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Meteorological Models for Estimating Phenology of Corn

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16. Abstract

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The thermal models were significantly less biased and more accurate than calendar days for predicting dates of silking. Differences among the thermal models were small. Significant improvements in both bias and accuracy were observed when the mixed models were used to predict dates of physiological maturity. The results indicate that statistical data for CRD can be used to evaluate models developed at agricultural experiment stations.

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ABSTRACT

Knowledge of when critical crop stages occur and how the environment affects them should provide useful information for crop management decisions and crop production models. This research evaluated two sources of data for predicting dates of silking and physiological maturity of corn (Zea mays L.). Initial evaluations were conducted using data of an adapted corn hybrid grown on a Typic Agriaquoll at the Purdue University Agronomy Farm from 1979 to 1981. The second phase extended the analyses to large areas using data acquired by the Statistical Reporting Service of USDA for crop reporting districts (CRD) in Indiana and Iowa from 1969 to 1980. Several thermal models were compared to calendar days for predicting dates of silking and physiological maturity. Mixed models which used a combination of thermal units to predict silking and days after silking to predict physiological maturity were also evaluated. At the Agronomy Farm the models were calibrated and tested on the same data. For each CRD the models were calibrated using 4 or 5 years of data and tested using 7 different years of data.

The thermal models were significantly less biased and more accurate than calendar days for predicting dates of silking. Differences among the thermal models were small. Significant improvements in both bias and accuracy were observed when the mixed models were used to predict dates of physiological maturity. The results indicate that statistical data for CRD can be used to evaluate models developed at agricultural experiment stations.

INTRODUCTION

Crop development, or ontogeny, involves complex physiological and biochemical processes which are influenced by the crop's environment in ways that are still inadequately understood. Temperature and photoperiod are the principal environmental variables which influence development of crops. In some situations, the availability of moisture and nutrients also may affect crop development.

During the past century numerous models to describe the ontogeny of various crops as a function of environmental variables, particularly temperature, have been proposed. There are many different methods of calculating and accumulating temperature or thermal units for corn (Zea mays L.); for example, Cross and Zuber (7) reported on 22 methods for corn. The simplest and most broadly researched method is Growing Degree Units (GDU). A base temperature for growth of 10°C is subtracted from the mean air temperature to give the daily GDU. Modifications of this simple method frequently impose some upper and lower limits on the daily temperature inputs (4,7,12,19), while other methods consider day and night temperatures separately (5). For corn these limits commonly are 30° C for the maximum temperature and 10° C for the minimum temperature. A GDU index is obtained by summing the daily GDU from planting to the stage of crop development desired, usually silking or physiological maturity.

Considerable effort has been directed at trying to predict flowering and physiological maturity dates of various crops on the basis of temperature data. When cumulative thermal units were used to compare maturation of corn hybrids at different locations, those with a base of 10° C more effectively described crop development than calendar days (2). Gilmore and Rogers (8) studied the development of 10 hybrids and 10 inbred lines of corn using 15 different methods of calculating thermal units. Thermal units calculated using temperatures taken at 3-hour intervals did not estimate silking significantly better than those calculated using daily maximum and minimum temperatures. Differences among hybrids in the rate of development based on accumulated thermal units to silking were noted. Other researchers also have observed differences in rate of development among hybrids (14,15).

Numerous empirical and theoretical methods of estimating the silking and physiological maturity stages of corn have been devised and compared (1,3,7,10,12,19). Although differences among the methods for estimating a particular stage of development were generally small, all methods of accumulating thermal units were better indicators of crop development than calendar days.

Stages of development can be estimated very well for corn hybrids of different maturity classes using the simple GDU system with a base temperature of 10° C (13). Frequent and detailed data on stages of development result in better measures of the relationship between crop development and GDU than has been indicated by previous studies using only one or two stages of development (13).

The thermal unit accumulation concept assumes that photoperiod does not influence the rate of crop development (19). For domesticated crops grown in areas where they are adapted, development may seem to be independent of photoperiod. This is because the photoperiod is either longer or shorter than the optimum photoperiod or because the crop is relatively insensitive to photoperiod. Corn development is influenced by photoperiod (1,6). Decreasing photoperiods hasten flowering (i.e., silking) and reduce the number of leaves per plant in corn (1). Increasing temperatures also hasten flowering but increase the number of leaves per plant (1). For corn grown in U.S. Corn Belt, the changes in photoperiod are confounded with changes in temperature and are nearly impossible to separate in field experiments. Coligado and Brown (6) developed a model incorporating temperature, photoperiod, and genetic factors to predict tassel initiation of corn. Their model appears to be sound theoretically but needs further research to extend it to other stages of development. Although temperatures and photoperiod interact to influence the development of corn, particularly tassel and ear initiation, thermal models are generally accepted as adequate to predict growth and development of corn (11).

In summary, thermal units are recognized as being superior to calendar days for predicting dates of flowering and physiological maturity of corn in research and demonstration plots. However, in the realm of crop production forecasting at the regional or national level, one needs to know more than the rate of development of a specific corn genotype. He needs information about the status of the whole corn crop over large areas that may have many different planting dates, genotypes, and management practices. The timeliness and reliability of this information influence many decisions of economic importance to individuals involved in producing, storing, marketing, or consuming corn products.

The Statistical Reporting Service (SRS) of USDA acquires, summarizes, and reports data on the progress of crops in each state at weekly or monthly intervals throughout the growing season. Additional information could be obtained by using daily meterological data and reliable models of crop development to assess the status of the crop in the region of interest. These models could be updated as needed using the data reported by SRS. However, the validity of using models of crop development for large areas has not been demonstrated.

The objective of this research was to evaluate the use of statistical data from SRS for assessing the development of corn in crop reporting districts (CRD) of Indiana and Iowa. These data from SRS represented means of adapted genotypes of corn in each CRD. Preliminary evaluation of the crop models used data acquired from research plots at an agricultural experiment station.

MATERIALS AND METHODS

Agronomy Farm

Agronomic and meteorological data used in the first phase of this analysis were acquired at the Purdue University Agronomy Farm in 1979, 1980, and 1981. An adapted hybrid, Becks 65X, was grown on Chalmers silt loam (fine-loamy, mixed, mesic Typic Argiaquoll) at three densities (25,000, 50,000, and 75,000 plants/ha) in 76-cm rows. Planting dates were 2, 16, and 30 May 1979, 7, 16, 22, and 29 May and 11 June 1980, and 8 and 29 May and 11 June 1981. Prior to planting, 200, 50, and 95 kg of N, P, and K per hectare, respectively, were applied. Stages of development (9) were observed once a week in 1979 and twice weekly in 1980 and 1981. Dates of silking and physiological maturity (black layer) were recorded when at least half of the plants of each planting date reached a particular stage of development.

Daily meteorological data were recorded at the cooperative National Weather Service station (West Lafayette 6 NW) which was within 300 m of the plots. Daily maximum and minimum air temperatures were measured in a standard Cotton Region shelter.

Crop Reporting Districts

The percentages of the acreages planted, silked, and mature in each of the nine crop reporting districts (CRD) of Indiana were taken from the Annual Crop and Livestock Summary (16). Similar data for the nine CRD of Iowa were extracted from the annual Iowa Crops Weather Summary (17). Dates on which 25, 50, and 75% of the crop in each CRD reached each stage of development were linearly interpolated from these data (16,17).

Meteorological data consisting of daily maximum and minimum air temperatures for 1969 to 1980 were selected for five National Weather Service (NWS) cooperative stations in each CRD of Indiana and Iowa (18). Stations with similar times of observation were selected to reduce any bias. Mean daily maximum and minimum temperatures for a CRD were computed from daily maximum and minimum temperatures reported by the five NWS stations in each CRD. The 12 years of data were assumed to represent a random selection of years for each location and were divided into calibration (1969, 1971, 1973, 1975, and 1977) and test (1970, 1972, 1974, 1976, 1978, 1979, and 1980) sets.

Models and Analyses

Four thermal indexing methods and the number of calendar days after planting (DAP) were evaluated for precision and accuracy. The first index, Growing Degree Unit (GDU), is the simplest thermal method and is defined as the daily mean air temperature minus a base temperature for growth of 10° C. The daily values of GDU are summed from the beginning to the end of each stage of development. For daily mean temperatures less than 10° C, GDU = 0. The dates that 25, 50, and 75% of the corn acreage had been planted in each CRD of Indiana and Iowa were used to start the accumulations of the thermal indexes. Dates that 25, 50, and 75% of the corn acreage in each CRD had silked or reached physiological maturity were the ending dates.

Modified Growing Degree Unit (MGDU) index (4) is the same equation as GDU but with a threshold of 30° C imposed on maximum temperature and a threshold of 10° C imposed on minimum temperature.

Heat Stress (HS) index (7) is the same equation as MGDU but with a decrease in thermal unit accumulations for maximum temperatures greater than 30° C.

Function of Temperature (FT) index (5) is the mean of the relative growth rates for the daily maximum and minimum air temperatures. Four line segments which define FT are as follows:

$$
\begin{aligned}
FT &= 0.027T - 0.162; && \text{if } 6^\circ C \leq T < 21^\circ C, \\
FT &= 0.086T - 1.41; && \text{if } 21^\circ C \leq T < 28^\circ C, \\
FT &= 1.0; && \text{if } 28 \leq T < 32^\circ C, \\
FT &= -0.083T + 3.67; && \text{if } 32 \leq T < 44^\circ C, \\
\text{and } FT &= 0 \text{ for } 6^\circ C > T \geq 44^\circ C.
\end{aligned}
$$

Daily FT was calculated as mean of the FT for the maximum temperature and the FT for the minimum temperature (5). The FT values used in this research were computed using air temperatures only rather than the combination of soil and air temperatures (5).

The average thermal units and the number of calendar days accumulated from planting to silking, planting to physiological maturity, and silking to physiological maturity were calculated for the calibration years and used to predict dates of silking and physiological maturity for test years. Accuracy was measured as absolute errors in days, that is, the predicted date of stage minus the actual date of stage . Bias was measured as errors in days for predicted minus actual dates. Multiple range tests were used to separate significant differences in bias and accuracy among the models.

RESULTS AND DISCUSSION

Agronomy Farm

The means, standard deviations, and coefficients of variation (CV) for the five models evaluated at the Agronomy Farm are shown in Table 1. The GDU model had the smallest CV and the calendar days model had the largest CV for planting to silking. All the thermal models depicted silking better than calendar days for the wide range of planting dates used in the three years at the Agronomy Farm.

The corn hybrid grown at the Agronomy Farm did not reach physiological maturity (i.e., black layer) before frost when planted after 10 June in 1980 or 1981. Thus the statistics in Table 1 for physiological maturity are based on fewer observations than for silking. Differences in CV among the models were very small for planting to physiological maturity. However, for the silking to physiological maturity interval CV for the calendar days model was much smaller than CV for the thermal models. This observation is supported by Shaw and Thom (13) who noted that the interval from silking to physiological maturity is relatively constant over years.

Table 1. Means, standard deviations (s), and coefficients of variation (CV) of thermal and calendar days models at Purdue Agronomy Farm.

Statistic	Thermal Models				Calendar Days
	GDU	MGDU	HS	FT	
			Planting to Silking		
Mean	818	804	781	37.2	68.6
s	43	45	50	2.4	6.4
CV,%	5.3	5.6	6.4	6.4	9.3
(n=11)					
			Planting to Physiological Maturity		
Mean	1499	1497	1466	70.0	133.0
s	70	62	60	2.9	6.0
CV,%	4.7	4.2	4.1	4.1	4.5
(n=9)					
			Silking to Physiological Maturity		
Mean	676	686	677	32.4	62.7
s	64	50	44	2.4	2.6
CV,%	9.5	7.3	6.6	7.4	4.1
(n=9)					

Comparing models solely on the basis of CV of accumulated units for a number of environments provides an incomplete evaluation. A better way is to use the mean cumulative units from Table 1 for the respective models to predict the dates of silking and physiological maturity. Mean errors and mean absolute errors in number of days for the predicted date minus the actual date of each stage provide more realistic evaluations than simply CV. Mean error ($\bar{e}$) is a measure of the bias of a model's predictions while mean absolute error ($|\bar{e}|$) measures its accuracy. The standard deviation of the absolute error ($s_{|\bar{e}|}$) provides a measure of the precision or variability of a model's errors in predicting dates of corn silking or physiological maturity. Low variability signifies high precision. When silking dates of corn grown at Agronomy Farm were predicted, the thermal models were significantly more accurate than calendar days (Table 2). There were no significant differences among the thermal models. Rounding to the nearest whole day probably accounts for the slight positive bias (i.e., less than 1.0 day) exhibited by all of the models.

Table 2. Errors in days for predicted minus actual dates of silking at Purdue Agronomy Farm.

Year	Planting Date	Thermal Model GDU	MGDU	HS	FT	Calendar Days
		-------------------	-------------------	Days	-------------------	-------------------
1979	2 May	-5	-6	-7	-7	-11
	16 May	-1	-2	-3	-6	-2
	30 May	-4	-4	-5	-5	3
1980	7 May	2	2	3	2	-6
	16 May	1	2	2	2	-1
	22 May	1	2	3	2	2
	29 May	0	0	1	1	2
	11 June	-1	0	2	1	7
1981	8 May	5	3	3	3	-5
	29 May	5	5	5	5	7
	11 June	6	6	5	6	9
	$\bar{e}$†	0.8a‡	0.7a	0.8a	0.4a	0.5a
	$\lvert\bar{e}\rvert$†	2.8b	2.9b	3.6b	3.6b	5.0a
	$s_{\lvert\bar{e}\rvert}$†	2.2	2.1	1.8	2.2	3.3

† Mean error ($\bar{e}$), mean absolute error ($\lvert\bar{e}\rvert$) and standard deviation of mean absolute error ($s_{\lvert\bar{e}\rvert}$).

‡ Within each line, means followed by the same letter are not significantly different at α = 0.05 level using Duncan's multiple range test.

The errors and absolute errors for predicting physiological maturity dates using thermal models (Table 3) are at least double the errors for predicting silking dates using the same models (Table 2). The major source of the variation unaccounted for by thermal models in predicting date of physiological maturity appears to occur between silking and physiological maturity. In contrast, the absolute errors for the calendar days model remain relatively constant for both stages of

Table 3. Errors in days for predicted minus actual dates of physiological maturity at Purdue Agronomy Farm.

Year	Planting Date	Thermal Models GDU	MGDU	HS	FT	Mixed Models† GDU′	MGDU′	HS′	FT′	Cal. Days
		---Days---								
1979	2 May	-13	-14	-17	-14	-5	-6	-7	-7	-12
	16 May	3	0	-3	1	3	2	1	-2	2
	30 May	14	11	2	7	-4	-4	-5	-5	3
1980	7 May	-6	-4	-2	0	5	5	6	5	-3
	16 May	-6	-2	-1	-2	5	6	6	6	3
	22 May	-6	-2	1	-2	4	5	6	5	5
	29 May	-2	4	6	4	3	3	4	4	5
1981	8 May	23	10	6	9	3	1	1	1	-7
	29 May	26	26	24	26	2	2	2	2	4
	$\bar{e}$‡	3.7a§	3.2a	2.0b	3.2a	1.8b	1.6b	1.6b	1.0c	0.0d
	$\lvert\bar{e}\rvert$	11.0a	8.1b	7.1b	7.2b	3.8c	3.8c	4.2c	4.1c	4.9c
	$s_{\lvert\bar{e}\rvert}$	8.7	8.2	8.7	8.4	1.1	1.9	2.3	2.0	3.1

† The mixed models predict physiological maturity by using thermal models to estimate date of silking and then adding the mean number of days from silking to physiological maturity from Table 1.

‡ Mean error ($\bar{e}$), mean absolute error ($\lvert\bar{e}\rvert$), and standard deviation of mean absolute error ($s_{\lvert\bar{e}\rvert}$).

§ Within each line, means followed by the same letter are not significantly different at $\alpha = 0.05$ level using Duncan's multiple range test.

development. The large positive errors observed in 1981 for all of the thermal models (Table 3) were due to very slow accumulations of thermal units late in the fall. Calendar days, on the other hand, accumulate uniformly.

A "mixed" model could exploit both the advantages of the thermal models for predicting silking dates and the reliability of the calendar days model for predicting physiological maturity. To test this mixed model concept, the original thermal models were used to predict silking dates and then the mean interval in days from silking to physiological maturity (from Table 1) was added to predict dates of physiological maturity. For example, the expected silking date would occur when 818 GDU had accumulated after planting and the expected physiological maturity date would occur 63 days later (Table 1).
A prime (′) distinguishes the mixed models (thermal + days) from the conventional thermal models (Table 3). The accuracies of the mixed models are better than the accuracies of the conventional thermal or calendar days models for predicting physiological maturity of corn. There were no significant differences in accuracy among the mixed models. The mixed models appear to capitalize on the advantages of the thermal models for predicting date of silking and on the advantages of calendar days for predicting physiological maturity.

Crop Reporting Districts

The means of thermal and calendar days models for each CRD in Indiana are presented in Table 4 for the five calibration years. The number of thermal units accumulated for each interval increased from northern to southern CRDs while the number of calendar days remained nearly constant or decreased slightly. Similar trends were observed in the data for Iowa and only the state means are presented in Table 5.

Calendar days consistently had the lowest CV and GDU had the highest CV for each of the three intervals in Indiana (Table 4) and Iowa (Table 5). during the calibration years. These results, using statistical data from CRDs, contrasted sharply with our data from the Agronomy Farm (Table 1) and with many previous reports which have concluded that thermal units are significantly superior to calendar days in predicting dates of flowering (3,5,7,8,12,19). However, the trends for the intervals from planting to physiological maturity and from silking to physiological maturity (Tables 4 and 5) were consistent with trends observed at the Agronomy Farm (Table 1).

One possible source of error introduced by using these statistical data for CRD was that the first 25% of corn planted was assumed to be the first 25% to reach all other stages of development. This assumption should be reasonable unless most farmers in a CRD shift to short-season corn genotypes as planting progresses. Such a shift is most likely to occur only in years when planting is delayed much later than normal. Other factors, not present in controlled experiments, also may affect analysis of statistical data on crops over large areas. For example, soil productivity and level of management may vary greatly from location to location and cannot be controlled by the investigator. The statisti-

Table 4. Means of thermal and calendar days models for planting to silking, planting to physiological maturity, and silking to physiological maturity of corn in crop reporting districts (CRD) of Indiana in calibration years. Data for CRD are means of three planting dates per year and 5 years (n=15).

CRD	Thermal Models GDU	MGDU	HS	FT	Calendar Days
			Planting to Silking		
NW	728	728	688	35.4	67.6
NC	728	728	691	35.5	66.2
NE	717	721	693	35.4	66.3
WC	764	759	722	36.8	66.9
C	747	747	718	36.5	67.3
EC	735	736	708	36.2	67.0
SW	840	815	775	38.5	64.8
SC	789	777	743	37.6	65.1
SE	850	824	785	39.4	65.7
Mean	767	759	725	36.8	66.3
s	73	61	62	2.8	4.0
CV,%	9.5	8.0	8.6	7.6	6.0
			Planting to Physiological Maturity		
NW	1385	1380	1326	67.6	124.8
NC	1353	1352	1299	66.6	122.8
NE	1303	1308	1265	64.9	121.2
WC	1452	1440	1386	70.4	125.1
C	1429	1424	1381	70.1	126.1
EC	1378	1379	1333	68.1	125.4
SW	1607	1562	1498	74.3	121.9
SC	1461	1435	1382	69.7	118.7
SE	1563	1516	1451	72.6	120.4
Mean	1437	1422	1369	69.4	122.9
s	113	95	91	3.9	6.1
CV,%	7.9	6.7	6.6	5.6	4.9
			Silking to Physiological Maturity		
NW	657	652	638	32.2	57.2
NC	625	624	608	31.1	56.6
NE	585	587	572	29.5	54.9
WC	688	681	664	33.6	58.3
C	682	677	663	33.6	58.8
EC	643	642	626	31.9	58.4
SW	767	747	723	35.8	57.1
SC	671	659	639	32.1	53.5
SE	713	692	666	33.2	54.7
Mean	670	662	644	32.6	56.6
s	67	60	59	2.7	4.5
CV,%	10.0	9.1	9.1	8.2	7.9

+ Crop reporting districts are North West, North Central, North East, West Central, Central, East Central, South West, South Central and South East, respectively.

Table 5. Means, standard deviations(s) and coefficients of variation (CV) of thermal and calendar days models in Iowa during calibration years. Data are means of nine CRD, three planting dates, and 4 years (n=108).

Statistic	Thermal Models				Calendar Days
	GDU	MGDU	HS	FT	
			Planting to Silking		
Mean	781	773	734	37.6	70.1
s	59	49	50	2.2	3.0
CV,%	7.5	6.3	6.8	5.8	4.3
			Planting to Physiological Maturity		
Mean	1376	1355	1293	65.9	120.8
s	79	66	67	3.1	5.2
CV,%	5.7	4.9	5.2	4.8	4.3
			Silking to Physiological Maturity		
Mean	595	583	559	28.3	50.8
s	70	58	58	2.5	3.0
CV,%	9.0	7.5	7.9	6.6	4.2

cal data on crops acquired by SRS represent the average genotypes, planting dates, soil productivity, and level of management of each CRD.

When the models were used to estimate dates of silking and physiological maturity for the calibration years in Indiana and Iowa, no significant differences were observed in bias or accuracy. However, evaluating a model on the same data used to develop the model tests only the goodness of fit of the model to the original data and does not test the predictive ability of the model. For a more rigorous test, we assumed that years are random and divided the data into two series. The mean thermal units and calendar days accumulated during the calibration years for each CRD were used to predict the dates of silking and physiological maturity in 7 additional test years.

The thermal models were significantly less biased and more accurate than the calendar days model for predicting dates of silking in both Indiana and Iowa (Table 6). Predicting silking date simply as the num-

Table 6. Mean errors ($\bar{e}$), mean absolute errors ($|\bar{e}|$), and standard deviations of absolute errors ($s_{|\bar{e}|}$) in days for predicted minus actual dates of silking in test years. Data are means of nine CRD, three planting dates per year, and 7 years for both Indiana and Iowa (n=189).

Location	Statistic	Thermal Models				Calendar Days
		GDU	MGDU	HS	FT	
		--------------------Days--------------------				
Indiana	e	0.5a†	0.0b	0.0b	-0.8c	-4.1d
	$\lvert\bar{e}\rvert$	2.8b	2.4c	2.3c	2.4c	5.9a
	$s_{\lvert\bar{e}\rvert}$	2.3	2.1	2.0	2.0	4.3
Iowa	$\bar{e}$	0.7a	0.3b	0.7a	0.0b	-2.5c
	$\lvert\bar{e}\rvert$	3.6b	3.5b	3.3b	3.4b	4.7a
	$s_{\lvert\bar{e}\rvert}$	3.1	2.8	2.7	2.5	3.3

† Within each development stage and statistic, means followed by the same letter are not significantly different at the α = 0.05 level using Duncan's Multiple range test.

ber of days after planting produced a mean bias of -4.1 days in Indiana and -2.5 days in Iowa. The length of the average interval from planting to silking was slightly shorter in the test years compared to the calibration years. The biases of all the thermal models (except for FT model in Indiana) were positive and were within 0.8 days of the expected date. Thus mean air temperatures probably were slightly warmer for the planting-to-silking interval during the test years than during the calibration years. Differences among the thermal models were small. This contrasts with a previous report (5) which indicated that the FT model was clearly superior for predicting silking of corn.

The calendar days model underestimated (i.e., negative bias) physiological maturity (Table 7) by approximately the same number of days as it underestimated silking (Table 6). The number of days from silking to physiological maturity changed little during calibration and test years. All of the thermal models had a positive bias for estimating physiological maturity (Table 7). The FT model was more accurate and less biased than other thermal or calendar days models. This extends the FT model concept (5) to predict physiological maturity as well as silking.

Table 7. Means errors ($\bar{e}$), mean absolute errors ($|\bar{e}|$) and standard deviations of absolute errors ($s_{|\bar{e}|}$) of thermal, mixed, and calendar days models for predicted minus actual dates of physiological maturity in test years. Data are means of nine CRD, three planting dates per year, and 7 years (n=189).

Loc.	Stat.	Thermal Models				Mixed Models†				Cal. Days
		GDU	MGDU	HS	FT	GDU′	MGDU′	HS′	FT′	
		---------------------				Days			---------------------	
Ind.	$\bar{e}$	7.4a‡	4.0c	5.4b	2.6d	0.8e	0.3e	0.3e	-0.5e	-3.8f
	$\|\bar{e}\|$	11.0a	7.3b	8.2b	5.9c	3.4d	3.3d	3.2d	3.3d	6.7bc
	$s_{\|\bar{e}\|}$	8.6	5.8	7.4	5.2	2.7	2.6	2.6	2.7	4.5
Iowa	$\bar{e}$	4.6a	1.6b	3.7a	1.2b	-0.4c	-0.8c	-0.4c	-1.1c	-3.7d
	$\|\bar{e}\|$	11.0a	8.0b	9.8b	7.8b	5.3c	5.2c	4.9c	4.9c	6.4c
	$s_{\|\bar{e}\|}$	9.4	6.9	9.1	6.7	4.0	3.9	3.6	3.5	4.7

† The mixed models predict maturity date in each CRD by using the thermal models to estimate silking date and then adding the mean number of days from silking to physiological maturity.

‡ Within each line, means followed by the same letter are not significantly different at the $\alpha = 0.05$ level using Duncan′s multiple range test.

Significant improvements in both bias and accuracy occurred when the mixed models were used to predict physiological maturity (Table 7). For example, the accuracy of the FT′ model in Indiana was 3.3 days compared to 5.9 days for the conventional FT model. There were no significant differences among the mixed models. These results were consistent with our data from the Agronomy Farm (Table 3). The improved accuracies of the mixed models occurred mainly in years when the rate of accumulation of thermal units late in the season was much slower than normal. The mixed models predicted a date of physiological maturity whereas the thermal models accumulated the expected number of units for physiological maturity too slowly.

This experiment evaluated thermal, calendar days, and mixed models to predict dates of silking and physiological maturity of corn. The results obtained using statistical data from CRDs were comparable to those obtained using observations of plants in controlled experiments. In general, the data from CRDs may be used to extend and test models developed at agricultural experiment stations.

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Table A1. Dates (days from 1 January) of corn planting in Indiana.

Year	PCT*	NW	NC	NE	WC	C	EC	SW	SC	SE	AVE
		Crop Reporting District									
1969	25	127	135	140	131	126	127	125	125	132	130
	50	142	144	145	139	135	136	136	137	139	139
	75	149	150	150	147	144	144	148	151	148	148
1970	25	132	133	133	133	132	130	137	133	134	133
	50	139	142	141	142	140	137	145	142	142	141
	75	147	152	149	154	147	152	152	151	149	150
1971	25	124	126	125	124	123	123	114	123	122	123
	50	131	133	133	133	130	133	121	131	132	131
	75	137	138	142	142	137	146	140	141	145	141
1972	25	136	141	141	131	132	140	133	134	142	137
	50	143	145	146	137	141	145	140	144	147	143
	75	148	150	152	144	147	150	148	150	154	149
1973	25	132	133	136	131	133	134	140	136	139	135
	50	137	140	146	137	138	140	148	146	152	143
	75	145	149	165	146	146	155	166	163	168	156
1974	25	127	130	130	130	125	126	125	126	133	128
	50	148	147	144	158	148	141	137	136	142	145
	75	158	156	153	169	159	153	166	152	159	158
1975	25	126	128	130	125	124	131	126	128	131	128
	50	132	134	134	131	130	135	134	134	136	133
	75	137	138	138	137	136	138	142	139	141	138
1976	25	122	119	119	117	115	117	115	113	117	117
	50	128	126	125	123	122	124	121	121	125	124
	75	136	134	133	128	128	128	128	130	134	131
1977	25	121	126	130	118	123	126	125	130	131	126
	50	128	133	134	126	131	133	134	135	135	132
	75	134	138	138	134	136	138	141	142	140	138
1978	25	135	138	140	141	141	142	142	141	143	140
	50	144	146	145	149	147	148	147	148	150	147
	75	151	154	150	156	154	155	154	155	156	154
1979	25	132	129	127	128	125	128	134	130	131	129
	50	139	138	135	136	132	133	142	138	135	136
	75	145	145	143	143	138	138	147	146	140	143
1980	25	123	124	125	123	124	123	123	124	123	124
	50	127	128	131	127	128	127	128	132	128	128
	75	132	135	138	132	134	132	136	140	134	135
MEAN	25	128	130	131	128	127	129	128	129	132	129
	50	137	138	138	137	135	136	136	137	139	137
	75	143	145	146	144	142	144	147	147	147	145
SD	25	5.2	6.2	6.9	6.7	6.6	7.1	9.1	7.2	7.9	6.4
	50	7.1	7.1	7.1	9.9	7.8	6.9	9.1	7.4	8.4	7.3
	75	8.0	7.9	8.9	11.4	8.9	9.2	11.2	8.8	10.4	8.7

* Percent of corn acreage at or beyond planted.

Table A2. Dates (days from 1 January) of corn silking in Indiana.

Year	PCT*	NW	NC	NE	WC	C	EC	SW	SC	SE	AVE
		Crop Reporting District									
1969	25	198	200	203	195	193	194	191	194	195	196
	50	205	207	209	201	199	202	197	199	203	202
	75	212	212	214	208	207	210	206	212	213	210
1970	25	197	200	201	200	197	196	195	194	198	198
	50	205	209	210	208	206	205	211	206	207	207
	75	213	216	218	217	215	215	221	217	215	216
1971	25	194	195	196	193	195	196	192	194	199	195
	50	199	201	203	199	200	204	198	202	206	201
	75	205	209	208	207	207	212	208	210	212	209
1972	25	204	204	204	199	202	205	202	203	207	203
	50	212	211	210	207	207	213	207	210	215	210
	75	219	218	216	215	212	222	213	217	223	217
1973	25	198	202	206	201	203	205	202	204	205	203
	50	206	207	213	209	207	210	211	209	211	209
	75	215	215	224	218	213	221	222	217	227	219
1974	25	204	208	203	207	203	206	195	199	203	203
	50	211	216	215	221	215	214	210	207	213	214
	75	223	223	224	233	226	224	229	221	225	225
1975	25	194	193	195	190	191	192	191	192	193	192
	50	200	200	203	196	197	197	198	198	199	199
	75	207	209	210	204	205	203	208	208	214	208
1976	25	200	195	197	195	195	195	193	196	199	196
	50	205	202	204	201	200	201	198	203	205	202
	75	209	210	208	208	207	209	207	209	210	209
1977	25	189	191	193	188	190	193	190	193	194	191
	50	194	196	198	194	195	198	196	199	199	197
	75	200	201	206	201	200	207	202	207	206	203
1978	25	201	202	204	201	200	203	202	199	202	202
	50	206	207	210	207	209	211	208	207	208	208
	75	213	216	219	215	217	219	216	218	217	217
1979	25	203	203	204	201	201	202	201	201	203	202
	50	207	208	208	206	206	207	207	207	208	207
	75	212	215	215	211	211	213	216	216	215	214
1980	25	196	200	203	194	196	197	193	196	199	197
	50	201	206	207	200	202	202	199	201	207	203
	75	210	211	211	207	209	209	207	210	215	214
MEAN	25	198	199	201	197	197	199	196	197	200	198
	50	204	206	208	204	204	205	203	204	207	205
	75	212	213	214	212	211	214	213	214	216	213
SD	25	4.5	5.0	4.3	5.4	4.6	5.2	4.8	4.0	4.4	4.4
	50	5.1	5.4	4.8	7.2	5.7	5.7	6.1	4.2	4.9	5.0
	75	6.1	5.6	6.1	8.5	6.7	6.6	8.0	4.7	6.2	6.0

* Percent of corn acreage at or beyond silking.

Table A3. Dates (days from 1 January) of corn maturity in Indiana.

		Crop Reporting District									
Year	PCT*	NW	NC	NE	WC	C	EC	SW	SC	SE	AVE
1969	25	249	255	255	255	252	254	246	240	249	251
	50	258	261	260	261	259	264	257	256	258	259
	75	265	274	271	270	267	272	266	270	268	269
1970	25	247	255	250	253	249	252	252	242	252	250
	50	258	264	260	263	264	260	262	252	261	260
	75	269	273	271	274	274	276	271	269	271	272
1971	25	249	254	249	253	254	250	246	248	255	251
	50	259	261	258	261	260	261	259	259	263	260
	75	270	272	266	271	272	275	276	271	276	272
1972	25	262	265	258	261	258	261	252	252	260	259
	50	270	271	265	269	267	273	264	262	272	268
	75	279	277	278	277	277	289	284	275	289	281
1973	25	255	252	257	257	254	257	255	252	259	255
	50	262	262	265	264	262	264	267	263	267	264
	75	276	272	273	273	271	272	279	274	274	274
1974	25	260	261	262	265	266	262	256	255	264	261
	50	271	272	275	279	277	271	271	267	271	273
	75	283	283	287	293	288	279	288	283	279	285
1975	25	247	247	247	245	248	254	245	242	245	247
	50	257	256	259	257	257	262	256	253	257	257
	75	267	265	269	267	265	270	269	267	269	268
1976	25	252	254	251	252	253	253	245	251	249	251
	50	260	259	259	259	258	258	255	259	258	258
	75	269	265	267	269	264	265	266	267	266	266
1977	25	244	242	248	238	245	245	241	235	243	242
	50	255	250	259	247	255	254	249	250	251	252
	75	261	264	268	259	263	266	258	261	263	263
1978	25	253	251	259	256	256	263	252	250	256	255
	50	261	261	267	263	264	269	262	260	262	263
	75	270	270	275	272	270	276	270	270	271	272
1979	25	256	256	261	258	256	256	256	256	257	257
	50	266	263	267	266	265	267	264	263	265	265
	75	276	271	272	272	271	275	273	272	271	273
1980	25	255	255	256	248	252	254	243	248	249	251
	50	260	260	262	257	259	259	251	255	258	258
	75	268	267	269	266	266	264	259	262	266	265
MEAN	25	252	254	254	253	254	255	249	248	253	253
	50	261	262	263	262	262	264	260	258	262	261
	75	271	271	272	272	271	273	272	270	272	272
SD	25	5.5	5.9	5.2	7.2	5.4	5.2	5.3	6.5	6.4	5.2
	50	5.1	5.9	5.0	7.7	5.9	5.6	6.5	5.1	6.1	5.6
	75	6.2	5.5	5.8	8.1	6.9	6.9	9.1	5.9	7.0	6.4

* Percent of corn acreage at or beyond maturity.

Table A4. Dates (days from 1 January) of corn planting in Iowa.

		Crop Reporting District									
Year	PCT*	NW	NC	NE	WC	C	EC	SW	SC	SE	AVE
1970	25	125	123	123	124	122	123	123	123	124	123
	50	130	127	127	129	125	127	127	128	129	128
	75	137	133	134	136	129	133	134	136	138	134
1971	25	123	122	126	123	122	123	122	124	119	123
	50	127	126	132	129	126	128	127	130	126	128
	75	132	132	137	136	131	135	135	137	134	134
1972	25	131	130	133	133	130	138	133	137	136	133
	50	135	134	138	137	135	144	138	144	143	139
	75	139	138	145	142	140	148	144	148	150	144
1973	25	126	133	134	131	133	135	134	136	137	133
	50	132	137	139	136	138	141	141	144	144	139
	75	137	143	146	143	145	150	148	150	150	146
1974	25	123	123	123	122	122	123	122	123	122	123
	50	127	128	131	126	127	134	128	132	128	129
	75	134	142	148	133	142	156	136	151	144	143
1975	25	133	133	131	132	129	124	126	129	124	129
	50	137	137	136	136	135	129	133	135	131	134
	75	141	141	141	141	140	136	139	140	138	140
1976	25	121	123	125	123	125	125	125	127	127	125
	50	125	127	130	127	129	130	129	133	135	129
	75	129	130	134	130	133	134	134	139	142	134
1977	25	117	118	119	116	115	117	116	116	115	117
	50	123	123	124	122	121	123	122	122	122	122
	75	129	127	130	127	124	129	129	128	128	128
1978	25	126	122	128	128	126	127	136	141	140	130
	50	131	127	135	133	132	136	141	153	148	137
	75	136	133	140	138	138	144	150	159	156	144
1979	25	132	130	133	130	130	129	131	133	129	131
	50	136	135	136	135	134	133	136	137	133	135
	75	140	138	139	139	138	137	139	141	138	139
1980	25	120	120	121	120	119	121	121	120	120	120
	50	122	122	126	123	122	124	126	124	124	124
	75	126	126	130	129	124	129	130	130	129	128
MEAN	25	125	125	127	126	125	126	126	128	127	126
	50	130	129	132	130	129	132	132	135	133	131
	75	135	135	139	136	135	139	138	142	141	138
SD	25	5.1	5.3	5.2	5.5	5.4	6.1	6.4	7.8	8.1	5.4
	50	5.2	5.4	5.1	5.4	5.7	6.7	6.5	9.3	8.6	5.9
	75	5.0	5.9	6.2	5.5	7.2	9.0	6.9	9.4	8.9	6.4

* Percent of corn acreage at or beyond planted.

Table A6. Dates (days from 1 January) of corn maturity in Iowa.

Year	PCT*	NW	NC	NE	WC	C	EC	SW	SC	SE	AVE
		Crop Reporting District									
1970	25	239	243	247	247	246	242	245	241	245	244
	50	247	250	251	251	250	250	250	248	250	250
	75	254	257	256	257	257	257	257	257	255	256
1971	25	246	244	242	244	234	232	245	239	238	240
	50	253	254	254	252	251	252	252	251	247	252
	75	258	262	261	259	258	259	260	259	259	259
1972	25	251	255	252	253	249	253	251	253	252	252
	50	258	261	259	259	259	261	257	260	259	259
	75	265	267	268	268	268	269	265	268	267	267
1973	25	246	253	252	251	255	254	248	254	253	252
	50	258	259	258	257	263	262	258	262	265	260
	75	265	265	268	265	270	272	267	270	272	268
1974	25	243	252	256	249	247	256	248	257	251	251
	50	257	260	266	259	261	268	257	268	262	262
	75	268	273	275	268	269	280	270	277	272	272
1975	25	243	247	243	243	247	238	239	243	243	243
	50	252	254	252	251	253	246	247	251	250	251
	75	262	262	261	258	261	255	255	259	258	259
1976	25	235	236	244	235	234	237	245	233	243	238
	50	242	245	250	244	243	247	251	246	251	247
	75	248	254	256	253	252	257	258	259	261	255
1977	25	231	234	237	231	237	235	233	241	240	235
	50	240	243	246	242	247	247	244	251	250	246
	75	251	253	256	253	256	258	264	265	260	257
1978	25	250	245	247	247	246	248	248	251	251	248
	50	256	250	256	254	251	254	258	262	261	256
	75	261	259	263	262	260	261	264	269	265	263
1979	25	258	253	258	255	253	252	252	256	257	255
	50	264	259	263	261	259	260	260	264	262	261
	75	270	268	269	267	264	267	267	270	268	268
1980	25	249	251	250	250	252	247	247	250	250	250
	50	256	261	260	259	260	258	255	260	258	259
	75	266	268	267	265	265	265	264	263	265	265
MEAN	25	245	247	248	246	245	245	246	247	248	246
	50	253	254	256	254	254	255	254	257	256	255
	75	261	263	264	261	262	264	263	265	264	263
SD	25	7.7	7.0	6.3	7.4	7.4	8.5	5.4	8.0	6.0	6.6
	50	7.3	6.5	6.0	6.3	6.5	7.3	5.1	7.4	6.4	5.8
	75	7.2	6.3	6.3	5.7	5.9	7.8	4.7	6.3	5.7	5.7

* Percent of corn acreage at or beyond maturity.

Table A5. Dates (days from 1 January) of corn silking in Iowa.

Year	PCT*	NW	NC	NE	WC	C	EC	SW	SC	SE	AVE
		Crop Reporting District									
1970	25	195	196	197	193	192	193	191	193	192	194
	50	200	202	204	200	198	200	197	198	199	200
	75	207	208	210	208	205	209	206	207	207	207
1971	25	196	196	199	195	193	193	195	194	193	195
	50	202	202	205	202	199	200	200	200	199	201
	75	208	208	211	209	205	208	209	207	207	208
1972	25	200	200	203	199	197	201	197	201	198	200
	50	206	206	208	205	204	208	204	207	206	206
	75	210	210	215	210	210	217	210	211	214	212
1973	25	195	197	200	196	199	203	198	202	204	199
	50	202	204	207	203	206	210	207	208	210	206
	75	208	211	217	209	212	221	214	217	228	215
1974	25	198	199	203	194	196	203	190	188	196	196
	50	205	206	210	203	205	210	204	205	205	206
	75	211	213	219	210	212	221	221	226	215	216
1975	25	203	204	202	197	197	197	196	196	194	198
	50	208	208	207	203	203	202	203	202	201	204
	75	214	213	213	210	210	209	211	211	207	211
1976	25	197	197	197	195	196	196	196	196	195	196
	50	199	199	201	198	199	199	199	199	199	199
	75	201	202	210	202	203	204	202	204	207	204
1977	25	185	186	185	185	186	186	185	187	187	186
	50	190	190	190	190	191	191	192	195	193	191
	75	197	196	198	199	199	198	199	201	199	198
1978	25	200	199	202	200	196	202	203	205	205	201
	50	204	204	206	204	201	206	207	209	208	205
	75	208	208	210	209	207	210	211	215	213	210
1979	25	206	206	207	205	202	203	204	205	204	205
	50	212	211	211	209	207	207	210	212	208	210
	75	215	216	216	214	212	212	215	217	213	214
1980	25	198	198	200	198	195	197	198	198	196	198
	50	201	201	204	202	199	201	203	202	200	201
	75	206	206	208	210	205	207	210	208	206	207
MEAN	25	198	198	200	196	195	198	196	197	197	197
	50	203	203	205	202	201	203	202	203	203	203
	75	208	208	212	208	207	211	210	211	211	209
SD	25	5.4	5.1	5.6	5.0	4.1	5.5	5.5	6.1	5.6	4.8
	50	5.6	5.5	5.7	4.8	4.6	5.8	5.1	5.3	5.2	5.1
	75	5.2	5.6	5.7	4.1	4.3	7.0	6.0	7.1	7.4	5.3

* Percent of corn acreage at or beyond silking.