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A Heat Unit Model to Predict Growth and Development of Muskmelon to Anthesis of Perfect Flowers

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Abstract. **Growth of 'Earligold' muskmelon (*Cucumis melo* L.), expressed as plant dry weight from transplanting to anthesis, could be predicted using a multiple linear regression based on air and soil temperatures for 11 mulch and rowcover combinations. The two independent variables of the regression model consisted of a heat unit formula for air temperatures, with a base temperature of 14C and a maximum reduced threshold of 40C, and a standard growing-degree day formula for soil temperatures with a base temperature of 12C. Based on 2 years of data, 86.5% of the variation in the dry weight (on a log scale) could be predicted with this model. The base temperature for predicting developmental time to anthesis of perfect flowers was established at 6.8C and the thermal time ranged between 335 and 391 degree days in the 2 years of the experiment.**

Plastic mulches and rowcovers are successfully used to promote earliness and yield of muskmelon, particularly in northern climates (Argall and Stewart, 1988; Taber, 1983; Wells and Loy, 1985; Wiebe, 1973). However, little work has been done to predict the effects of these microclimates on growth and development of a crop. Significant straight-line relationships between standard growing-degree-day accumulation (base temperature of 10C) during tunnel placement and biomass at cover removal, as well as early and total yields, were found with cucumber (Wolfe et al., 1989). A significant correlation was reported between total yield of muskmelon and standard growing-degree-day accumulation with a base temperature of 10C, but the relationship was not significant for time to first harvest and early yield (Hemphill, 1989).

To predict more precisely yield curves of muskmelon grown under various mulch and rowcover combinations, fruit maturity may be divided into two developmental phases. The first is from planting to anthesis of perfect flowers and the second from anthesis to first mature fruit (Bohn and Davis, 1957). Mulches and particularly rowcovers influence the growth and development of muskmelon before anthesis (Loy and Wells, 1975); first, the rowcover is in place during this period, and, second, a maximum surface of the mulch is exposed to solar radiation since plant canopy is restricted. Variations in vegetative growth and time of onset of flowering affect subsequent yield earliness and potential. It is therefore important to characterize plant biomass at anthesis as a function of physiological age before developing models that predict yield. Assuming that air and soil temperatures of the mulch/rowcover microclimates are the major factors affecting growth and development of a muskmelon crop before anthesis, physiological age could be expressed in terms of growing-degree days, integrating air and soil temperatures during the period of rowcover placement.

Extreme high and low temperatures have been reported in some of the standard mulch tunnel combinations used in Quebec (Jenni et al., 1991). This is particularly noted in clear perforated tunnels where temperatures >35C are frequently observed during sunny days in the spring, coupled with below freezing temperatures at night due to radiative cooling. Lower and upper thresholds have been included in heat unit models to compensate for the detrimental effects of extreme temperatures. Madariaga and Knott (1951) introduced the idea of a maximum upper threshold, setting the maximum at the value of the upper threshold whenever the maximum exceeded that value. Later, Gilmore and Rogers (1958) used a maximum reduced method, which subtracted from the mean the difference between the upper threshold and the daily maximum temperature. Wolfe et al. (1989) evaluated several low and high temperature thresholds to account for the differences in temperature sensitivity among vegetable crops. The first objective of this field study was to determine a heat unit formula that could accurately predict growth of muskmelon cultivated under various mulches and rowcovers. Growth was expressed in terms of dry weight of plants before anthesis of perfect flowers. A second objective was to predict developmental time to anthesis of perfect flowers of muskmelon under the previous conditions.

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Table 1. Selected heat unit formulas (in degree days) tested to predict plant dry weight before anthesis of muskmelon plants grown under various mulch and row covers. Formulas F1 to F7 are a function of daily minimum temperatures (MN), daily maximum temperatures (MX), a base temperature(BT), an upper threshold (UT), a lower threshold (LT), or the minimum on the previous day (PREVMN).

Standard heat unit formula (average accumulation)
$F1 = (MX + MN)/2 - BT$
Maximum accumulation
$F2 = MX - BT$
Maximum-limited on average accumulation
$F3 = (MXL + MN)/2 - BT$
$MXL = MX \text{ IF } MX \quad UT; MXL = UT \text{ IF } MX > UT$
Maximum reduced on average accumulation
$F4 = (MXR + MN)/2 - BT$
$MXR = MX \text{ IF } MX \quad UT; MXR = UT - (MX - UT) \text{ IF } MX > UT$
Minimum-limited on average accumulation
$F5 = (MX + MNL)/2 - BT$
$MNL = MN \text{ IF } MN \quad LT; MNL = LT \text{ IF } MN < LT$
Minimum-reduced on average accumulation
$F6 = (MX + MNR)/2 - BT$
$MNR = MN \text{ IF } MN \quad LT; MNR = LT - (LT - MN) \text{ IF } MN < LT$
Air minimum-stress factor on average accumulation
$F7 = (MX + MN)/2 - BT \text{ IF } PREVMN > LT;$
$F7 = 1/2\,[(MX + MN)/2 - BT] \text{ IF } PREVMN \quad LT$

Materials and methods

Experimental data. Muskmelon (‘Earligold’) was seeded into 7.5-cm square cell-packs in a greenhouse with night temperature maintained at 19C. Three-week old transplants were planted on 7 May 1993 and on 6 May 1994 in a randomized complete-block design with three blocks. Mulch treatments were a black embossed, a clear (Plastitech, St-Rémi, Qué.) and a photoselective polyethylene (IRT-76, AEP Industries, Moonachie, N.J.). Rowcover treatments were a perforated polyethylene (500 holes/m^2; Plastitech), a spunbonded polypropylene (Rotop, Plastitech) and two unperforated polyethylenes that included a standard clear polyethylene and an infra-red treated polyethylene (Polyon-Barkai, Polywest, Encinatas, Calif.). Each unperforated polyethylene tunnel contained an 8-m-long × 0.32-m-diameter clear polyethylene tube filled with 250 liters of water. These thermal tubes release the stored heat energy into the mini-tunnel during the night (Mawardi and Stewart, 1993). The combinations of mulches and rowcovers were as follows: 1) clear mulch/clear perforated tunnel/no thermal tube (CPO), 2) photoselective green mulch/clear perforated tunnel/no thermal tube (GPO), 3) black mulch/clear perforated tunnel/no thermal tube (BPO), 4) clear mulch/no tunnel/no thermal tube (COO), 5) photoselective green mulch/no tunnel/no thermal tube (GOO), 6) black mulch/no tunnel/no thermal tube (BOO), 7) clear mulch/clear nonperforated tunnel/thermal tube (CUT), 8) photoselective green mulch/clear nonperforated tunnel/thermal tube (GUT), 9) black mulch/clear nonperforated tunnel/thermal tube (BUT), 10) clear mulch/infra-red nonperforated tunnel/thermal tube (CIT), 11) clear mulch/agrotextile tunnel/no thermal tube (CAO).

The experimental field was limed and fertilized with P and K according to the soil test and recommendations (Conseil des Productions Végétales du Québec , 1982). Nitrogen was broadcast at a rate of 100 kg/ha. An herbicide, Naptalam (2-[(1-naphthalenylamino)carbonyl]benzoic acid) was applied on clear mulch plots according to manufacturer’s recommendations. One week before transplanting, drip irrigation was laid and the mulches were installed mechanically over 15-cm-high beds. Plots consisted of 11 plants with 70 cm between the plants and 1.95 m between the rows. Immediately following transplanting, all tunnels were stretched over 10-gauge wire hoops and placed over the plants. Tunnels were left unventilated until anthesis. Anthesis was defined as the time when 90% of the plants had fully open perfect flowers.

Replicated air and soil temperature data were collected from each plot by using copper-constantan thermocouples connected to three AM-32 multiplexers and a CR-10 datalogger (Campbell Scientific Canada, Edmonton, AL) installed in Stevenson shelters. Soil temperatures were taken 7.5 cm below ground level. Thermocouples used to measure air temperature 7.5 cm above ground were placed in white painted plastic tubes 15 cm in length and 3.3 cm in diameter to protect the sensors from direct solar radiation. The datalogger was set to record temperatures every 10 min and to average these over each hour during the time from transplanting to anthesis.

For each microclimate, data were taken at transplanting, 10 days after transplanting, and at anthesis, the dates differing for each microclimate. A destructive sample of two plants per replicate was collected at each time for measurement of fresh and dry weights. Due to severe frost damage during Spring 1994, plants in all treatments except CIT and CUT were replaced on 17 May with 19-day-old transplants. The fresh and dry weight of the transplants for these treatments were measured at planting time and on 27 May. However, sampling for CIT and CUT treatments occurred 18 days after the original date of transplanting.

Heat unit models

Although heat unit systems have been used mostly to predict rates of development (Monteith, 1977), this system has found application in predicting the growth of crops planted at different times during the season (Wurr and Fellows, 1984) or under different microclimates (Wolfe et al., 1989). In this paper, the two following approaches were used for predicting the growth and the development of muskmelon plants before anthesis.

Predicting growth before anthesis. Seven heat unit formulas were defined as a function of a base temperature (BT), an upper threshold (UT), a lower threshold (LT), minimum temperatures (MN), or maximum temperatures (MX). A SAS (SAS Institute, Cary, N.C.) computer software program was developed for each formula to calculate heat unit accumulation from transplanting to 10 days after transplanting and from transplanting to anthesis of perfect flowers under each microclimate.

The seven selected formulas are presented in Table 1. In all methods, negative daily accumulation was set to zero. Air- and soil-based heat units were calculated independently using the same formulas, but including different BT, LT, and UT values. The choice of LT and UT values was based on the range of temperatures found in the experimental microclimates. For calculations using air temperatures, base temperatures were 0, 5, 12, 10, or 15C, upper threshold 35, 40, or 45C, and lower thresholds 2, 4, or 6C. For calculations using soil temperatures, base temperatures were 5, 10, 12, 15, or 18C, upper thresholds 27, 29, or 31C, and lower thresholds 10, 12, or 14C. The maximum accumulation formula (F2) as suggested by Perry et al. (1986) and the minimum stress factor (F7) were tested in 1993, but did not improve the fit compared with average accumulation and were not used in 1994.

The computer software TableCurve (Jandel Scientific, San Rafael, Calif.) was used to fit regression curves between heat unit formulas and plant dry weights sampled in each microclimate at transplanting 10 days after transplanting and at anthesis. This program was used to select the most appropriate among 3320 linear and nonlinear equations. Nonlinear equations such as logistic or

Gaussian did not improve the fit compared with the simple cubic equation. Therefore, only first-, second-, and third-order models were considered. Equations with greater adjusted coefficient of determination (adj r^2, SAS) for each of the air and soil based heat unit formulas were then included in a multiple regression model to predict plant dry weight before anthesis as a function of air and soil temperatures.

Predicting time to anthesis. A straight line approach was used to predict time to anthesis of muskmelon under eleven mulch and rowcover combinations. It assumed that the rate of development varies linearly with temperature between a minimum and an optimum (Monteith, 1977):

$$1/t = (T - BT)/\theta$$

where t is the time required to complete a development process (in days), T is the prevailing temperature (in C), BT is the base temperature (in C), and θ is the thermal time (in C/day). Therefore, by plotting on the vertical axis the rate of development (1/t) and on the horizontal axis the prevailing temperature during that period, a regression line can be drawn to determine the parameters BT, as the intercept of the regression line with the horizontal axis, and θ (the thermal time) as the reciprocal of the slope. Daily mean temperatures during the development period are usually used in the calculations under the assumption that no temperatures above an optimum occur. Although above-optimum temperatures are likely to occur under our experimental conditions, this method has been successfully used in peaches grown under different climatic conditions with maxima above 35C (Munoz et al., 1986).

Results

Description of microclimates

Table 2 is a summary of air temperature data measured in the tunnels from transplanting to anthesis of the perfect flowers. In 1994, plants in all treatments except CIT and CUT were killed by frost and replanted 11 days after the original planting date. Only temperatures occurring after the replanting date are considered for these treatments. Considering the cooler time period that CIT and CUT experienced compared with the other replanted treatments, only CUT had a cool night with temperatures below 2C. The Infrared treated tunnel increased night temperature more than did the standard polyethylene: CUT had 1 day below 2C compared with 0 under CIT and 4 days below 4C compared with 1 under CIT.

In 1993, perforated tunnels had 3 to 4 days below 2C compared with none in 1994. In both years, the perforated tunnels had more days with temperatures below 6C (6–8 days depending on mulch type) compared with the treatments without tunnels (2–5 days). This suggests that temperature inversions occurred under the perforated tunnels. Unperforated tunnels containing water tubes had warmer night temperatures: in 1993, there were 0 to 2 days with temperatures below 6C compared with 9 to 11 days for treatments with perforated tunnels, an agrotextile, or mulch alone.

The 1994 season was generally cooler, as shown by a lower average temperature for CIT (24.1C in 1993 vs. 23.1C in 1994) and CUT (21.0C in 1993 vs. 20.4C in 1994). These treatments were in position during approximately the same period of the year in 1993 and 1994. As a result of a cooler Spring 1994, plants in CIT took longer to reach anthesis (26 days) compared with the same treatment in 1993 (21 days). Plants growing in 1994 experienced more extreme temperatures than those in 1993. Using CIT as an example, there were 17 days with temperatures below 10C in 1994 compared with 6 days in 1993. In addition, temperatures were above 40C during 12 days in 1994 compared with 8 days in 1993. Greater average temperatures were found in 1994 under all treatments except for CIT and CUT. This was expected since these nine treatments were replanted 11 days after the original transplanting date and temperature data were recorded after the second transplanting.

Table 2. Air temperatures at 7.5 cm and time to anthesis of a muskmelon crop grown under mulch and row covers .

Mulch/row cover/thermal tube[z]		CIT	CAO	CPO	GPO	BPO	COO	GOO	BOO	CUT	GUT	BUT
Number of days <2C	1993	0	1	3	4	4	1	1	1	0	0	0
	1994	0	0	0	0	0	0	0	0	1	0	0
Number of days <4C	1993	0	4	6	8	7	4	5	5	0	0	0
	1994	1	2	6	7	7	2	3	2	4	0	0
Number of days <6C	1993	0	10	11	11	11	9	9	9	2	2	2
	1994	5	9	12	12	12	8	9	9	9	2	4
Number of days <10C	1993	6	26	21	23	23	26	27	27	9	9	9
	1994	17	18	17	18	18	17	17	17	20	11	11
Number of days >35C	1993	14	1	8	11	10	2	0	0	9	13	15
	1994	16	8	12	15	17	3	3	2	13	14	14
Number of days >40C	1993	8	0	1	6	6	0	0	0	2	7	9
	1994	12	0	5	11	13	0	0	0	6	12	13
Number of days >45C	1993	3	0	0	1	1	0	0	0	1	2	4
	1994	5	0	0	2	7	0	0	0	1	7	8
Average temperature	1993	24.1	15.7	17.7	19.2	19.1	15.3	15.4	15.4	21.0	22.3	23.0
	1994	23.1	19.6	20.2	21.7	22.7	17.8	18.3	17.8	20.4	24.6	24.6
Date of planting	1993	7 May	7 May	7 May	7 May	7 May	7 May	7 May	7 May	7 May	7 May	7 May
	1994	6 May	17 May	17 May	17 May	17 May	17 May	17 May	17 May	6 May	17 May	17 May
Date of anthesis	1993	27 May	7 June	2 June	3 June	3 June	17 June	21 June	21 June	28 May	28 May	28 May
	1994	31 May	14 June	10 June	12 June	14 June	21 June	23 June	30 June	3 Jne	8 June	8 June
Days to anthesis	1993	21	32	27	28	28	42	46	46	22	22	22
	1994	26	29	25	27	29	36	38	45	29	23	23

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[z] First letter indicates mulch type, either clear (C), photoselective-green (G) or black (B); second letter indicates tunnel type, either perforated clear polyethylene (P), unperforated clear polyethylene (U), infra-red treated unperforated polyethylene (I) or polypropylene agrotextile (A); third letter indicates presence of a thermal tube (T) or absence of a thermal tube (O).

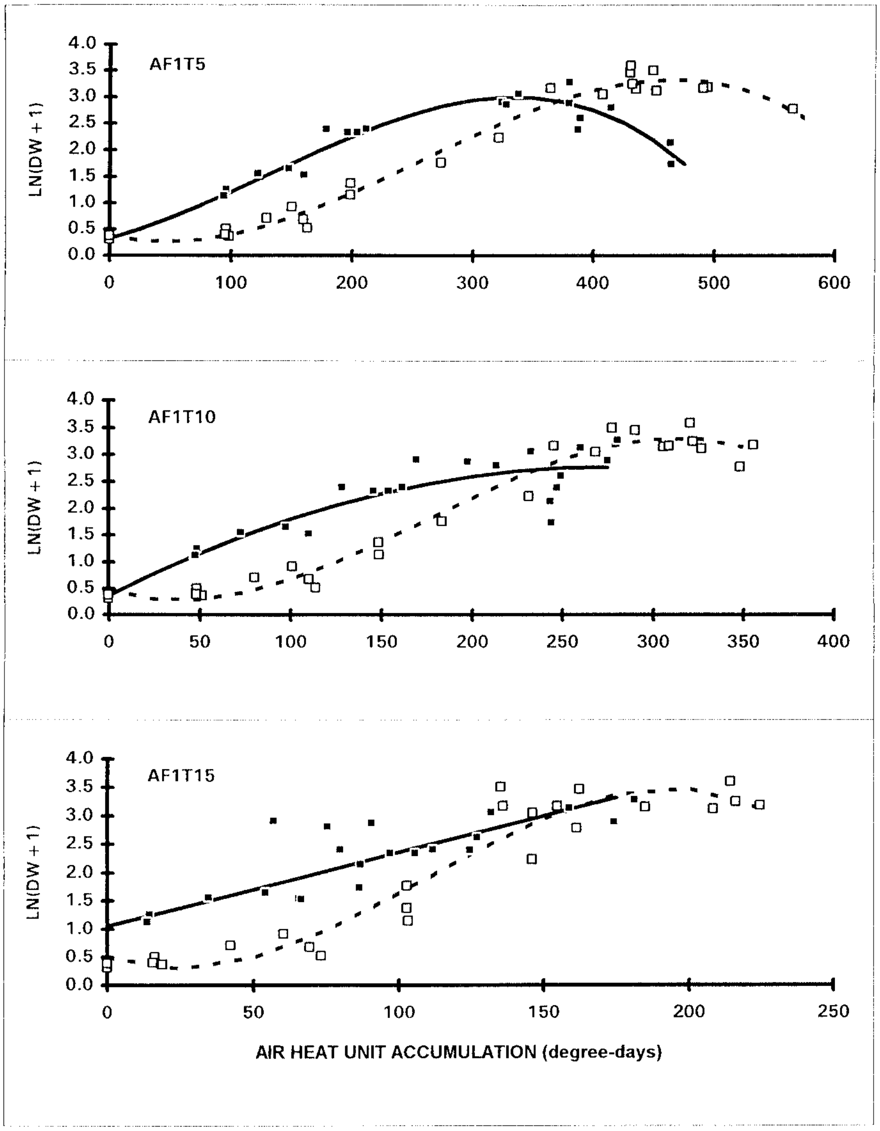

Fig. 1. (**A**) Relationship between heat unit accumulation (F1 in Table 1, in degree days) with base temperatures of 5C (AF1T5), 10C (AF1T10), and 15C (AF1T15) and dry weight (DW, in grams) of muskmelon plants at transplanting, 10 days after transplanting, and at anthesis during 1993 (■) and 1994 (❑). (**B**) Same as A without regression lines.

Predicting growth before anthesis

Air-based heat unit formulas. Figure 1 shows the relationship between the standard heat unit accumulation with base temperatures of 5, 10, and 15C and dry weight of muskmelon plant from transplanting to anthesis. At a base temperature of 5C, plant dry weight in both years increased more or less linearly until a maximum, which corresponded to 400 degree days. Although growth during the early development of the muskmelon plant was faster in 1993 than in 1994, this difference was small considering the log scale. This delay in early plant growth in 1994 compared with 1993 might reflect the less than optimal conditions (e.g., soil compaction) experienced by the 1994 transplants that were replanted in the same holes 11 days after their first planting.

Heat unit accumulation beyond 400 to 450 degree days did not increase the plant dry weight at anthesis as demonstrated by the downward slope of the curve. Points at the right end of the curve represent plants grown with black or green mulch alone and they experienced the lowest air mean temperatures compared with tunnel-grown plants. At low base temperatures (BT at 0 or 5C), these formulas accumulated heat units but no growth occurred. After the maximum was reached, the rate of decrease in 1993 was greater than in 1994 reflecting the cooler season of the former (Table 2). Increasing the base temperature from 5 to 10 and 15C had the effect of straightening up the tail end of the curves, mostly affecting the cumulative values of the microclimates which experienced lower temperatures. Using 15C as a base temperature resulted in more scattered points. Further increase to 18C (data not shown) tended to disperse the points even more, especially in the middle range (50–100 degree days), suggesting that the base temperature for muskmelon was below this value. Overall, black mulch treatment points tended to be located on the lower part of the graph, clear mulch points on the upper part and green mulch points, in between. For the same accumulation of heat units based on air temperature, clear mulch treatments had plants with greater dry weights. This suggests a positive effect of soil warming with this treatment compared with black and photoselective mulch.

For the standard heat unit formula 1 (F1) which accumulates average air temperature, the greatest adjusted coefficients of determination were obtained with a base temperature of 5C and third-degree polynomial in 1993 (0.914) and 1994 (0.977). However, when pooling both years, the optimal base temperature was 10C with an adj r^2 of 0.791 for a first-degree and 0.801 for a third-order polynomial. Including a minimum limited (F5) or reduced (F6) lower threshold of 2, 4, or 6C did not improve the fit compared

Table 3. Multiple regression equations predicting dry weight (DW on a ln scale) of muskmelon plants before anthesis of pistillate flowers as a function of heat unit formula based on air and soil temperatures. All terms are significant at the 0.05 level.

Equation^z	Adj r^2	R^2	CV (%)
Ln(DW) = a + b (AF1T10) + c (SF1T12)	0.831	0.842	21.0
Ln(DW) = a + b (AF4T13U40) + c $(\text{AF4T13U40})^2$ + d (SF1T12)	0.844	0.857	20.2
Ln(DW) = a + b (AF4T14U40) +c (SF1T12)	0.855	0.864	19.5
Ln(DW) = a + b (AF4T15U40) + c $(\text{AF4T15U40})^3$ +d (SF1T12)	0.860	0.873	19.1

^{z}In the body of the formula, the first letter indicates either air (A) or soil (S) temperatures. F1 indicates the standard heat unit formula and F4, the maximum-reduced formula. The number after T indicates the base temperature and the number after U, the level of the upper treshold.

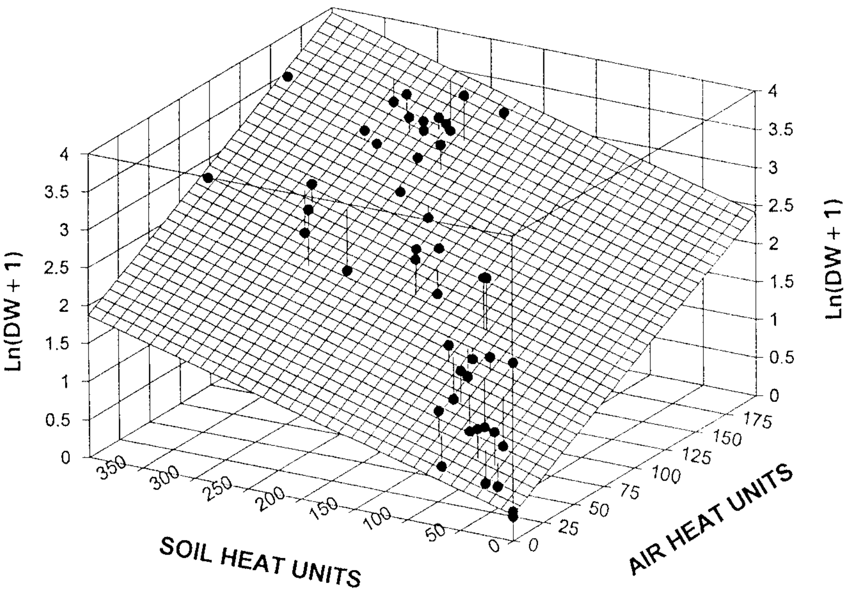

Fig. 2. Plant dry weight (in grams) before anthesis of pistillate flowers as a function of accumulated air heat units (in degree days, DD) with a base temperature of 14C and a maximum reduced temperature of 40C (AF4T14U40), and as a function of accumulated soil heat units (in DD) with a base temperature of 12C (SF1T12). See Table 1 for F1 and F4 formulations. The equation is z = 0.336 + 0.0104x + 0.00382y; adj r^2 = 0.885; n = 47.

with the simple average accumulation. The use of a higher base temperature in the standard heat unit formula (F1) apparently compensated for the effect of the low temperatures experienced by the muskmelon plants during early May.

The maximum accumulation formula (F2) did not improve the fit compared with the standard heat unit formula (F1).

Since formulas with a maximum reduced term (F4) gave greater adj r^2 values than maximum limited formulas (F3) for the combined years, the former was selected and intermediate BT values of 13 and 14C were tested. Results indicated that the greatest adj r^2 for the first order regression was 0.813 with a BT of 14C and an UT of 40C, and the greatest adj r^2s of the cubic curve were 0.833 and 0.831 with a 40C maximum and a BT at 13 and 14C, respectively. A finer screening was performed with the BT at 13C using upper thresholds of 37, 38, 39, 40, 41, 43, and 45C. The first-order equations gave an optimal adj r^2 of 0.812 at 40C and the third order equation resulted in an adj r^2 of 0.841 at 38C. The standard heat unit accumulation formula (F1) with a BT of 10C and the maximum reduced formula (F4) with BT of 13 (UT at 38 and 40C), with a BT of 14C (UT at 40C) and 15C (UT at 40C) were selected for the next step in the modeling process.

Soil-based heat unit formulas. For soil-based standard heat unit formulas, the greatest adjusted coefficients of determination were found with a BT of 12C for individual and combined years. In 1993, the response was quadratic with an adj r^2 of 0.750; in 1994, the response was cubic with an adj r^2 of 0.941; and for the combined years, the straight line response gave an adj r^2 of 0.762 and the cubic response an adj r^2 of 0.799. For any base temperature, inclusion of a minimum limited (F5) or reduced (F6) threshold did not increase the adj r^2 value compared with the simple average accumulation formula. No improvement of fit resulted from including maximum limits (F3) in the formulas. A slightly better adj r^2 of 0.811 was found for the combined years using a BT of 15C and an upper threshold of 29C (cubic response), but this tendency was not found in individual years. Therefore, the standard heat unit formula with a BT of 12 was selected for our model.

Combination of air and soil heat unit formulas. Two air heat unit formulas and one soil heat unit formula were used as independent variables in a multiple regression analysis to predict dry weight of muskmelon plants before anthesis. Formulas based on air temperature consisted of the standard average accumulation formula with a BT of 10C and the maximum reduced formula with BT of 13, 14, and 15C and an upper threshold at 40C. The soil temperature-based formula was the standard heat unit formula with a BT of 12C. Multiple regression models including independent variables up to the fourth order and interaction combinations up to the second order were tested using the SAS program.

The multiple regression equations with significant terms are presented in Table 3. No interaction between air and soil temperature was found in any combinations of air and soil heat unit formulas used, indicating that the mulch affected both factors independently. Dry weight of muskmelon plants could be predicted from accumulated average air temperature with a base temperature of 10C and accumulated average soil temperature with a base temperature of 12C with an adj r^2 of 0.831. The model with the greatest adj r^2 was a third order polynomial including a maximum reduced (40C) and a BT of 15C. However, the second best model was chosen for its simplicity and its similarity of adj r^2 to the best model. In this model, air and soil temperatures found under the different microclimates explained 85.5% (adj r^2) of the variation in plant dry weight. The equation shown graphically in Fig. 2 is

$$\mathrm{Ln(DW + 1)} = 0.33616 + 0.010356\ \mathrm{(AF5T14U40)} + 0.0038233\ \mathrm{(SF1T12)}$$

where DW is the plant dry weight before anthesis of the perfect flowers (in g), AF5T14U40 is a heat unit formula for air temperature with a maximum reduced of 40C and a base temperature of 14C, SF1T12 is a heat unit formula for soil temperature with a base temperature of 12 C (Table 1).

Table 4. Parameters of the simple linear equation between developmental rate (1/t, t=time from transplanting to anthesis of a muskmelon crop, in days^{-1}) and average air temperature (T, in C) during two seasons according to the equation 1/t = a + bT.

Year	Parameter	Estimate	SE	Base temperature	Thermal time	r^2 (n = 11)
1993	a	–2.0124	0.5955	6.7	335	0.912
	b	0.2982	0.0308			
1994	a	–1.7510	0.9895	6.9	392	0.709
	b	0.2553	0.0469			

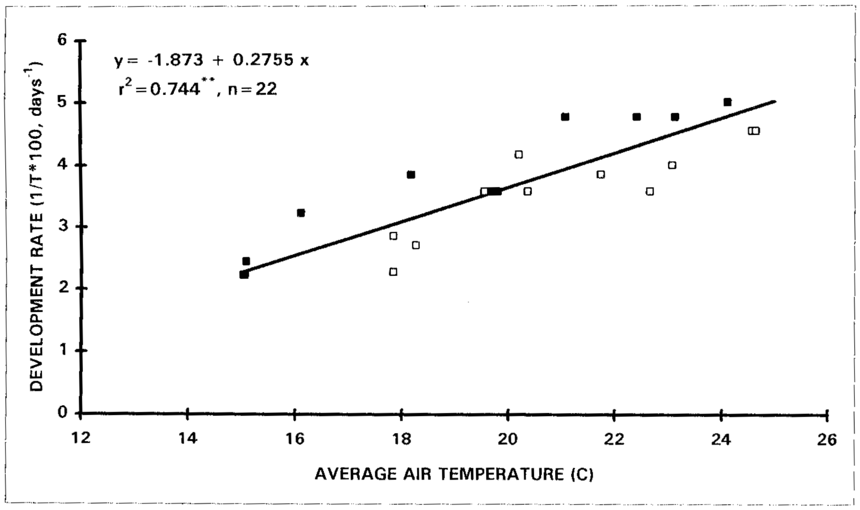

Fig. 3. Rate of muskmelon plant development to anthesis (1/T × 100) regressed on the average air temperature prevailing under various mulch and rowcover combinations. Data are shown for two growing seasons: 1993 (■) and 1994 (❑).

Predicting time to anthesis

Table 4 shows the results of the simple linear regression analysis between development rate, expressed as the reciprocal of time to anthesis, and average air temperature experienced by the plants during this time. Base temperature calculated as (–a/b) was found to be 6.7C in 1993 and 6.9C in 1994. Thermal times, calculated as the reciprocal of the slope (b) were 335 degree days and 392 degree days in 1993 and 1994, respectively. The data are presented in Fig. 3 for both years, using an average value of 6.8C for base temperature and 363 for thermal time. With this model, 74.4% of the variation in the rate of development of muskmelon from transplanting to anthesis could be explained by air temperature alone.

Discussion

Many authors have used different minimum and maximum thresholds in an attempt to obtain a straight line relationship between heat unit accumulation and growth and therefore a constant increase in growth rate with degree days (Gilmore and Rogers, 1958; Madariaga and Knott, 1951; Perry et al., 1986; Wolfe et al., 1989; Perry and Wehner, 1990). The heat unit formulas used in this paper included a minimum threshold since it was thought that low temperature was a limiting factor for growth in early plantings of a heat-loving crop such as muskmelon. The negative influence of minimum air temperature on muskmelon yield was reported even in more southern latitudes such as North Carolina (Bonanno and Lamont, 1987; Motsenbocker and Bonanno, 1989). However, the inclusion of a maximum threshold seemed to have a greater beneficial effect on the model (greater adj r^2) than the inclusion of a minimum threshold. The fact that maximum temperatures usually showed greater fluctuation compared with minimum temperatures may have accounted for the greater influence of this parameter on heat unit accumulation. Further, the results have shown that the inclusion of a higher base temperature tended to affect treatments with low air temperatures (plots with no rowcovers) more than those with higher air temperatures (Fig. 1).

Optimal air temperature range for muskmelon was estimated to be 18 to 24C (Lorenz and Maynard, 1988). However, tolerance in excess of 30C has been reported (Hemphill and Mansour, 1986; Wells and Loy, 1985; Wien and Bell, 1981). Excessively high air temperatures resulting from the use of polyethylene rowcovers could contribute to temperature stress and may offset the beneficial soil warming effects provided by mulches and rowcovers (Bonanno and Lamont, 1987; Motsenbocker and Bonanno, 1989). Our results indicated that the inclusion of a maximum threshold in a heat unit formula improved the prediction of muskmelon growth before anthesis. These results are in contrast with those obtained by Wolfe et al. (1989) who found that cucumber biomass at rowcover removal was correlated to a standard growing-degree-day formula but including a high-temperature threshold did not improve the fit. However, these authors did not test base temperatures above 10C. Our results with muskmelon indicated a greater correlation with plant dry weight before anthesis when a base temperature of 14C was used in conjunction with a maximum reduced at 40C. Perry et al. (1986) selected a base temperature of 15.5C to predict time to harvest for field cucumber. Although no mulch or rowcovers were used, these authors also included a maximum reduced threshold at 32C to improve the fit of their model. In squash, NeSmith and Hoogenboom (1994) tested a single standard heat unit formula with a base temperature of 8C and a maximum limited at 32C for predicting time to anthesis of pistillate flowers. Depending on the cultivar used, the coefficient of variability was reduced from 13.3% to 19.5% to 7.9% to 13.3% when using the heat unit formula as compared to counting the number of days.

According to Risser et al. (1978), minimum soil temperature for growth of muskmelon under controlled environment is 12C. These authors defined an upper threshold for soil temperature of 18C above which leaf number and plant weight remained constant. This is in accord with our results, which indicated that the best correlation was obtained with a base soil temperature of 12C. However, the inclusion of an upper soil temperature threshold in the heat unit formula did not improve the fit.

Based on 2 years of data for 11 mulch and rowcover combinations, 86.5% of the variation in the dry weight of muskmelon plants could be predicted from air and soil temperatures. Nonrandom errors associated with this model may include other environmental factors such as wind, relative humidity, and CO_2 levels that may have differed between the various mulch and rowcover treatments and quantity of solar radiation that differed between years. Another source of errors might be the inaccuracies in temperature measurements, particularly soil temperatures, which tended to vary more over replicates than air temperatures due to soil heterogeneity.

No significant interactions were found between air and soil temperatures, as mulch type affected soil temperatures differently depending on color and properties. The black mulch, by absorbing incoming solar radiation, tended to increase air temperatures under the rowcovers but had a limited effect on soil warming. The clear mulch tended to transmit solar radiation resulting in higher soil temperatures and lower air temperatures under rowcovers compared with black mulch. The photoselective mulches were intermediate between black and clear mulches.

Time to anthesis of the first perfect flowers was predicted simply from air temperature records (Fig. 3). This information could easily be used in a crop management program to plan and predict time to first anthesis of the first perfect flowers. Muskmelon is a crop that develops linearly in air temperatures averaging between 15 and 25C. Under the growing conditions of the project, mulches and rowcovers could be seen mostly as temperature modifiers. Although time to anthesis could be drastically reduced by higher average air temperatures, the selection of mulch and rowcover combinations should also be based on maximum air temperatures. Particularly, combinations that increase air temperatures beyond 40 C will tend to reduce plant biomass before anthesis and therefore should be avoided. For this reason, clear or photoselective mulch should be preferred over black mulch when combined with tunnels.

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