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A Simple Phenological Model of Muskmelon Development

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Utilizing information gathered in previous growth chamber and field experiments, we developed a simple temperature-driven crop phenology model of muskmelon (*Cucumis melo* L.) to help commercial growers time crop phenological events and predict harvest dates. The model quantifies vegetative development in terms of main vine node numbers which allows the model to simulate either a direct-seeded or a transplanted crop. The model operates on an hourly time-step but requires only daily weather data and a few cultivar-specific parameters including plastochron interval and thermal time requirements to reach six predefined developmental stages. The model was tested against an independent data set consisting of three muskmelon cultivars grown at five transplanting dates. Tests of the model indicate an average ability to predict main vine node numbers to within one to two nodes of observed values. Estimated harvest date predictions were more variable than those for main vine node number but an average model accuracy of 1 to 3 d was obtained in model tests with a data set used to construct the model. Procedures for calibrating the model for different cultivars, cultural practices or environments are outlined.

Key words: *Cucumis melo* L., cantaloupe, temperature, model, thermal time, plastochron interval, growth duration.

INTRODUCTION

The complexity and detail involved in currently available crop simulation models spans a considerable range, from very statistical type regression models (Ravelo and Decker, 1981) to highly detailed physiological models that explicitly simulate processes such as photosynthesis and respiration (Baker *et al.*, 1983; Acock and Trent, 1991; Boote and Pickering, 1994). Even in process-level crop simulation models, sub-models of crop development are very important, partly because correctly partitioning assimilates among various organs of a plant is critical to predicting growth, and phenological development provides an inventory of leaves intercepting light and plant organs available to receive assimilates.

Harvest timing or seasonality of many vegetable crops, including muskmelon, plays a major role in determining produce prices in the marketplace (Tronstad, 1995). Commercial growers must also schedule labour for harvest and arrange transportation of the produce to market. Harvest date predictions based on chronological time often fail due to unseasonable weather. Temperature is a major determinant of crop phenological development. Since the early work of Boswell (1929) on peas, numerous studies have utilized thermal unit models to time phenological development of crops. Although Wang (1960) criticized equations relating growth to thermal units as being empirical and having no theoretical basis, Bauer *et al.* (1984) pointed out that thermal unit systems are still being used because they are equal or superior to other energy summation methods and are easily derived from air temperatures routinely measured by weather stations.

The objectives of this paper are: (1) to utilize results from growth chamber and field studies on muskmelon (Baker and Reddy, 2001) to develop a simple temperature-driven muskmelon phenology model for use by growers to quantify crop developmental stage and predict harvest dates; (2) to test this model against an independent data set from a field trial with five planting dates and three cultivars of muskmelon; and (3) to describe how this model can be calibrated for different cultivars, cultural practices or environments.

MATERIALS AND METHODS

The phenological model for muskmelon management (MelonMan v. 1.0) consists of four main components: a graphical user interface (GUICS; Acock *et al.*, 1999); a main program that handles input and output files; a weather subroutine that generates hourly air temperatures from daily weather data; and a phenology subroutine that sums hourly accumulated thermal units (Baker and Reddy, 2001), tracks main vine node numbers and calculates crop developmental stage. The graphical user interface provides a user-friendly environment for assembling input data sets into various scenarios and allows viewing of the results of a simulation in graphic, tabular and text forms. Inputs to the model are a weather data file consisting of the date, maximum and minimum daily air temperatures (°C) and total daily solar

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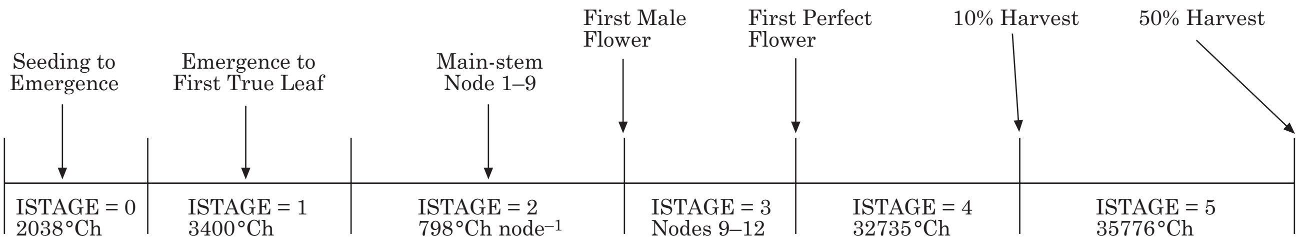

FIG. 1. Time line of six muskmelon developmental stages (ISTAGE) simulated by the model. Default values for plastochron interval and ΣTu were determined from experiments conducted in the field and controlled environment chambers for the muskmelon cultivar 'Gold Rush'.

radiation (MJ m^{-2}), and a field file that contains planting date, planting method (either direct seeded or transplanted), and cultivar-specific parameters including the plastochron interval (PI) and the thermal time required to reach each of six developmental stages (ISTAGE, Fig. 1). Also shown in Fig. 1 are default values for the cultivar 'Gold Rush' determined from growth chamber and field experiments. To simulate a transplanted crop, the number of main vine nodes on the transplants is also required as an input in the field file. On the day of transplanting, the model uses PI and the number of main vine nodes on the transplant to back-calculate how many hourly thermal units (Tu) would have been accumulated had the crop been direct seeded and begins the simulation at that point. This feature allows the user to simulate development of not only transplanted and direct-seeded crops but also to compare the effects of using transplants of different ages.

Weather subroutine

Hourly air temperatures provide a more precise measure of the thermal environment to which a crop is exposed than daily maximum and minimum air temperatures (Soltani *et al*., 1995). However, many weather stations record only daily maximum and minimum air temperatures and solar radiation. To generate hourly air temperatures for these weather data sets, the modular WEATHER subroutine from the GLYCIM soybean model (Acock and Trent, 1991) was adapted for the cantaloupe phenology model. The WEATHER subroutine uses standard meteorological data and celestial geometry to calculate, among other things, daylength, effective photoperiod for soybean, cloud cover and hourly air temperatures. Here, in this adapted version, inputs to this subroutine include latitude, day of year, daily values of maximum and minimum air temperatures and total solar radiation. This subroutine then generates hourly air temperatures for each day. Daily minimum air temperature is assumed to occur at dawn and hourly air temperatures during the day are approximated by a half sine wave. At night, air temperature is assumed to fall logarithmically.

Model tests

To provide independent data sets to test the model, a field experiment was conducted at Uvalde, TX, USA in 1998. Three cantaloupe cultivars, 'Explorer', 'Gold Rush' and 'Mission' were grown in polystyrene trays (35 × 68 cm) with inverted pyramid cells of 3·2 × 4·6 cm (square side length × depth) and 128 cells per tray. Prior to seeding, a plastic insert was placed in each tray to facilitate plant pulling. Seeds were sown in a Speedling tobacco peat-lite mix (Speedling Inc., Sun City, FL, USA) at seven planting dates (hereafter referred to as PD1–PD7): 4 March, 18 March, 1 April, 15 April, 29 April, 13 May and 27 May. After seeding, seeds were covered with 5 ml vermiculite grade 2-3-4 (W.R. Grace & Co., Cambridge, MA, USA). Trays were held in a dark room at 23 ± 2 °C for 1 d, and then transferred to a greenhouse at 18/32 °C, min/max. After seedling emergence, plants were irrigated by an ebb-and-flow system twice a week, and a soluble fertilizer was applied weekly by ebb-and-flow for 5 weeks to provide N-P-K at 50, 12 and 40 mg l^{-1}, respectively. One day prior to field transplanting, seedlings were soaked for 15 min in a soluble blended fertilizer containing 200, 350 and 200 mg l^{-1} of N, P and K respectively.

The experiment was established at the Texas A&M Agricultural Research and Extension Center, Uvalde, TX, USA. Transplants were set in the field on 14 April (PD1 and PD2), 22 April (PD3), 18 May (PD4), 27 May (PD5), 18 June (PD6) and 6 July (PD7). Soil was a Uvalde silty clay loam (fine-silty, mixed, hyperthermic Aridic Calciustoll), pH 7·7, organic matter 2·3 %, with a textural analysis of 9 % sand, 55 % clay and 36 % silt. Elemental soil analysis before planting indicated adequate levels of macro- and micro-nutrients. The experiment was arranged in a split-plot design with four replications. Planting date constituted the main plot and cultivar the sub-plot. Plants in each sub-plot were grown in 15 m single raised beds covered with black polyethylene mulch (0·038 mm thick) on 1·92 m centres with one row per bed and 0·3 m within row spacing. A buried drip irrigation system with drip tape positioned at a depth of 10 cm was used. Preplant fertilizer (kg ha^{-1}; 45N-45P-45K) was broadcasted and incorporated into the soil. Additional fertilizer (kg ha^{-1}; 10N-5P-13K) was applied weekly for 9 weeks using KNO_3 and H_3PO_4 as sources of N, P and K, respectively.

Two plants per plot were tagged at transplanting and the number of nodes on the main vines was counted sequentially as described by Baker and Reddy (2001). Measurements were made between 22 April and 26 June, 4 May and 26 June, 25 May and 14 July, 6 June and 16 July, 25 June and 3 August and 14 July and 3 August 1998 for the first to the seventh transplanting dates, respectively.

Mature and marketable fruits were harvested twice in the first and second plantings on 26 June and 2 July. The third

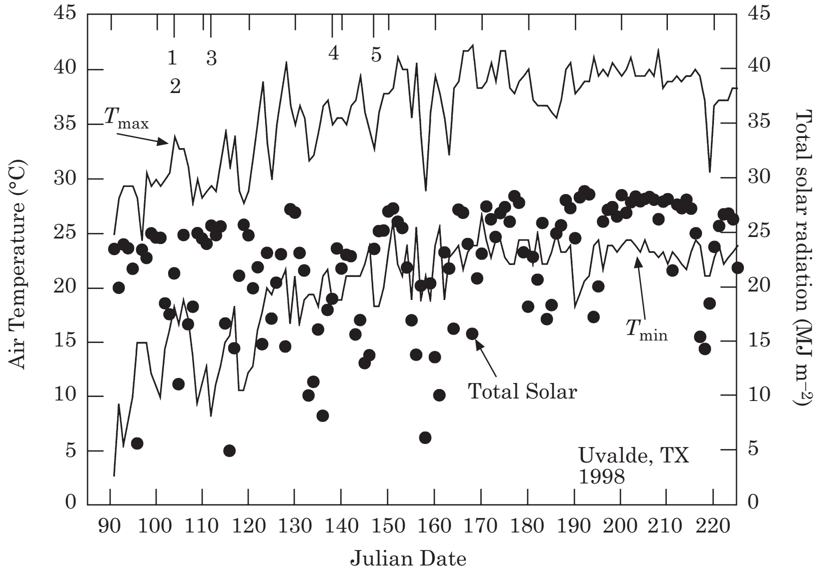

FIG. 2. Weather data from Uvalde, TX, USA used to test the model. T_{max} and T_{min} are daily maximum and minimum air temperatures, respectively. Closed symbols are daily total solar radiation. Transplanting dates for the six plantings are indicated on the upper *x*-axis. Transplanting dates 1 and 2 were seeded in the greenhouse on 4 and 18 March, respectively.

transplanting was harvested once on 2 July and the fourth and fifth transplantings were both harvested on 27 July. Due to excess rainfall combined with high temperatures during mid–late June, fruits from the sixth and seventh transplantings were unmarketable due to lack of full development and maturity.

Air temperature and solar radiation data were collected in the field at 15 min intervals over the growing season. To test the model, these data were averaged to generate the season-long daily weather input file (Fig. 2). Also, cultivar-specific averages for plastochron interval and accumulated hourly thermal time for the different developmental stages (Fig. 1) obtained from a field experiment conducted at Overton, TX, USA (Baker and Reddy, 2001) were applied to the field files to test the model with the daily weather data from Uvalde.

The model was evaluated by regressing predicted *vs.* observed values. In cases where these regression models were significant ($P < 0{\cdot}05$), *t*-tests were conducted to determine whether the slope and intercepts were significantly different from 1·0 and 0·0, respectively (Steel *et al.*, 1997). Good statistical agreement between observed and predicted values was inferred when the regression *F*-value was significant, slope and intercept were not significantly different from 1·0 and 0·0, respectively and the regression yielded a high coefficient of determination (R^2). Bias and regression root mean square error (RMSE) were calculated to determine overall model performance (Willmott, 1982):

$$\text{Bias} = 1/N \sum_{i=1}^{N} (S_i - O_i) \qquad (1)$$

$$\text{RMSE} = \left(1/N \sum_{i=1}^{N} (S_i - O_i)^2\right)^{1/2} \qquad (2)$$

where S and O are the simulated and observed values for the ith observation and N is the total number of observations.

RESULTS AND DISCUSSION

Hourly air temperatures

An example of observed and simulated hourly air temperatures for a 10 d period from the experiment at Overton, USA is shown in Fig. 3. As noted previously, the model generates hourly air temperatures using observed maximum and minimum air temperatures, total solar radiation, latitude and day of year (Acock and Trent, 1991). In most cases, the model performed well in simulating hourly air temperatures. Deviations of the model from observed values were largely associated with inaccuracies in predicting the time of day when minimum and maximum air temperatures occurred. For example, the model assumes that the minimum daily air temperature occurs at dawn and does not account for events such as rain or the passage of warm or cold fronts that may alter this timing. The regression of predicted *vs.* observed hourly air temperatures from the Overton experiment are shown in Fig. 4. Here, the calculated *F*-statistic was significant. The *t*-tests indicated that the intercept was not significantly different from 0 while the hypothesis that the slope was 1 was rejected at $P \leqslant 0{\cdot}05$. Although the bias estimate [eqn (1)] indicated an average tendency to under-estimate air temperature by about 0·74 °C over the growing season, we decided that this was sufficiently accurate for our purposes since most of the inaccuracies would average out over the time scales (days to weeks) used in model predictions. Furthermore, our goal was to develop an easy-to-use model for commercial growers and requiring hourly as opposed to daily weather data would impose a major obstacle in many situations.

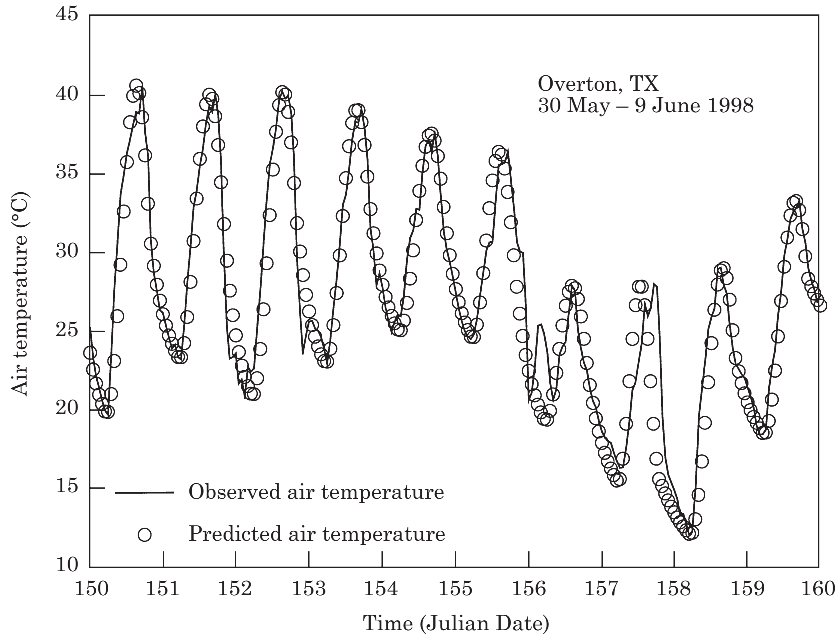

FIG. 3. Time trends in observed *vs.* predicted hourly air temperatures for a 10 d period at Overton, TX, USA.

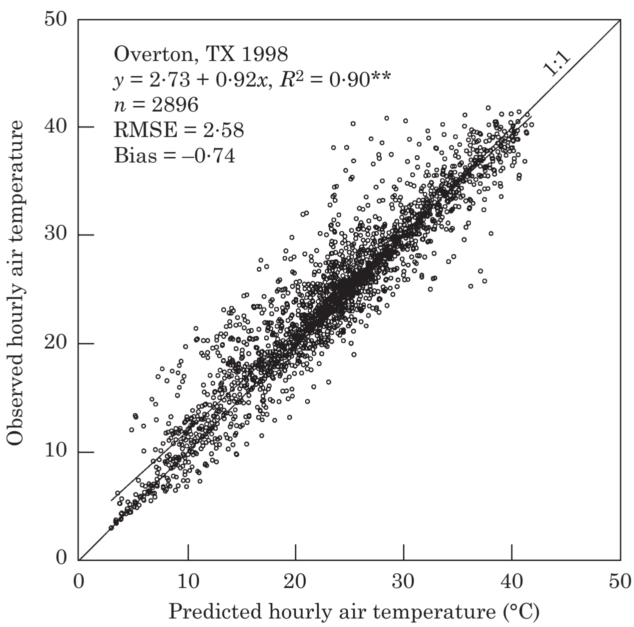

FIG. 4. Predicted *vs.* observed hourly air temperatures over the growing season at Overton, TX, USA. R^2 was significant at $P < 0{\cdot}01$.

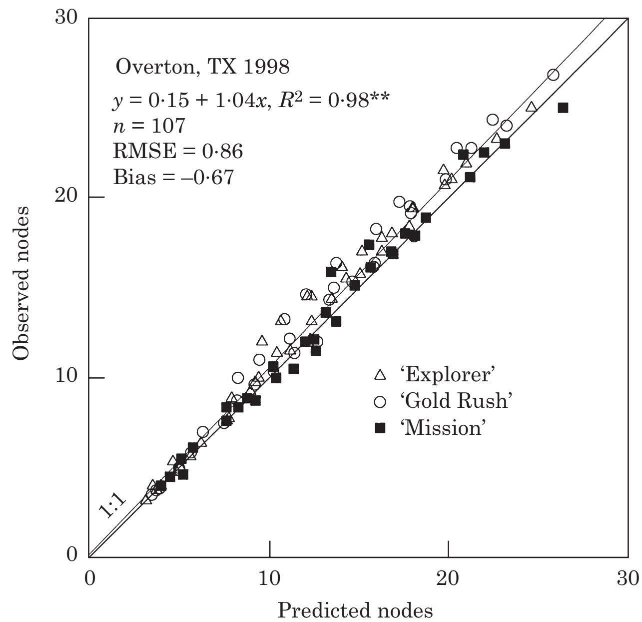

FIG. 5. Predicted *vs.* observed main vine node numbers for the Overton, TX, USA data set used to construct the model.

Main vine node numbers

Using both the predicted hourly air temperatures and the cultivar-specific averages for plastochron interval determined at Overton, a good agreement between predicted and observed main vine node numbers was obtained (Fig. 5). Once again, the calculated *F*-statistic for the regression was significant and *t*-tests indicated that the intercept was not significantly different from 0 while the hypothesis that the slope was 1 was rejected at $P \leqslant 0{\cdot}05$. The bias estimate of $-0{\cdot}67$ nodes indicates an overall tendency of the model to under-estimate main vine node numbers by less than one node over the growing season. Although Fig. 5 does not represent a test of the model against a completely independent data set, it does lend support for the use of the average plastochron intervals determined in the Overton experiment and simulated hourly air temperatures to predict main vine node numbers for these three muskmelon cultivars.

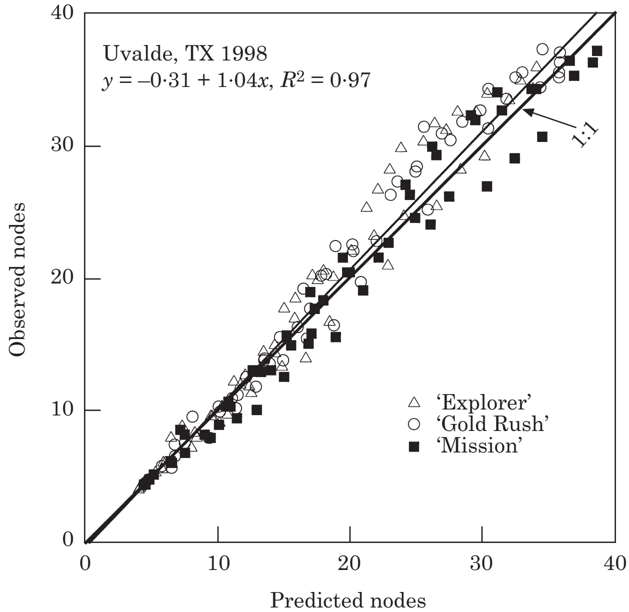

FIG. 6. Predicted *vs*. observed main vine node numbers for the Uvalde, TX, USA data set used to test the model.

Model tests of predicted *vs*. observed main vine nodes using the completely independent data set from Uvalde also agreed well (Fig. 6). A complete breakdown of model tests by cultivar and planting date is shown in Table 1. In all cases the coefficient of determination was high and calculated *F*-statistics were significant. The model performed best for the cultivar 'Mission' with slope and intercept not significantly different from 1 and 0, respectively, while both hypotheses were rejected for the cultivars 'Explorer' and 'Gold Rush'. Bias and RMSE values indicated an average ability of the model to predict main vine node numbers to within about one to two nodes (Table 1). Among transplanting dates, the model performed well with slopes and intercepts not significantly different from 1 and 0, respectively, except for the 18 May transplanting date. Once again, across transplanting dates, bias and RMSE calculations indicated an average ability of the model to predict main vine node numbers to within about one to two nodes (Table 1).

Harvest date prediction

Comparison of predicted *vs*. observed dates for 10 and 50 % harvest for the Overton data set are shown in Fig. 7. Here, predicted hourly air temperatures were used as well as the previously determined cultivar-specific average thermal time to 10 and 50 % harvest. In the Overton experiment, although thermal time was shown to be far superior to chronological time in predicting harvest dates, thermal time requirements to 10 and 50 % harvest were longer for early than later transplanting dates. This was attributed to either a differential heating effect of sunlight on the plastic mulch surface or possibly a previously unreported photoperiod effect on muskmelon phenology. Using average thermal time to harvest generally resulted in under-prediction of harvest dates for the first transplanting and over-prediction of harvest dates for the last transplanting date (Fig. 7). Overall, RMSE and bias estimates indicate an average model accuracy of 1 to 3 d in estimating harvest dates.

Because the Uvalde experiment was harvested only once or twice at each transplanting date, it was not possible to determine the actual dates in terms of days after planting for 10 and 50 % harvest. To compare the model predictions with observed harvest dates for the Uvalde data set we used thermal time summations for 10 and 50 % harvest predictions to extrapolate to a 100 % harvest date (Table 2). Somewhat similar to the Overton experiment, the model predictions of 100 % harvest dates for the Uvalde experiment appeared to be early for the first two transplanting dates, but generally within 2 to 3 d for the last three transplanting dates. Further experimental work is needed to

TABLE 1. *Statistics for the regression* ($y = b_1x + b_0$) *of predicted* (y) vs. *observed* (x) *main vine nodes for three muskmelon cultivars and five transplanting dates*

	$b_1 \pm$ s.e.	$b_0 \pm$ s.e.	n	R^2	RMSE	Bias
Overall	1·04 ± 0·015**	−0·31 ± 0·311**	173	0·97	1·88	−0·55
Cultivar						
'Explorer'	1·09 ± 0·026**	−0·53 ± 0·523	58	0·97	1·82	−1·05
'Gold Rush'	1·08 ± 0·021**	−0·63 ± 0·464	57	0·98	1·57	−0·94
'Mission'	0·99 ± 0·022	−0·19 ± 0·498	58	0·97	1·74	0·34
Transplanting date						
14 April†	1·02 ± 0·027	0·92 ± 0·668	44	0·97	1·86	−1·27
14 April‡	1·02 ± 0·025	1·18 ± 0·598	45	0··98	1·75	−1·71
22 April	1·00 ± 0·029	0·15 ± 0·620	39	0·97	1·73	−0·21
18 May	0·91 ± 0·021**	−0·08 ± 0·320	27	0·99	0·70	1·28
27 May	1·03 ± 0·056	−1·01 ± 0·789	18	0·95	1·11	0·63

Data are from Uvalde, TX, USA, 1998. Greenhouse seeding dates were 4 and 18 March, 1, 15 and 29 April for transplanting dates 1 to 5, respectively and transplanting dates were 14, 14 and 22 April, and 18 and 27 May 1998 for transplanting dates 1 to 5, respectively.

* 0·05 and ** 0·01 levels of significance of the t-statistic for testing the hypothesis: $H_o: b_1 = 1{\cdot}0$ *vs*. $H_a: b_1 \neq 1{\cdot}0$ and the hypothesis: $H_o: b_0 = 0{\cdot}0$ *vs*. $H_a: b_0 \neq 0{\cdot}0$.

† Seeded in the greenhouse on 4 Mar. 1998.

‡ Seeded in the greenhouse on 18 Mar. 1998.

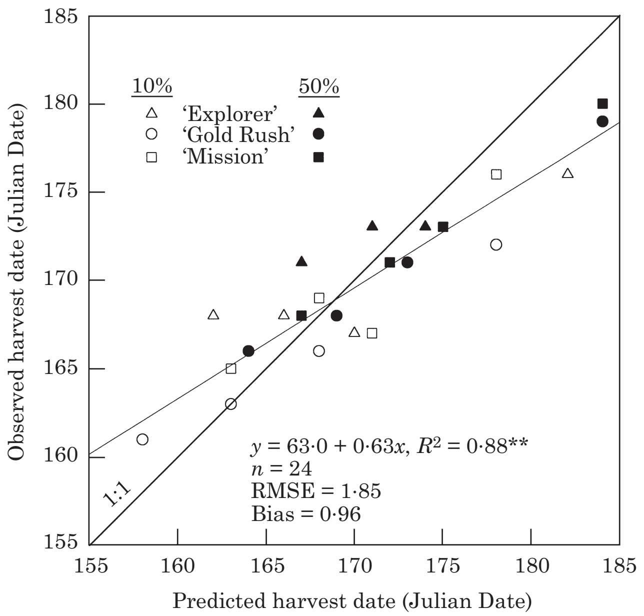

FIG. 7. Predicted *vs*. observed 10 (open symbols) and 50 % (closed symbols) harvest dates for the Overton, TX, USA data set. The slope of the equation and R^2 were significant at $P < 0{\cdot}01$.

develop independent data sets for a more complete validation of the harvest date predictions for these three cultivars of muskmelon.

Model calibration

The structure of the model is simple enough to allow relatively easy recalibration for different cultivars or cultural techniques in a single growing season. This involves the collection of a daily weather data set and estimation of the plastochron interval and thermal time requirements for the various growth stages shown in Fig. 1. Plastochron interval can be estimated by tagging a few plants of a particular cultivar and counting main vine nodes several times during the growing season. The model can then be run with default values to generate accumulated hourly thermal units (ΣTu) for each day of the growing season. PI can then be calculated as the reciprocal of the slope of the linear regression of main vine node number *vs*. ΣTu. Similarily, ΣTu required for each growth stage can be estimated from visual observations of the crop and repeated harvests at the end of the growing season.

Once calibrated, the model could be applied to a number of situations. For example, an historical weather file based on the average of several or many years of weather data for a particular location could be used to examine the effects of cultivar, planting date or planting method (direct seeded *vs*. transplant) on projected harvest date. The GUICS interface also allows the user to run the model with actual weather data to any point in the growing season and then resume the simulation with a projected weather data set. The projected weather data could be an historical weather file for that location or an unusually warm or cool year depending on what long-range weather forecasts currently predict. This allows a commercial grower to make mid-season harvest date projections based on expected or past weather trends.

CONCLUSIONS

Based on our previous experiments in growth chambers and the field, we constructed a simple muskmelon phenology

TABLE 2. *Comparison of simulated 10, 50 and 100 % harvest (days after planting) with actual harvest for three muskmelon cultivars and five transplanting dates*

Cultivar	Transplanting Date	Simulated Harvest, Julian Date 10 %	50 %	100 %	Actual Harvest
'Explorer'	14 April†	165	169	175	177, 183
	14 April‡	166	171	176	177, 183
	22 April	175	179	185	183
	18 May	193	198	205	207
	27 May	200	205	210	207
ΣTu (°C h $\times 1000^{-1}$)		34·676	37·400	40·802	
'Gold Rush'	14 April†	165	169	173	177, 183
	14 April‡	163	168	175	177, 183
	22 April	170	176	182	183
	18 May	189	195	201	207
	27 May	195	200	207	207
ΣTu (°C h $\times 1000^{-1}$)		32·624	35·669	39·475	
'Mission'	14 April†	165	169	177	177, 183
	14 April‡	166	170	177	177, 183
	22 April	175	178	186	183
	18 May	193	198	205	207
	27 May	199	203	210	207
ΣTu (°C h $\times 1000^{-1}$)		34·699	37·646	41·330	

Data are from Uvalde, TX, USA, 1998. ΣTu was adjusted for the number of nodes present on plants at transplanting.
† Seeded in the greenhouse on 4 Mar. 1998.
‡ Seeded in the greenhouse on 18 Mar. 1998.

model for use by commercial growers. We used the main vine node number and plastochron interval concepts to quantify relative differences in transplants of differing ages or differences in phenological age between a transplanted *vs*. a direct-seeded muskmelon crop. The model operates on an hourly time-step but requires only daily weather data and a few cultivar-specific parameters. We tested the model with an independent data set from Uvalde, TX, USA. We found that the ΣTu calculated from simulated hourly air temperatures was sufficiently accurate to estimate main vine node numbers to within one to two nodes through the growing season. Average model accuracy in predicting harvest dates ranged between 1 to 3 d for the data set used to construct the model. Although the model was sufficiently accurate in predicting main vine nodes, further testing is needed to fully validate the harvest date predictions.

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