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Temperature Effects on Phenological Development and Yield of Muskmelon

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Our goal was to construct a simple muskmelon phenology model that could be run with easily obtainable weather station data and used by growers to quantify phenological development and aid in projecting harvest dates. A growth chamber experiment was conducted with two cultivars of muskmelon ('Gold Rush' and 'Mission') to determine how main vine leaf appearance rates responded to temperature. We identified three cardinal temperatures for leaf appearance rate: the base temperature (10 °C) at which leaf appearance rate was zero; an optimum temperature (34 °C) at which the rate of leaf appearance was maximal; and an upper threshold temperature (45 °C) at which leaf appearance rate returned to zero. Using these three cardinal temperatures, we constructed a simplified thermal unit accumulator for hourly measurements of air temperature. Main vine plastochron interval (PI), thermal time to harvest, and final yield were determined for three cultivars of muskmelon ('Explorer', 'Gold Rush' and 'Mission') grown in the field at Overton, TX, USA, over six transplanting dates from March to June 1998. PI was calculated for each cultivar × transplanting date combination as the reciprocal of the slope of main vine node number *vs.* accumulated hourly thermal units (ΣTu). PI was significantly affected by both cultivar and transplanting date. Final yield was sharply reduced in the last two planting dates, presumably due to high temperature stresses impairing reproductive development. As air temperatures increased during the field experiment, the time interval from transplanting to 10 % final harvest was reduced by 21 to 28 d among the three cultivars and the first four transplanting dates. Main vine node number was a useful descriptor of vegetative development for muskmelon.

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

INTRODUCTION

It is often difficult for commercial growers of many important horticultural crops to select planting dates that result in desired harvest date windows; this is due mainly to temperature differences among growing seasons. Temperature is a major environmental variable influencing crop development. Various forms of temperature summations, commonly referred to as thermal units or growing degree days, have been utilized in numerous studies to predict phenological events for both agronomic and horticultural crops. Daily thermal units (Tu) are calculated most simply as:

$$\mathrm{Tu} = [(T_{\max} + T_{\min})/2] - T_b$$

where $T_{\max}$ and $T_{\min}$ are maximum and minimum daily air temperatures and T_b is the base temperature below which development ceases. Accumulated thermal units (ΣTu) are then summed over the time period of interest. As noted by Ritchie and NeSmith (1991), this approach is valid for predicting phenological events only as long as the following conditions are met: (1) developmental rate is linear over the temperature range experienced; (2) daily temperatures do not fall below T_b or rise above an upper temperature threshold (T_{opt}) for a significant portion of the day; and (3) the average daily temperature of both the air and growing point of the plant are the same. One or more of these conditions are often violated in the field, hence, a number of adjustments or modifications to the Tu equation have been used. Both Wolfe *et al.* (1989) and Jenni *et al.* (1996) incorporated adjustment factors to their temperature summations to account for declining plant responses above T_{opt}.

Accurate determination of T_b is necessary for results of experiments using thermal units to be applied elsewhere (Wang, 1960). This is also true for T_{opt} especially in situations where temperatures exceed T_{opt} and development then declines. Since the developmental rate is often linear above T_b and below T_{opt}, T_b can be estimated by extrapolation of development rate to the temperature axis where the rate is zero (Gallagher, 1979; Baker and Gallagher, 1983; Baker *et al.*, 1986; Jenni *et al.*, 1996). A more empirical method of estimating both T_b and T_{opt} is to calculate thermal units using a range of T_b and T_{opt} values and selecting the method that minimizes the coefficient of variation (c.v.) or maximizes the correlation of the regression of development *vs.* ΣTu (Wolfe *et al.*, 1989; Jenni *et al.*, 1996). Here, the selected values of T_b and T_{opt} could be influenced by specification of the initial search grid for T_b and T_{opt}, as well as the temperature ranges experienced in a given experiment.

In some situations, an additional complication in the study of temperature *vs.* development rate is warming of the crop microclimate caused by the use of mulches and/or rowcovers (Bonanno and Lamont, 1987; Maiero *et al.*, 1987; Albright *et al.*, 1989). Furthermore, the degree to which a particular mulch alters crop microclimate depends

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on mulch colour and optical properties (Ham *et al*., 1993; Soltani *et al*., 1995; Schmidt and Worthington, 1998). Finally, the degree to which a mulch alters the crop microclimate will probably be moderated as the developing crop canopy progressively shades more of the mulched bed (Ham *et al*., 1993).

Another factor influencing harvest date for some horticultural crops, such as watermelon and muskmelon, is whether the crop is direct seeded or transplanted. In the case of a transplanted crop, the transplants are phenologically further advanced when they are placed in the field compared to a direct-seeded crop and, as a result, usually mature earlier. Furthermore, the age of the transplants can vary among growing seasons or due to different greenhouse seeding dates. To account for these kinds of differences in phenological age, we adapt concepts developed for agronomic crops and apply them to muskmelon.

The importance of leaf area of a crop in terms of light interception, growth and yield has long been recognized. In addition to individual leaf size, an important determinant of crop leaf area is the rate at which leaves appear on a tiller (e.g. wheat or rice), branch (e.g. soybean or cotton) or vine (e.g. watermelon or muskmelon). In all these examples, auxillary buds are formed in the axes of leaves and so the potential maximum rate of side branching is determined by the rate at which leaves appear on a parent shoot or vine.

In soybean, vegetative or V-stages are quantified independently of reproductive development by counting the number of main stem nodes (Fehr and Caviness, 1977). A similar system is used in small grain cereals using the Haun scale (Haun, 1973; Klepper *et al*., 1982) in which vegetative development is quantified by the number of leaves on the main culm. In monocots such as wheat, leaves are numbered acropetally with the coleoptile of the main stem or prophyll of a tiller being designated as 0 and the first, second and third foliar or true leaves being designated as 1, 2 and 3, respectively. Similarly, in dicots such as soybean, the cotyledonary node is designated as 0 and the remaining nodes are numbered sequentially as they appear. The time interval between initiation of successive main stem nodes of dicots is referred to as the plastochron interval, while the time interval between the appearance of successive leaves in monocots is referred to as a phyllochron interval. For a moderate range of temperatures, both the plastochron and the phyllochron interval have been shown to be constant for a given cultivar under constant temperatures in growth chamber experiments, and vegetative stage was linearly related to temperature summations in the field for both soybean (Hesketh *et al*., 1973; Sinclair, 1984) and wheat (Klepper *et al*., 1982; Cao and Moss, 1989).

We suggest that a simple way of quantifying the phenological stage of a muskmelon transplant is by counting the number of main vine nodes on the transplants. This information, coupled with a knowledge of a particular cultivar's rate of node addition or plastochron interval, should make it possible to quantify relative differences in phenological development for transplants of differing ages or even transplanted *vs*. direct-seeded plants.

Our goal was to develop a temperature summation model for muskmelon development that could utilize routinely collected weather data commonly available to growers. First, we describe a controlled environment experiment that was used to estimate three cardinal temperatures: T_b, T_{opt} and a critical upper temperature threshold beyond which development ceases, T_c, for two cultivars of muskmelon. Based on these results, we then develop a simple thermal unit (Tu) accumulator that operates on average hourly temperatures. We applied our thermal unit accumulator to a field experiment where we determined the plastochron interval and ΣTu to harvest for three cultivars of muskmelon grown over six transplanting dates. In this paper we describe the experimental basis for the muskmelon phenology model. A complete description of the model along with methods for site-specific calibration and model tests against independent data sets are the topic of a subsequent paper (Baker *et al*., 2001).

MATERIALS AND METHODS

Field experiment

A field experiment was conducted in 1998 at the Texas A&M University Agricultural Research and Extension Center at Overton, Texas, USA on three cultivars of muskmelon: 'Explorer', 'Gold Rush' and 'Mission'. To obtain a range of air temperatures over the growing season, six transplanting dates were utilized: 30 March, 8 April, 21 April, 4 May, 20 May and 1 June. Seed for each transplanting date was sown in the greenhouse in flats (cell size 5·1 × 6·4 × 7·6 cm) filled with a commercial peat-vermiculite mix (Fison's No. 2, Sun Gro Horticulture, Inc., Bellview, Washington, USA) on 20 February, 5 March, 19 March, 2 April, 15 April and 1 May respectively. The experiment was arranged as a split-plot design with four replications (Gomez and Gomez, 1984). Planting date constituted the main plot and cultivar the sub-plot. The experiment was conducted on 0·9 m wide shaped beds spaced 2·4 m apart, centre to centre. Individual plots consisted of 6·1 m of bed length with 10 plants per plot spaced every 0·6 m.

Bensulide (O,O-diisopropyl S-2-benzenesulfonamino-ethyl phosphorodithioate) was incorporated on 23 March at 5·4 kg ha^{-1}. Fertilizer was band-applied over row centres at rates of 73, 31 and 60 kg ha^{-1} for N, P and K, respectively, prior to shaping the beds. The soil is a Bowie fine sandy loam (fine-loamy, siliceous thermic Plinthic Paleudult). In one operation, photodegradable black polyethylene mulch (0·038 mm thick and 1.2 m wide) and drip tape was applied. Two commercial bee hives were placed adjacent to the field plot area prior to flowering.

Two plants in each plot were tagged at transplanting. Since leaves are associated with a particular node and these leaves normally senesce as they age, hereafter we refer to node rather than leaf position or number on a vine. The number of main vine nodes on these tagged plants was counted two to three times per week through the growing season. To facilitate counting, the main vines were periodically labelled by loosely tying a length of coloured, non-adhesive, plastic tape around an internode on which the node number of the next youngest adjacent node was recorded. Nodes were counted acropetally with the cotyledonary node being node 0 and the node associated with the first true-leaf being node 1, etc. A node was considered to have appeared when its associated leaf exceeded 3 cm in length. Plastochron interval (Tu per node) was calculated as the reciprocal of the slope of the regression of main vine node number against accumulated hourly thermal units (ΣTu). Specific methods for calculating ΣTu are described below.

During harvest, the fruit in each plot to reach 'full slip', when the abscission zone between the fruit and peduncle easily separated, were counted and weighed two to three times per week. Precisely defining a harvest date for an indeterminate crop like muskmelon is difficult, and repeated harvests of a single crop are not uncommon. We selected 10 and 50 % of total harvest as the most relevant harvest dates for muskmelon producers (Ross LaGrange, Star Produce Company, Inc., Rio Grande City, TX, USA, pers. comm.). To estimate these two dates, each day's yield data were expressed as a percentage of the total final yield. Percent yield was then regressed against ΣTu using third-order polynomials and corresponding ΣTu, and dates for 10 and 50 % harvest for each cultivar and planting date were obtained by solving these regressions.

Replicated air temperature data were collected in the field at 5 min intervals over the growing season by using three copper-constantan thermocouples connected to an AM-416 multiplexer and a CR-10 datalogger (Campbell Scientific Canada, Edmonton, AL, Canada). These data were averaged over each hour at the end of the field experiment. The thermocouples were placed in white polystyrene cups to shield the sensors from direct solar radiation. Solar irradiance was measured with a pyranometer (LI-COR Model LI-200S, Lincoln, NE, USA).

Growth chamber experiment

To determine the shape of the node appearance rate *vs.* temperature response curve, a controlled temperature experiment was conducted in six lamp-lit controlled environment chambers (Environmental Growth Chambers, Inc. Chagrin Falls, OH, USA) at Beltsville, MD, USA. Four seeds of muskmelon cultivars 'Gold Rush' and 'Mission' were sown on 22 Oct. 1998 in 3·8 l plastic pots filled with Jiffy Mix (Jiffy Products, Batavia, IL, USA) consisting of sphagnum peat and medium grade vermiculite (1 : 1 by volume). The growing medium was amended with 4·5 g l^{-1} of a slow release fertilizer (Osmocote 14·0N-6·1P-11·6K, Scotts-Sierra Horticultural Products Co., Marysville, OH, USA) and 2·4 g l^{-1} dolomitic lime. Six pots per cultivar or a total of 12 pots per chamber were used.

Each chamber was illuminated with a combination of six high pressure sodium and six metal halide lamps that were arranged alternately in three rows. Photosynthetically active radiation (PAR) inside the growth chambers was maintained at 1000 ± 100 μmol (photons) m^{-2} s^{-1} at the top of the plant canopy during the experiment by adjusting a high intensity discharge dimmer. The photoperiod was set to 12 h. The air temperature during seed germination and plant emergence was maintained at a constant 30 ± 1 °C day/night. On 29 Oct., plants were thinned to one plant per pot and the following constant day/night air temperature treatments were initiated: 18, 22, 26, 30, 34 and 38 °C. Relative humidity ranged from 50 to 70 %. Temperature, light intensity and humidity were monitored and recorded by computer. Main vine node number was determined for each plant on a nearly daily basis as previously described in the field experiment. Main vine node number was averaged across all six plants of each cultivar in each chamber. Node appearance rate was calculated for each cultivar × temperature treatment combination as the slope of the regression of main vine number *vs.* days after planting (DAP).

RESULTS AND DISCUSSION

Growth chamber experiment

An example of the regression of main vine node number *vs.* DAP for three of the temperature treatments is shown in Fig. 1. These regressions fit the data well, with R^2 values exceeding 0·96 in all cultivar × temperature treatment combinations. In general, the slope of these regressions tended to increase with increasing temperature up to about 34 °C. Rate of node appearance (nodes d^{-1}) is plotted against air temperature treatments for both cultivars (Fig. 2). The response curves were used to estimate appropriate base (T_b), optimum (T_{opt}) and upper critical temperatures (T_c) to develop a simplified method for calculating appropriate hourly thermal units (Tu) for node appearance rates per day. T_b was estimated by extrapolating the regression of nodes d^{-1} *vs.* temperature treatment to the point on the *x*-axis where nodes d^{-1} reached zero using the linear section of the response curves below 34 °C. Estimates of T_b were 11·5 °C for 'Gold Rush' and 8·0 °C for 'Mission' (Fig. 2), or an average T_b of 9·7 °C which we rounded to 10 °C for convenience.

Estimates of T_{opt} and T_c were determined from third-order polynomials (Fig. 2). Estimates of T_{opt} were 34·6 and 33·3 °C for 'Gold Rush' and 'Mission', respectively, and

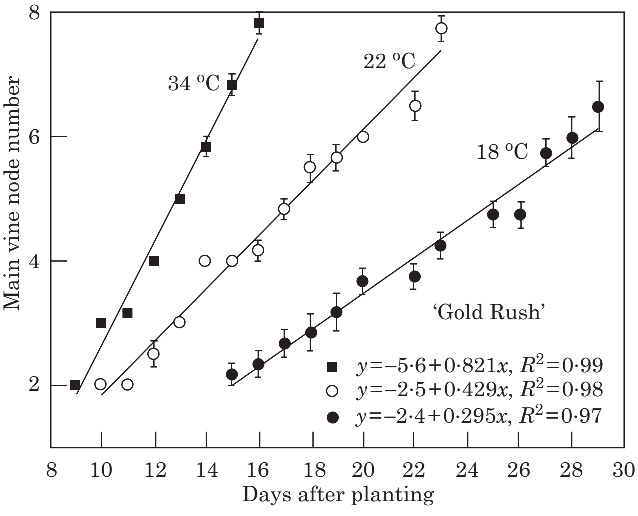

FIG. 1. Main vine node number *vs.* days after planting for the muskmelon cultivar 'Gold Rush' grown in controlled environment growth chambers at Beltsville, MD, USA. Each datum point is the mean of six plants ± s.e. In some cases symbol size is larger than ±s.e.

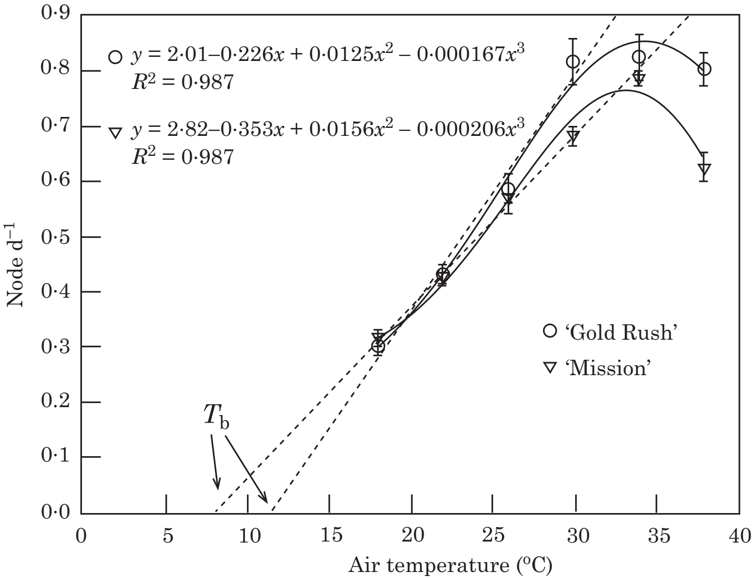

FIG. 2. Main vine node addition rate *vs.* air temperature for two muskmelon cultivars grown in controlled environment growth chambers at Beltsville, MD, USA. Each datum point is the reciprocal of the slope of the regression of main vine nodes *vs.* days after planting ±s.e.

averaged 34 °C. T_c was estimated by extrapolating the polynomials to the x-axis at high temperature (above 34 °C). Estimated T_c was 45·9 and 43·6 °C for 'Gold Rush' and 'Mission', respectively, with an average of 44·8 °C which we rounded to 45 °C.

Based on these three estimated cardinal temperatures (T_b, T_{opt} and T_c), we constructed a simplified hourly thermal unit calculator (Fig. 3). This method of calculating hourly Tu is similar to, but more simple than that used by Soltani *et al.* (1995) for watermelon. They used cardinal temperatures from previous studies of 16, 33 and 42 °C for T_b, T_{opt} and T_c respectively (Buttrose and Sedgley, 1978; Sedgley and Buttrose, 1978; Lorenz and Maynard, 1988).

The maximum muskmelon node addition rates observed in this experiment (approx. 0·7 to 0·8 nodes d^{-1}, Fig. 2) were much faster than those measured for several other C_3 crop species. Baker *et al.* (1996) measured vegetative phase phyllochron intervals for rice (*Oryza sativa*, L. 'IR-30') at about 3 to 4 d per leaf (approx. 0·3 to 0·25 leaves d^{-1}). Leaf appearance during reproductive development dropped further to between about 0·1 to 0·2 leaves d^{-1}. Reddy *et al.* (1995) reported maximum node addition rates for cotton (*Gossypium hirsutum* L.) at just over 0·4 nodes d^{-1} or about half the rate found for muskmelon in this experiment. Similarly, Baker *et al.* (1989) reported minimum plastochron intervals for soybean (*Glycine max* L.) grown at ambient atmospheric CO_2 concentrations (330 µmol mol^{-1}) of 3·2 d per trifoliate (approx. 0·3 nodes d^{-1}). Reasons for this rapid rate of vegetative development of muskmelon compared with other crop species are unknown but may be related to the decumbent growth habit of muskmelon. This decumbent growth habit should require less structural support material in the stems and may free up more of the crop's assimilated carbon for a more rapid node addition rate. Indeed, elevated atmospheric CO_2 concentration has been shown to accelerate node addition rate in some experiments (Imai *et al.*, 1985; Baker *et al.*, 1989; Cure *et al.*, 1989; Ingram *et al.*, 1995) but not in others (Baker *et al.*, 1996; Ziska *et al.*, 1997).

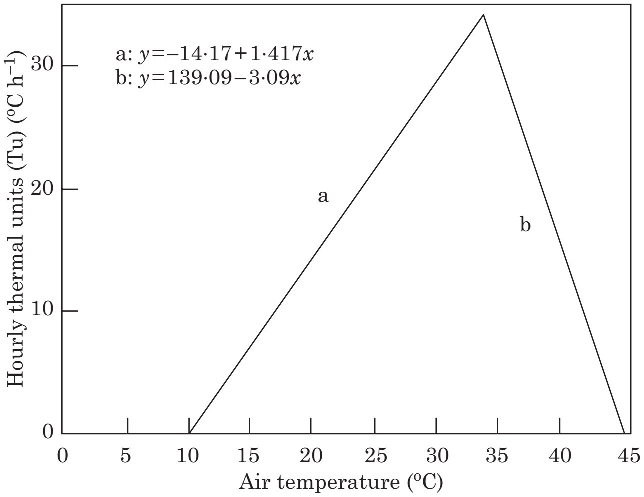

FIG. 3. Simplified model for calculating hourly thermal units as a function of air temperature. Cardinal temperatures utilized are 10, 34 and 45 °C for T_b, T_{opt} and T_c, respectively.

Field experiment

Daily maximum and minimum air temperatures as well as total solar radiation for the planting date experiment at Overton, TX, USA, were recorded during the experiment. As anticipated, the range of transplanting dates resulted in a wide range of air temperatures over the respective growing seasons, from minimum daily air temperatures below 5 °C early in the experiment, to maximum daily air temperatures exceeding 40 °C later in the experiment.

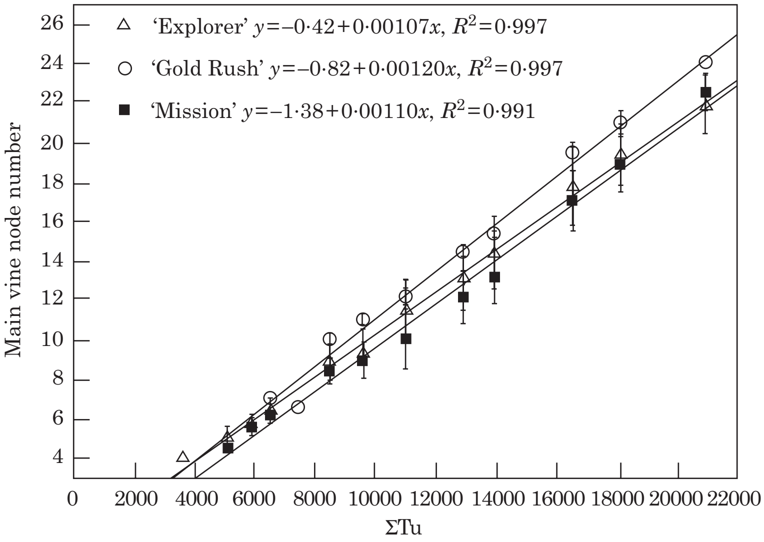

FIG. 4. Examples of the regression of main vine node number *vs*. accumulated hourly air temperature (ΣTu) for three cultivars of muskmelon in the field experiment conducted at Overton, TX, USA. Data are from the 8 Apr. 1998 transplanting date.

Examples of main vine node number *vs*. accumulated hourly thermal time are shown in Fig. 4. As with numerous other crop species, muskmelon main vine node addition was linearly related to accumulated thermal time, and a simple linear regression fits the data quite well (R^2 exceeding 0·97 in most cases; c.v. ranging from 2·0 to 7·4). The reciprocal of the slope of these regressions or plastochron intervals is shown in Table 1. The significant cultivar effect (Table 1) is not surprising and has also been found among cultivars in other crop species. For example, Baker *et al.* (1986) found that individual leaf size and phyllochron interval were related in wheat, and cultivars with small leaves generally produced leaves and tillers at a faster rate than cultivars with larger leaves.

The transplanting date effect in Table 1 is less easily explained. Here, the first and second planting dates appear to have a longer plastochron interval than later transplanting dates. If plastochron interval were solely a function of ambient air temperature, as calculated by ΣTu, one would expect plastochron interval to be unaffected by planting date. The most likely explanation for this appears to be a differential heating effect of the plastic mulch among the transplanting dates with a lower solar radiation load caused by shorter daylengths and lower solar elevation angle early in the experiment compared with later transplanting dates. Ham *et al.* (1993) found that air near a mulched surface could be 4–5 °C warmer than air measured at a height of 1.5 m. However, we calculated photothermal units (Nuttonson, 1958) (data not shown) by multiplying each day's total solar radiation by hourly Tu. The regression of main vine node numbers against accumulated photothermal units did not improve the fit or reduce the c.v. in two-thirds of the transplanting date by cultivar combinations. On the other hand, the effect of plastic mulch on heating the plants relative to air temperature would be at least partially offset by the latent heat loss of the actively transpiring crop canopy. This effect of reducing leaf temperature compared with air temperature has been shown to be a linear function of atmospheric vapour pressure deficit (Idso *et al.*, 1981; Jackson *et al.*, 1981), and crop foliage temperature of a well watered crop can easily be 4 to 10 °C below air temperature under very dry atmospheric conditions (Idso *et al.*, 1987). Precisely accounting for these types of effects would require the development of a complete mass and energy balance (Albright *et al.*, 1989; Ham *et al.*, 1991, 1993) of the crop, which was beyond the scope of this study. Furthermore, the

TABLE 1. *Plastochron interval (PI)† for three cultivars of muskmelon and the effects of planting date (PDATE) and cultivar (CULT) on PI*

	PI		
Planting date	'Explorer' (°C h per node)	'Gold Rush' (°C h per node)	'Mission' (°C h per node)
30 March	1023·2	860·5	948·1
8 April	932·6	836·5	906·8
21 April	873·8	741·6	753·3
4 May	844·7	783·5	688·8
20 May	887·7	826·9	757·4
1 June	887·8	736·1	682·4
Average ± s.e.	908·3 ± 25·7	797·5 ± 21·21	789·5 ± 45·8

ANOVA for PI

Source	d.f.	Mean square	*F*-value
Rep	3	10 673	
PDATE	5	29 343	1.3 ns
Error	15	22 366	
CULT	2	108 499	$10{\cdot}9^{**}$
PDATE*CULT	10	17 769	1·8 ns
Error	33	9925	
Total	68		

Total number of observations is 69 rather than 72 due to missing values for three individual plots.

† PI was calculated as the reciprocal of the slope of the regression of main vine node number *vs*. accumulated hourly thermal units (ΣTu).

$^{**}P < 0{\cdot}01$; ns, not significant.

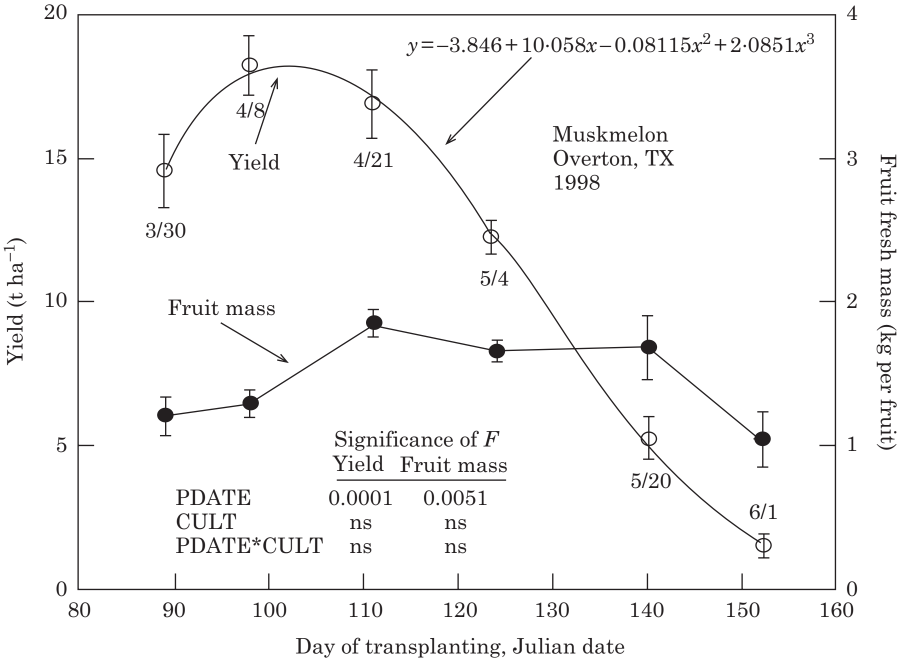

FIG. 5. Effects of transplanting date (PDATE) on muskmelon yield and individual fresh fruit mass. Cultivar (CULT) effect and PDATE*CULT interactions were not significant (ns). Each datum point is the mean of three cultivars ±s.e. for each planting date.

energy balance of a mulched crop will probably also change with time during a cropping season as the canopy grows and increasingly shades more of the mulched surface. Our goal was to develop a simple muskmelon phenology model for use by growers, and inclusion of a complete mass and energy balance would greatly expand the number of required inputs to the model. In a subsequent paper, we more fully examine the consequences of utilizing the average plastochron intervals shown in Table 1 on the ability to predict muskmelon development (Baker *et al*., 2001).

One final possible explanation of the differences among transplanting dates in plastochron intervals (Table 1) is a photoperiod effect. In cereal crops, phyllochron interval is apparently influenced by the rate of change of daylength at crop emergence (Baker *et al*., 1980; Baker and Gallagher, 1983) but the exact nature of this relationship has been questioned by others (Ritchie, 1991). To date, we are unaware of any published reports testing the effects of photoperiod on muskmelon development. Clearly, this is an area in need of further research.

The effects of transplanting date on muskmelon yield and individual fruit mass are shown in Fig. 5. The cultivars did not differ significantly but planting date had a large effect on yield and severely reduced yield in the final two transplanting dates. These yield declines were mainly the result of a reduction in number of muskmelons produced since individual fruit mass, although significantly affected by transplanting date, was relatively more stable across transplanting dates. It has been reported that reproductive physiology is much more sensitive to high temperature stress than vegetative growth in both rice (Baker and Allen, 1993), and cotton (Reddy *et al*., 1995). In rice, spikelet sterility caused by high temperature is induced almost exclusively on the day of anthesis (Satake and Yoshida, 1978), and temperatures greater than 35 °C for as little as 1 h at flowering can induce a high degree of spikelet sterility (Yoshida, 1981). Following temperature increases from 25 to 35 °C, the number of flowers per watermelon plant and the proportion of male flowers both increased, while very few flowers were produced at 40 °C (Sedgley and Buttrose, 1978). In tomato [*Lycopersicon esculentum* (Mill)], vegetative foliage has been shown to be fairly tolerant to high temperatures, but temperatures exceeding 30 to 35 °C result in poor reproductive development (El Ahmadi and Stevens, 1979; Abdalla and Verkerk, 1988; Wolfe *et al*., 1989). Reddy *et al*. (1992) examined the effects of high temperature on cotton fruit retention and found that a 3 week exposure to 40 °C for 2 or 12 h d^{-1} resulted in 64 or 0 % of the bolls, respectively, being retained on the plants. In the present study, it is also possible that the higher air temperatures later in the season may have had a negative impact on bee activity and pollination of flowers.

An example of the third-order polynomial regressions of percent melons harvested *vs*. ΣTu used to estimate thermal time required to 10 and 50 % harvest is shown in Fig. 6. In general, these polynomial regressions fit the data well with R^2 values in excess of 0·96 in all cases. The number of days and ΣTu required to reach 10 and 50 % harvest are shown in Table 2. The last two planting dates failed to produce sufficient fruit to adequately fit regression equations to the data and are omitted from Table 2. As with the estimates of PI (Table 1), more thermal time was required to reach harvest for the first two transplanting dates than the 21 and 4 May transplanting dates. Once again, this may have been associated with a differential heating effect (discussed previously). As temperatures increased over the course of

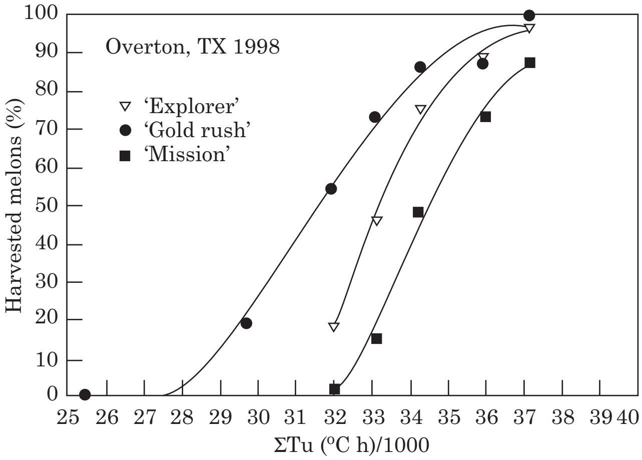

FIG. 6. Example of third-order polynomial regressions of percent melons harvested *vs.* accumulated hourly thermal units (ΣTu) used to estimate chronological time and ΣTu from transplanting to 10 and 50 % harvest. Data are from the 30 Mar. 1998 transplanting date, Overton, TX, USA.

the experiment, the number of days to harvest was greatly reduced. Averaged over the three cultivars, the number of days to 10 % harvest was reduced by about 34 % while ΣTu was reduced by about 13 %, clearly illustrating the superiority of using ΣTu over chronological time in estimating harvest dates.

These reductions in the length of the growing season with transplanting date (Table 2) probably also contributed to reduced yield of muskmelon (Fig. 5). Crop growth is inherently coupled with photosynthetic gains and respiratory losses. It is usually assumed that maintenance respiration increases with increasing temperature while growth respiration varies with temperature only as relative growth rate varies with temperature (McCree and Silsbury, 1978; McCree and Amthor, 1982). Traditionally, plant growth has been modelled as the net balance between photosynthetic gains and respiratory losses, with photosynthesis being relatively insensitive to temperature compared with respiration, and respiration increasing exponentially with temperature according to the Arrhenius function. Gifford (1994) points out that many previous experiments reporting respiratory quotients (Q_{10}, the change in respiration for a 10 °C change in temperature) of 2.0 and higher are from short-term temperature switches rather than long-term temperature treatments. Averaged across seven diverse species, he found a Q_{10} value of about 1·3 under long-term temperature treatments. Thus, the short-term temperature response of respiration may not be representative of respiratory responses to long-term temperature treatments. Nevertheless, crop ontogeny directly influences growth and yield through growth duration, which determines the amount of solar radiation the crop can intercept (Horie, 1994).

SUMMARY AND CONCLUSIONS

We conducted a growth chamber experiment to identify three cardinal temperatures for muskmelon development: the base, optimum and maximum temperatures. Using this information we constructed a simplified hourly air temperature accumulator for use in field experiments to quantify muskmelon development. Concepts previously developed for agronomic crops were applied to muskmelon to quantify vegetative development for a transplanting date experiment in the field. We determined muskmelon plastochron intervals and thermal time from transplanting to 10 and

TABLE 2. *Accumulated hourly thermaly units (ΣTu) and number of days from transplanting to 10 and 50 % harvest for three muskmelon cultivars grown at four transplanting dates at Overton, TX, USA in 1998*

Cultivar	Transplanting date	10 % Harvest ± CLI	50 % Harvest ± CLI	10 % Harvest	50 % Harvest	Number of observations
		[ΣTu (°C h*1000^{-1})]		(d)		
'Explorer'	30 March	31·321 ± 5·355	33·185 ± 3·209	76	79	5
	8 April	29·665 ± 2·447	31·916 ± 2·435	68	72	6
	21 April	26·818 ± 2·726	30·260 ± 2·513	56	62	7
	4 May	26·096 ± 7·083	30·557 ± 6·301	48	56	5
Average ± s.e.		28·475 ± 1·222	31·480 ± 0·673			
'Gold Rush'	30 March	27·979 ± 2·982	32·048 ± 2·999	70	77	7
	8 April	27·860 ± 2·534	30·448 ± 2·508	65	69	8
	21 April	26·014 ± 2·101	28·895 ± 1·655	55	60	6
	4 May	26·216	29·700	49	54	4
Average ± s.e.		27·017 ± 0·523	30·273 ± 0·671			
'Mission'	30 March	32·668 ± 4·030	34·546 ± 4·178	78	81	5
	8 April	28·393 ± 3·770	32·611 ± 1·937	66	73	7
	21 April	26·988 ± 2·714	30·094 ± 2·586	56	61	7
	4 May	27·236	31·318	50	57	4
Average ± s.e.		28·821 ± 1·318	32·142 ± 0·952			

Here, ΣTu has been adjusted to account for the number of nodes on the plants at transplanting which ranged from 3 to 3·5 nodes per plant. The 95 % confidence limit intervals (CLI) were calculated from third-order linear regression of ΣTu *vs.* percent harvested melons. Missing values for CLI are for regressions with too few observations to calculate error degrees of freedom.

50 % harvest dates. Muskmelon node addition rates were well described by accumulated hourly thermal units and time to 10 and 50 % harvests were far better described by thermal time compared with chronological time. We found large yield reductions at later transplanting dates, presumably caused by effects of high temperature stress on reproductive development and/or high temperatures shortening the duration of growth. Using the information presented here, we describe the development of a simple phenology model for muskmelon in an accompanying paper (Baker *et al*., 2001).

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