in 76-cm rows at a depth of 4 cm, and fertilized at 101 kg N ha^{-1}. Planting pattern consisted of four female rows alternating with one male row. Inbreds were detasseled prior to silking in 1995, but not in 1996 and 1997 because male-sterile female plants were used in those years. Male rows were chopped following complete pollination. Weather data used for the simulations were collected at Grand Island, located 16 km north of the research site.

The second set of field experiments was conducted on an Elston sandy loam (coarse-loamy, mixed, active, mesic Typic Argiudolls) at Constantine (St. Joseph County) in southwestern Michigan from 1990 to 1997. Inbred lines were an early-season (P02, Pioneer line), a mid-season (P38), and a late-season maturity (T10, Pioneer line) type. Two N treatments were considered: (i) 101 kg N ha^{-1} applied as 34 kg N ha^{-1} preplant and 67 kg N ha^{-1} sidedress, and (ii) a zero-N control. Nitrogen was applied in the form of NH_4NO_3 (34–0–0), and sidedress applications were conducted between the sixth and the eighth leaf stage. The experiment was established in a randomized complete block design with a split-plot arrangement of treatments with N fertilizer as main plots and inbred lines as subplots. Plots were 6 m long and comprised 10 rows of inbred corn. Each year, inbred corn was planted at 6.2 plants m^{-2} in 76-cm rows at a depth of 4 cm. Planting pattern consisted of four female rows alternating with one male row. Female rows were detasseled. Male rows were chopped following complete pollination. Plots were irrigated according to a computer software scheduling that uses precipitation and air temperature data from the research site to estimate the soil water balance (Martin, 1992). Daily precipitation, air temperature, and solar irradiance used for the simulations were measured with a weather station at the research site. Severe corn smut (*Ustilago maydis*) infestation in the experimental plots at Constantine in 1994 and 1995 drastically reduced grain yields. Therefore, these two growing seasons were not used in the simulation of grain yield production, as our research did not consider simulation of pest damage.

Because of cross-pollination between small research plots as well as confidentiality of commercial hybrids' parent lines, individual research plots were planted with only one inbred line per plot at both sites. This practice should not affect the experimental results, given that female grain yields are not modified by inbred pollen source (Culy et al., 1991). One row out of five was managed as male, while the remaining blocks of four rows were managed as female. Dates of detasseling and male-row removal were recorded at both sites. Grain yields were measured at both sites by harvesting two female rows of each plot. Grain numbers per ear in NE measured only during the 1996 growing season were used for calibration of the model. Dates of leaf appearance, silking, blister and milk stages were recorded at the NE site for the 1995–1997 growing seasons, and at the MI site for the 1995 growing season only. Maximum leaf area index (LAI) was measured in NE in 1995 and 1996 using a Li-Cor LAI-2000 (Li-Cor Environmental Div., Lincoln, NE). Measurements were taken between two female rows at times when no direct sunlight could hit the sensor. Phenological and LAI data from NE were used for model calibration.

Statistical Analysis

The RMSE was used to estimate the variation, expressed in the same unit as the data, between simulated and measured values (Loague and Green, 1991; Xevi et al., 1996). This parameter is defined by

$$\mathrm{RMSE} = \left(\sum_{i=1}^{n}(S_i - M_i)^2/n\right)^{1/2} \qquad [1]$$

where M_i and S_i are the measured and simulated values, respectively, for the ith data point of n observations. The RMSE can also be expressed as a coefficient of variation by dividing it by the mean of the measured values. The RMSE tests the accuracy of the model, which is defined as the extent to which simulated values approach a corresponding set of measured values (Loague and Green, 1991). The coefficient of residual mass (CRM) was used to measure the tendency of the model to overestimate or underestimate the measured values. A negative CRM indicates a tendency of the model toward overestimation (Xevi et al., 1996). The CRM is defined by

$$\mathrm{CRM} = 100 \times \left(\sum_{i=1}^{n}M_i - \sum_{i=1}^{n}S_i\right)\Big/\sum_{i=1}^{n}M_i \qquad [2]$$

For graphical representations, only the 1:1 line of measured vs. simulated values was used. Linear regressions are not appropriate for evaluation of model accuracy. A model that departs from a 1:1 relationship between simulated and measured values is neither accurate nor precise. Correlation coefficients were also reported to express the scatter of the simulated values compared with the measured data.

Development of the Model

Male-Row Removal

Male-row removal was introduced in CERES-IM by modifying plant population accordingly on male-cutting date. Male-cutting simulation in CERES-IM can either be triggered on a given date specified in the input file, or automatically 10 d after 75% silking, which corresponds to the end of leaf growth in CERES-IM. Proportion of male to total land area and a special code for male rows (ML) were entered in the input files. Plant and ear populations, treated separately in CERES-Maize, were decreased by the male–to–total-land-area ratio on male-cutting date. Male plants are generally chopped and left on the soil surface, which adds fresh organic matter and N to the uppermost soil layer. This additional N is unlikely to affect grain yields, given the time needed for decomposition and the fact that inbred grain yields respond little to N fertilization (Rasse et al., 1999). Nevertheless, to be consistent with field operations and allow for multiyear N budgets, male-row removal effects on soil N were simulated. In CERES-IM, the fresh organic matter and N pools of the uppermost soil layer were increased by the total mass and N content of the chopped male plants.

Detasseling

Detasseling is treated in CERES-IM as a separate harvest, handled by a subroutine that can either be triggered on a given date specified in the input file, or automatically when the last leaf tip has been produced. When this subroutine is invoked, two leaves are subtracted from the total number of leaves, the total leaf mass is decreased by 10.5%, the total stem mass is decreased by 5.0%, and the plant leaf area is decreased by a factor proportional to the leaf loss. These values are averages derived from measurements at the MI site as well as published data for other sites (Wilhelm et al., 1995b).

Following detasseling, the total leaf number remains unchanged because the uppermost part of the maize plant has been removed. CERES-Maize 3.0 simulates leaf production until the thermal time requirement for leaf production is satisfied. Therefore, if the simulated leaf number is decreased by two units at any given time, CERES-Maize 3.0 continues to simulate new leaf production until the thermal time requirement is satisfied. We introduced a conditional test in CERES-IM that prevents new leaf appearance from being simulated after the detasseling subroutine has been triggered.

Detasseled plant tissues add fresh organic N to the soil surface. This additional N is unlikely to affect grain yields given the small quantity of N involved, the time needed for decomposition, and the fact that inbred grain yields respond little to N fertilization (Rasse et al., 1999). The main impact of detasseling on inbred grain yields is expected to stem from the reduction in LAI (Wilhelm et al., 1995b). Nevertheless, to be consistent with field operations, we decided to simulate the addition of fresh organic matter and N to the soil surface. In CERES-IM, the fresh organic matter and N pools of the uppermost soil layer were increased by the total mass and N content of maize tissues that were removed by the detasseling subroutine.

Inbred Growth and Development

Inbred-maize plants produce less biomass and grain yield than hybrids (Wilhelm et al., 1995a and 1995b) and have reduced leaf area (Martin, 1992; Orr et al., 1997). CERES-Maize 3.0 uses four physiological and two growth parameters, which are specific to each hybrid maize variety. These coefficients are (i) thermal time from emergence to end of the juvenile phase (P1, °Cd), (ii) photoperiodism coefficient (P2, d h^{-1}), (iii) thermal time from silking to physiological maturity (P5, °Cd), (iv) thermal time between successive leaf tip appearances, known as phyllochron interval (PHINT, °Cd), (v) maximum possible number of kernels plant^{-1} (G2), and (vi) kernel filling rate (G3, mg seed^{-1} d^{-1}) (Tsuji et al., 1994). To better simulate leaf appearance of inbreds, processing of the phyllochron interval and calculation of the total leaf number were modified in CERES-IM.

Initiation of leaf primordia is a linear function of thermal time (Ritchie and NeSmith, 1991). The determination of the final leaf number in CERES-Maize 3.0 was based on the assumption that 21°Cd were necessary to initiate a leaf primordium. This formula consistently led to an overestimation of the final leaf number of inbreds (data not shown). We concluded that the computation of the final leaf number needed to be better tailored to specific inbred traits. This was supported by the fact that the measured PHINT was different for inbreds than for hybrids. Two factors were taken into consideration in the development of a new formula: (i) applicability to inbreds as well as hybrids, and (ii) integration of PHINT as a measured parameter. We changed the degree-day requirement for leaf initiation from 21°Cd to half the value of the phyllochron interval, according to

$$\text{TLNO} = \text{CUMDTT}/(\text{PHINT} \times 0.5) + 5.0 \qquad [3]$$

where TLNO is the total leaf number and CUMDTT is the cumulative daily thermal time from germination to panicle initiation.

Reduced LAI for inbred compared with hybrid maize was simulated by multiplying the expansion rate of leaf area (cm^2 d^{-1}) by a leaf reduction factor of 0.75. This factor was estimated from the maximum LAI measurements conducted in NE in 1995 and 1997. Genetic coefficients and growth parameters for the inbred used in this study are presented in Table 1. Phyllochron intervals for the three inbred varieties grown in NE were derived from the experimental data by plotting the rate of leaf appearance vs. the accumulated degree-days since emergence. Thermal time was computed from the weather data as the accumulated degree-days over a base temperature of 8°C. Phyllochron intervals computed for these inbreds averaged 54 (± 2)°Cd. This value, adopted for all inbreds in this study, is rather high compared with reported PHINTs for temperate and even tropical hybrids (Birch et al., 1998; Kiniry, 1991). Birch et al. (1998) reported a PHINT between 50 and 67°Cd for shaded hybrid-maize plants grown in Texas. Higher PHINT in shaded conditions was attributed to a reduced production of photosynthates. We can only hypothesize that the high PHINT measured in our study for inbred maize resulted from the reduced LAI of inbreds compared with hybrids and the associated reduction in photosynthate production.

Sensitivity analyses showed that simulated inbred grain yields did not respond to modifications of the photoperiodism coefficient (P2) (data not shown). The six inbred varieties used in this study were probably well adapted to high latitude conditions. Consequently, a common P2 value of 0.4 was adopted for all inbreds (Table 1). The available data did not provide conclusive evidence that P5 was inbred-dependent,an d indicated that P5 is somewhat lower for inbred than for hybrid plants. Consequently, a common P5 value was adopted for all inbreds (Table 1). This value was estimated to be 680°Cd. Grain yield simulations suggested that G3 was fairly constant among inbreds and approximated 8 mg seed^{-1} d^{-1}. Therefore, all simulations were conducted with only one genetic coefficient (P1) and one growth parameter (G2) subject to modification in the input files.

The estimation of the number of grain per plant (GPP) was modified in CERES-IM because CERES-Maize 3.0 did not accurately simulate inbreds with a low G2 (data not shown). CERES-Maize 3.0 computes GPP according to

Table 1. Genetic coefficients and growth parameters for the different inbred varieties simulated with CERES-IM.

Variety	P1	P2	P5	G2	G3	PHINT†
	°Cd	d h^{-1}	°Cd	kernels	mg $seed^{-1}$ d^{-1}	°Cd
P38	240	0.4	680	320	8.0	54
PO2	200	0.4	680	300	8.0	54
T10	240	0.4	680	255	8.0	54
RO3	230	0.4	680	350	8.0	54
FR1075	260	0.4	680	370	8.0	54
FR1064	260	0.4	680	370	8.0	54

† PHINT, phyllochron interval.

$$\mathrm{GPP} = (\mathrm{G2} \times \mathrm{PSKER}/7200) + 50.0 \qquad [4]$$

where PSKER is the average rate of photosynthesis from silking to the beginning of grain filling. Most hybrids have a G2 between 560 and 834 kernels $plant^{-1}$ (Ritchie et al., 1986), while inbred G2 ranged from 255 to 370 kernels $plant^{-1}$ (Table 1). The low G2 value of inbreds is not compatible with the GPP calculation used in CERES-Maize 3.0. Kiniry and Knievel (1995) reported that GPP is a linear function of intercepted phosynthetically active radiation, which is directly linked to PSKER. In CERES-IM, GPP was calculated as a linear function of PSKER, reaching a plateau at G2, according to

$$\mathrm{GPP} = 165 \times (\mathrm{PSKER} - 0.75) \qquad [5]$$

Genetic coefficients were calibrated with measurements conducted in NE; i.e., dates of leaf appearance, phenological stages, and number of grains $plant^{-1}$. Data from MI were further used for validating simulations of the phenology. Grain yield data from NE and MI were used together for model validation to demonstrate that CERES-IM could accurately simulate inbred grain yields for different sets of environmental conditions.

RESULTS

Accurate calibration of the model was obtained for the simulation of leaf appearance in NE (Fig. 1A, 1B, and 1C). Simulated values matched measured data for each of the three growing seasons, while the calibration was conducted with the measured PHINT averaged over the 3-yr period. In 1997, the period from planting to emergence lasted 3 wk. The model did not simulate such a delay, but instead simulated 1 wk from planting to emergence, which was similar to emergence times measured in 1995 and 1996. Therefore, emergence date was used for starting phenological simulations in 1997. For model validation, phenological data in MI were available only for the 1995 growing season. Using the genetic coefficients determined in NE, excellent simulation of the rate of leaf appearance was obtained for P38 grown in MI in 1995 (Fig. 1D).

Inbred grain yields at the MI site were simulated with and without male-row removal (Fig. 2). When the male-row removal subroutine was not used, simulated grain yields were multiplied by 80% to account for the fact that female plants only should have been present in the field at the time of harvest. Simulated inbred grain yields remained nearly unchanged regardless of whether the male-row removal subroutine was used or not. We conducted a sensitivity analysis on the timing of simulated male-row removal. Accuracy of grain yield simulation, as measured by RMSE between simulated and measured values, increased sharply with date of male-row

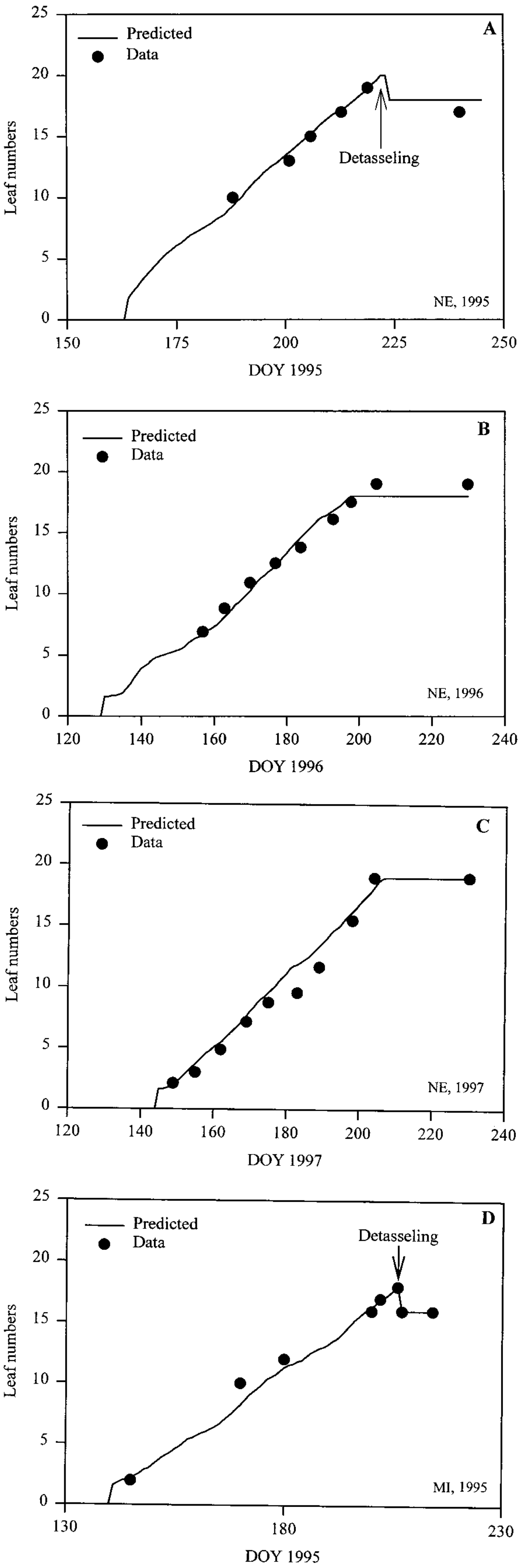

Fig. 1. Simulation of the rate of leaf appearance for inbred P38 at the NE site in (*A*) 1995, (*B*) 1996, and (*C*) 1997, and (*D*) at the MI site in 1995.

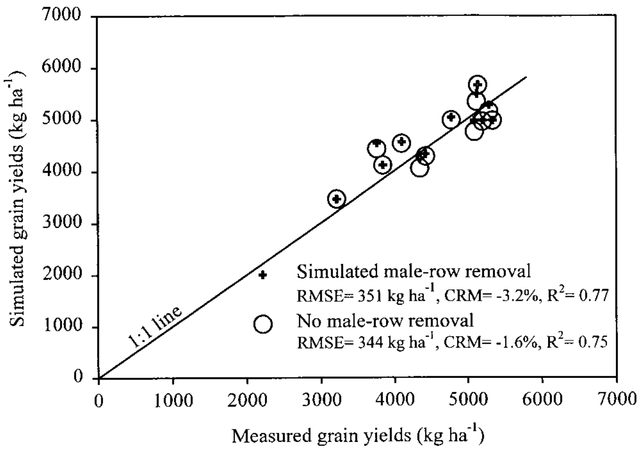

Fig. 2. Comparison of accuracy between inbred grain yield simulations conducted without male-row removal and with male-row removal triggered 10 d following 75% silking, for inbreds grown in MI. CRM, coefficient of residual mass; RMSE, root mean square error.

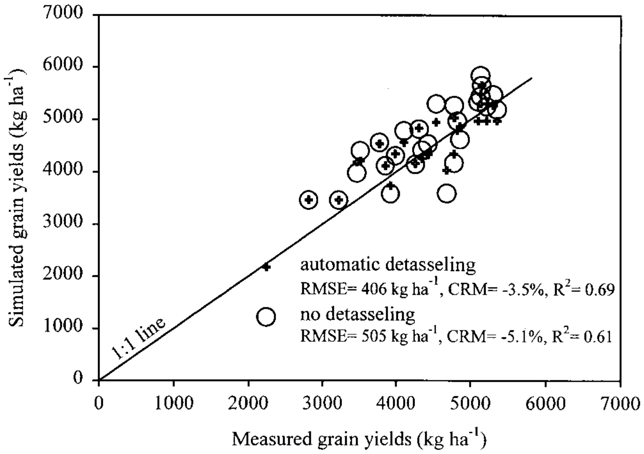

Fig. 4. Comparison of accuracy between inbred yield simulations conducted without detasseling and with automatic detasseling triggered at the appearance of the last leaf tip, for inbreds grown in MI from 1990 to 1993. CRM, coefficient of residual mass; RMSE, root mean square error.

removal simulated from 0 to 6 d after 75% silking, and reached a plateau 10 to 12 d following 75% silking (Fig. 3). Effects of the detasseling subroutine on the simulation of grain yields were assessed with a set of 24 treatment-year simulations at the MI site (Fig. 4). The RMSE of grain yield simulation was 406 kg ha^{-1} with the automatic detasseling subroutine turned on, and 505 kg ha^{-1} when no detasseling was simulated.

Grain yields of the P38 inbred in MI and NE were simulated with an RMSE of 559 kg ha^{-1} and a CRM of −0.1% (Fig. 5). CERES-IM accurately simulated inbred maize grain yields (RMSE = 432 kg ha^{-1}) when multiple inbreds were considered (Fig. 6). The average of the simulated values was close to the average of the measured data (CRM = −0.2%).

DISCUSSION

Phenology

Accurate simulation of the phenological development of the P38 inbred in MI was obtained when using the genetic coefficients determined for the same inbred in NE (Fig. 1). Few studies have reported simulations of maize phenological development with CERES-Maize. Otegui et al. (1996) accurately simulated maize silking and maturity dates using CERES-Maize. However, their study was conducted with several varieties and few growing seasons, and genetic coefficients were adjusted for each hybrid so that phenology was accurately simulated. Subjecting one set of genetic coefficients to multiyear and multisite simulations constitutes a much more stringent test of the model. Hence, several studies stressed the difficulty of determining the specific genetic coefficients for maize and accurately simulating phenology (Castelan-Ortega et al., 1998; Roman-Paoli et al., 1998). Birch (1996) working with AUSIM-Maize, a modified version of CERES-Maize, reported that the model consistently overpredicted leaf numbers and intervals from silking to emergence. Our results demonstrate that CERES-IM provided robust simulations of the phenological development of inbred maize for one set of genetic coefficients used for four site-year simulations. These results also indicate that the value of the PHINT interval used in CERES-IM corresponds to the actual phyllochron interval as computed by accumulated thermal time vs. leaf appearance.

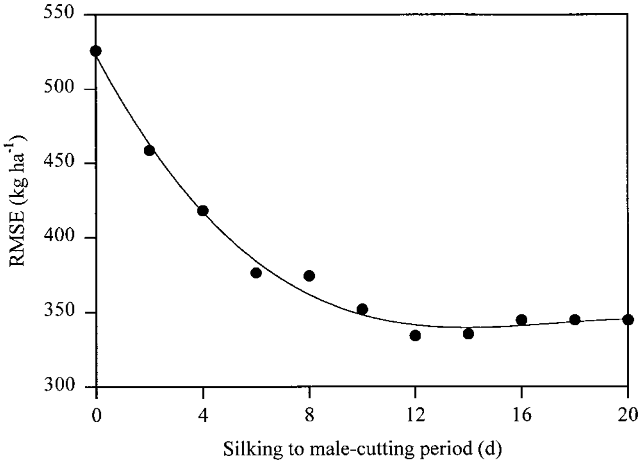

Fig. 3. Accuracy of yield simulation as a function of the number of days between 75% silking and simulated male-row removal. Each root mean square error (RMSE) data point was obtained with a set of 13 inbred-year simulations for inbreds grown in MI.

Male-Row Removal

Simulated inbred grain yields were modified by the triggering date of the male-row removal subroutine (Fig. 2). Nevertheless, male-row removal simulated on the actual date of the field operation had negligible impact on simulated female grain yields of irrigated inbred corn. Simulated rates of grain yield accumulation appeared to be sink-limited 8 to 10 d after silking. Before that time, the system was source-limited, and simulated female grain yields benefited from the additional water, N, and light resources provided by the removal of the male plants. Accuracy of the simulation rapidly increased with male-cutting date fixed from 0 to 6 d after 75% silking. Therefore, we would recommend the automatic triggering of the male-cutting subroutine when

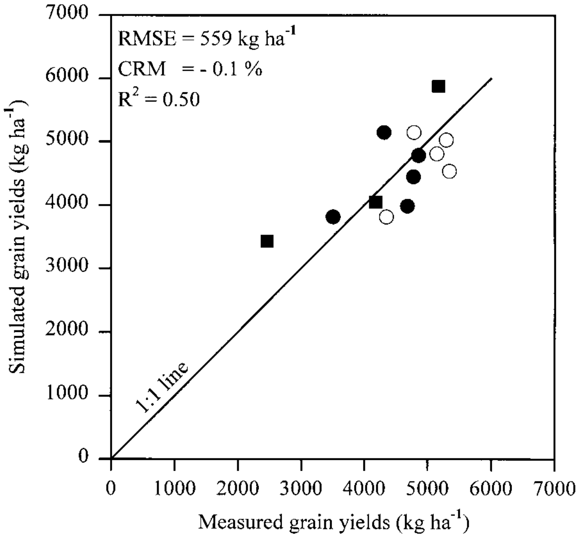

Fig. 5. Simulated vs. measured grain yields for the P38 inbred at NE (solid squares) and at MI unfertilized (open circles) and fertilized with 101 kg N ha^{-1} (solid circles). CRM, coefficient of residual mass; RMSE, root mean square error.

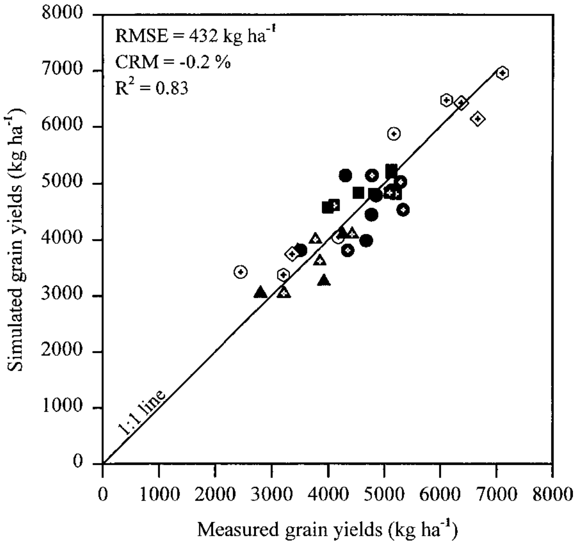

Fig. 6. Simulated vs. measured grain yields for varieties P38 (circles), PO2 (squares), T10 (triangles), RO3 (diamonds), and FR1064-75 (hexagons), in MI (solid symbols) and NE (open symbols), fertilized at 101 kg N ha^{-1} (with crosses) and unfertilized (without crosses). CRM, coefficient of residual mass; RMSE, root mean square error.

the phenological development, and associated silking date, is uncertain. This sensitivity analysis conducted with CERES-IM on the timing of male-row removal illustrates how a model can help explain uncertain agronomic processes. Wych (1988) reported that the theoretical increase in female grain yields due to male-row removal had not been clearly demonstrated in field experiments. A potential source for this uncertainty is indicated by CERES-IM simulations, which suggest that the potential benefit to female grain yields depends on how close to 75% silking male-row removal is conducted.

Detasseling

The detasseling subroutine improved grain yield simulation. These results were expected as the detasseling subroutine contributed to the accurate simulation of the final leaf number (Fig. 1A and 1D), which drives the amount of photosynthates available for starch accumulation. The automatic detasseling subroutine of CERES-IM simulates removal of the uppermost two leaves of the plant. When detasseling is simulated prior to the appearance of the last leaf tip, CERES-IM will decrease the total leaf number by two and will prevent further leaf appearance. If the phenological development of an inbred is uncertain, detasseling simulated on the actual reported date could introduce an error. For example, if appearance of the last leaf tip is simulated with a 7-d delay, detasseling on reported dates would be conducted 7 d earlier than automatic detasseling. In this case, detasseling on reported dates would simulate greater leaf loss (i.e., four leaves in most cases) than the actual two leaves lost during detasseling operations. Simulation of detasseling on reported dates is likely to improve grain yield simulation when two conditions are met: (i) the phenological development of the inbred is accurately simulated, and (ii) detasseling was conducted in the field earlier than the appearance of the last leaf tip, which resulted in the removal of more than two leaves. If these two conditions are not met, we recommend the use of the automatic detasseling subroutine.

Grain Yield

Results for grain yield simulation are promising, even though we worked with several constraints that generally decrease the accuracy of the simulations. First, inbred maize was grown in both experimental sites under irrigated conditions. Kiniry et al. (1997) stated that models such as CERES-Maize that simulate grain yield reductions based largely on drought stress do not accurately describe year-to-year variations in grain yield when crops are irrigated. Second, experimental plot data are not as buffered against pest damage and individual management errors as averaged county grain yields. Hence, Kiniry et al. (1997) reported accurate grain yield simulation using averaged county grain yields, while Otegui et al. (1996) reported poor simulation of the year-to-year grain yield variability from research plots. Third, we ran a set of simulations with the P38 inbred alone, which prevents the adjustment of genetic coefficients to fit individual growing seasons or fields.

CERES-IM performed well for grain yield simulation of a variety of inbreds (Fig. 6). These results were obtained when only P1 and G2 were allowed to vary. Maize grain yields were accurately simulated by Kovács et al. (1995) using CERES-Maize when different hybrids were used for each growing season. Our results demonstrate that CERES-IM can accurately simulate a wide range of grain yields even though the adjustment of the genetic coefficients was tightly guided by field measurements conducted in NE.

CONCLUSIONS

CERES-IM accurately simulated the phenological development and grain yields of inbred maize. These two elements are essential to the management of inbred fields and the final seed production. This study exemplifies that a greater understanding of a production system can be gained through modeling. The sensitivity analysis conducted on the timing of male-row removal helped us understand why grain yields remain fairly unaffected by this operation. We have also demonstrated that accurate grain yield simulation of multiple varieties can be obtained without greatly adjusting the genetic coefficients. Accurate simulated grain yields from 3 to 7 Mg ha^{-1} were obtained when only P1 and G2 were allowed to vary within limited ranges while P2, P5, G3, and PHINT were kept constant.

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