Predicting Yield and Time to Maturity of Muskmelons from Weather and Crop Observations

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ABSTRACT. A simple method to predict time from anthesis of perfect flowers to fruit maturity (full slip) and yield is presented here for muskmelon (*Cucumis melo* L.) grown in a northern climate. Developmental time for individual muskmelons from anthesis to full slip could be predicted from several heat unit formulas, depending on the temperature data set used. When temperature at 7.5 cm above soil level was used, the heat unit formula resulting in the lowest coefficient of variation ($CV = 6.9\%$) accumulated daily average temperatures with a base temperature of 11°C and an upper threshold of 25°C . With temperatures recorded at a meteorological station located 2 km from the experimental field, the method showing the lowest CV (8.9%) accumulated daily maximum temperatures with a base temperature of 15°C . This latter method was improved by including a 60-degree-day lag for second cycle fruit. The proportion of fruit volume at full slip of 22 fruit from the first cycle could be described by a common Richards function ($R^2 = 0.99$). Although 65% of the plants produced two fruit cycles, fruit from the first cycle represented 72% of total yield in terms of number and mass. The blooming period of productive flowers lasted 34 days, each cycle overlapping and covering an equal period of 19 days. Counting the number of developing fruit >4 cm after 225 degree days from the start of anthesis (when 90% of the plants have at least one blooming perfect flower) could rapidly estimate the number of fruit that will reach maturity.

Heat unit systems are frequently used to characterize plant development because developmental rates vary with temperature (Monteith, 1977). The prediction of stages of development is then based on accumulated degrees per unit time above a base temperature, often referred to as a threshold for growth. Most commonly, time and temperature from planting to maturity of a crop grown at various locations or over several years are used to define base temperatures (Dufault, 1997; Dufault et al., 1989; Munoz et al., 1986; Perry et al., 1986). Another way is to alter the microclimate around the plants, for example using plastic mulches and rowcovers, to modify plant development within a production year (Hemphill, 1989; Wolfe et al., 1989).

Most of the heat unit systems have been developed for crops with a single commercial harvest, such as sweet corn (*Zea mays* L.) (Magoon and Culpepper, 1932), spinach (*Spinacia oleracea* L.) (Boswell, 1935), lettuce (*Lactuca sativa* L.) (Madariaga and Knott, 1951), mechanically harvested peas (*Pisum sativum* L.) (Boswell, 1929), and cucumbers (*Cucumis sativus* L.) (Perry et al., 1986). The muskmelon plant produces fruit that progressively ripen over several weeks and require multiple harvests. It is an indeterminate vining crop that tends to produce fruit in cycles. In northern latitudes, the crop produces one or two cycles. In warmer climates, it can produce up to three cycles (McGlasson and Pratt, 1963). Under our climate, fruit from the second cycle are produced in the cooler part of the growing season and fruit maturation usually takes longer.

A heat unit system was developed to predict time to anthesis of

perfect flowers for muskmelon grown under various plasticulture regimes in a northern climate (Jenni et al., 1996). A second logical step was to predict time from anthesis to fruit maturity. The objectives of this study were to 1) investigate the fruiting behavior of muskmelon grown under various microclimates using mulches and rowcovers, 2) determine a heat unit system that would predict time from anthesis of perfect flowers to full slip for first- and second-cycle fruit, and 3) develop a simple technique for predicting quantity and timing of muskmelon yield.

Materials and Methods

'Earligold' muskmelon seeds were placed into $6 \times 60 \times 58$ -mm plastic cell pots filled with a moist commercial peatmoss medium (Promix BX, Premier Horticulture, Rivière-du-Loup, Que.) and allowed to grow in a greenhouse. The research plots were located at the Horticulture Research Center at Macdonald Campus in Sainte-Anne-de-Bellevue, Que., Canada. The soil was a sandy loam fertilized with nitrogen at a rate of $100 \text{ kg} \cdot \text{ha}^{-1}$ and rototilled before laying the mulch. Phosphorus and potassium fertilizers were applied according to soil tests (Conseil des Productions Végétales du Québec, 1982). At least 1 week before planting, a drip irrigation line and either a wavelength-selective green (IRT-76, AEP Industries, Moonachie, N.J.), a black embossed, or a clear polyethylene mulch (Plastitech, St-Rémi, Que.) were applied mechanically over a 15-cm-high bed. Plots consisted of 11 plants spaced at 0.7 m within and 2.0 m between rows. Weekly sprays to control insects and diseases followed Quebec recommendations for growing muskmelon. An herbicide, naptalam(2-[(1-naphthalenyl-amino)carbonyl]benzoic acid) (Alanap 3, Uniroyal Chemical, Elmira, Ont.) was applied on clear mulch plots according to manufacturer's recommendations. Weeds were controlled between the rows by hoeing and rototilling.

EXPERIMENT 1. MONITORING FRUIT GROWTH AND DEVELOPMENT DAILY ON FIVE PLANTS. On 1 June 1994, 4-week-old muskmelon

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transplants were planted in three 8-m rows covered with black mulch. On 8 July 1994, all fruit that had already developed beyond the Bloom stage were removed on five randomly selected plants in the center rows. The remaining perfect flowers were labeled daily as they became visible. The length and the diameter of the inferior ovary and subsequently the fruit were recorded daily from tagging to fruit maturity (full slip) or until the fruit aborted. Phenological stage of the developing ovary was also recorded according to a specific classification (Jenni, 1997). In total, 199 flowers were labeled on these five plants.

EXPERIMENT 2. MONITORING FRUIT GROWTH AND DEVELOPMENT WEEKLY ON THREE PLANTS GROWN IN FOUR MICROCLIMATES. Three-week-old transplants were planted on 6 May 1994. Four treatments were defined to expose the plants to various heat units: 1) a wavelength-selective green mulch with no rowcover (GOO); 2) a wavelength-selective green mulch with a perforated polyethylene minitunnel (500 holes/m²; Plastitech, St-Rémi, Qué.) and no thermal tube (GPO); 3) a wavelength-selective green mulch with an unperforated clear polyethylene rowcover and a thermal tube (GUT); and 4) a clear mulch with an infra-red treated polyethylene rowcover (Polyon-Barkai, Polywest, Encinatas, Calif.) and a thermal tube (CIT). Each unperforated polyethylene tunnel contained a 8-m-long × 0.32-m-diameter clear polyethylene tube filled with 250 L of water (thermal tube). All rowcovers were stretched over 80-cm-long hoops (10-gauge wire) spaced every 87.5 cm along the plot. Treatments were arranged in a randomized complete block design with three replications. Tunnels were left unventilated until anthesis. Start of anthesis was defined as the time when 90% of the plants had fully open perfect flowers.

On one randomly selected plant in each of the four microclimates and each of the three blocks, all perfect flowers were labeled as they appeared on the plant. Length and diameter of the ovary and the phenological stage were recorded weekly from labeling time to full slip or until the fruit aborted. In total, 1220 perfect flowers were

labeled on 12 plants. Volume of all growing fruit reaching full slip was calculated from polar and equatorial diameters (Jenni et al., 1997). Richards growth functions (Richards, 1959) were fitted to the growth curves of fruit volume using an SAS (SAS Institute, Cary, N.C.) procedure.

Replicated air temperature data were recorded hourly from copper-constantan thermocouples placed in the middle of each plot at 7.5 cm above the ground and connected to a CR-10 datalogger (Campbell Scientific Canada, Edmonton, Alta.) installed in Stevenson shelters. Thermocouples were placed in white painted plastic tubes 15 cm long and 3.3 cm in diameter to protect them from being hit by direct solar radiation. Ambient air temperature data were obtained from the meteorological station on the Macdonald Campus located 2 km from the research field.

PREDICTING TIME FROM ANTHESIS TO FULL SLIP. The number of days from bloom stage to full slip of 55 fruit from the first and second cycles was compared with accumulated heat units. Fruit from Expts. 1 and 2 were used. Heat units were calculated using either air temperature from each plot at 7.5 cm above the soil surface or the ambient temperature recorded from the meteorological station. Two basic equations (GDD1 and GDD2, in degree days) were evaluated, namely the average temperature accumulation

$$\text{GDD1} = (\text{MX} + \text{MN})/2 - \text{BT}$$

and the maximum temperature accumulation

$$\text{GDD2} = \text{MX} - \text{BT}$$

where MX = the maximum temperature (°C), MN = the minimum temperature (°C) and BT = the base temperature (°C). In both methods, a negative daily accumulation was set to zero. Further, an upper threshold (UT) was included to account for a potentially negative effect of high temperatures on fruit development. A new maximum was defined as a function of the actual daily maximum

Table 1. Coefficient of variation (CV) of two methods for calculating accumulated heat units with varying limited and reduced upper thresholds versus days from bloom stage to full slip of individual muskmelons. The heat units were calculated from temperatures taken at 7.5 cm above soil level in the muskmelon canopy and the meteorological station at Macdonald Campus (Ste-Anne-de-Bellevue, Quebec, Canada). The CV based on calendar-day-count was 12.1%.

Upper threshold (°C)	Base temp (°C)							
	Avg. temp accumulation				Max temp accumulation			
	6	10	14	18	6	10	14	18
Air temp at 7.5 cm								
Maximum limited								
28	10.6	10.8	11.4	13.3	10.8	11.0	11.4	12.1
32	11.4	11.9	13.0	15.5	12.1	12.5	13.3	14.6
36	12.2	13.0	14.5	17.7	13.2	13.9	14.9	16.7
Maximum reduced								
28	8.3	7.9	7.5	10.4	8.2	8.2	9.1	11.5
32	10.1	10.2	10.7	12.4	10.4	10.6	11.1	12.1
36	11.7	12.3	13.5	16.2	12.5	13.1	13.9	15.4
None	12.8	13.7	15.5	19.5	14.0	14.8	16.1	18.2
Air temp from meteorological station								
Maximum limited								
28	9.2	9.2	9.7	11.5	9.6	9.5	9.4	9.5
32	9.0	9.1	9.8	12.0	9.3	9.2	9.0	9.2
Maximum reduced								
28	9.4	9.4	9.9	11.5	10.0	10.1	10.1	10.5
32	9.1	9.1	9.8	11.9	9.4	9.3	9.1	9.6
None	9.0	9.0	9.8	12.1	9.2	9.1	8.9	9.1

(MXa) in two ways:

For maximum-limited formulas

$MX = MXa$ if $MXa \leq UT$; $MX = UT$ if $MXa > UT$

For maximum-reduced formulas

$MX = MXa$ if $MXa \leq UT$; $MX = UT - (MXa - UT)$ if $MXa > UT$

Base temperatures tested included 6, 10, 14, and 18 °C and upper thresholds 28, 32, and 36 °C. Selection of base temperatures and thresholds were based on a minimum coefficient of variation (cv) to determine the best method to predict fruit maturity (Arnold, 1959; Perry et al., 1986; Yang et al., 1995).

Results

DETERMINING A HEAT UNIT SYSTEM FOR FRUIT DEVELOPMENT. The cvs calculated for all combinations of heat unit formulas, base temperatures, and upper thresholds are presented in Table 1 using two sets of air temperature data, either at a height of 7.5 cm in each experimental plot or 1.5 m at the meteorological station.

When using temperature data at a height of 7.5 cm in each plot, the method with the lowest cv was the average temperature accumulation with a base temperature of 14 °C and maximum reduced with an upper threshold of 28 °C. This combination reduced the cv to 7.5% compared with 12.14% when days from anthesis to full slip was used (Table 1). However, when fruit from only the first cycle were considered, calendar-day count was more precise (cv = 5.6%) than any of the heat unit formulas (data not shown). To determine whether the cv could be reduced further, smaller intervals of 0.5 °C for BT and UT were tested for the average temperature-accumulation formula. Using a base temperature of 11 °C and an UT of 25 °C reduced the cv to 6.9% (Table 2).

When using the set of air temperature data from the meteorological station, the inclusion of an upper threshold in the heat unit formula did not reduce the cv (Table 1). Because the maximum temperature accumulation resulted in a slightly better prediction than the average temperature accumulation, a set of the formula accumulating maximum temperature was tested using 0.5 °C increments of base temperature values between 10 and 16 °C (Table 2). Then, the method showing the lowest cv for prediction

of time from anthesis to fruit maturity using air temperature data from the meteorological station was a maximum temperature accumulation with a base temperature of 15 °C. When only fruit from the first cycle were considered, this heat unit formula resulted in a cv of 5.7%, which was similar to the calendar-day-count method (data not shown). This formula will be used in the following steps of this work since it improved the prediction of fruit maturity when fruit from first and second cycle were considered (8.9% versus 12.1% for calendar-day count) and since temperature data from meteorological stations are usually more accessible to growers than direct recordings of temperature from the field.

Minimum temperatures recorded at the meteorological station were highly correlated with the minimum temperatures recorded in the experimental field with the datalogger ($r = 0.91$, $n = 91$, Fig. 1). However, although significant, the simple linear correlation coefficient between maximum temperatures of the two recording sites was smaller ($r = 0.65$, $n = 91$). Minimum and maximum temperatures from the meteorological station were consistently lower than those from the datalogger and the differences were larger for the maximum temperatures. From the period between 14 June (day of year, DY 165) and 12 Sept. 1994 (DY 255), maximum temperatures were on average 6.0 °C higher and minimum temperatures were 1.7 °C higher for the datalogger than those from the meteorological station.

A MODEL FOR FRUIT GROWTH. The average time of occurrence of eight phenological stages from bud to full-slip stage in terms of days and degree days from the bloom stage is presented in Table 3. Ovary dimensions (length, diameter, and volume) were also estimated for each stage as a proportion of final fruit volume at full slip. An average of 414 degree days was necessary for an ovary at bloom stage to grow from 0.04% to its final fruit volume at full slip.

Fruit volume of 26 muskmelon fruit from five plants were expressed as the proportion of volume at full slip versus two time scales (Fig. 2). When the x-axis is expressed in terms of day of the year (DY), two sets of curves were distinguished (Fig. 2A). A first set of 22 fruit starting blooming between DY 189 and DY 193 represented the first fruit cycle; a second set of four fruit blooming between DY 202 and DY 203 represented the second fruit cycle. When proportion of fruit volume at full slip was expressed as a function of heat units (accumulated maximum temperature with a

Table 2. Coefficient of variation (CV) for heat unit accumulation with combinations of upper thresholds and base temperatures at intervals of 0.5 °C. Heat units were calculated from bloom to full-slip stage of individual muskmelons based on temperatures taken at 7.5 cm above soil level in the muskmelon canopy and the meteorological station at Macdonald Campus (Ste-Anne-de-Bellevue, Quebec, Canada). The CV based on calendar-day count was 12.1%.

Upper threshold (°C)	Base temp (°C)												
	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
Air temp at 7.5 cm—avg. temp accumulation													
24.5	7.0	7.0	7.1	7.2	7.3	7.6	8.0	8.4	---	---	---	---	---
25	7.0	6.9	6.9	7.0	7.1	7.2	7.5	7.8	---	---	---	---	---
25.5	7.1	7.0	7.0	7.0	7.0	7.1	7.2	7.5	---	---	---	---	---
26	7.1	7.1	7.0	7.0	7.0	7.0	7.1	7.2	7.5	7.8	8.2	8.7	---
26.5	7.3	7.2	7.1	7.0	7.0	7.0	7.0	7.1	7.2	7.5	7.9	8.3	---
27	---	---	---	---	7.1	7.1	7.1	7.1	7.2	7.4	7.7	8.1	---
27.5	---	---	---	---	7.1	7.3	7.3	7.3	7.3	7.5	7.6	7.9	---
28	---	---	---	---	7.6	7.6	7.5	7.5	7.5	7.6	7.7	7.9	---
28.5	---	---	---	---	7.9	7.8	7.8	7.7	7.7	7.7	7.8	7.9	---
29	---	---	---	---	8.2	8.1	8.1	8.0	8.0	8.0	8.1	8.1	---
Air temp from meteorological station—max temp accumulation													
None	---	---	---	---	---	---	9.0	9.0	9.0	9.0	8.9	8.9	9.0

Fig. 1. Minimum (MIN) and maximum (MAX) temperatures (°C) from a meteorological station (MET) located 2 km from the experimental field in 1994 and at a height of 7.5 cm (CR10) located in the experimental field.

base temperature of 15 °C), fruit from the first cycle followed a common curve, but the curves representing fruit from the second cycle were still to the right of the curves of the first cycle fruit (data not shown).

Richards growth functions were fitted to the fruit growth curves of the 22 fruit from the first cycle (Fig. 2B). The proportion of volume at full slip Y was expressed as a function of heat units X , in °C days, according to the following Richards function: $Y = Y_{\max} R^{1/(1-m)}$, with $R = 1 + (Y_0(1-m) - 1)e^{-kX}$ with $Y_0 = 0.00043$ being the proportion of ovary volume at the bloom stage (Table 3) and $Y_{\max}$ = asymptotic value for proportion of fruit volume at the full-slip stage. The parameter k was defined

as a rate constant determining the proportion of the final size at the inflexion point and m , a shape parameter determining the spread of the curve along the time axis. The non-linear regression procedure available in SAS estimated k at 0.009334, m at 0.8230, and $Y_{\max}$ at 1.083. This equation resulted in a coefficient of determination of 0.99.

The shift for second-cycle fruit on the right side of the common growth curves suggested a delay in growth and development of these fruit compared with the fruit from the first cycle (Fig. 2A). Including lags in development for second cycle fruit of 30, 35, 40, 45, 50, 55, 60, and 65 degree days had the effect of shifting the curves of second cycle fruit to the left along the x-axis. Based on the temperatures recorded at the meteorological station, the cv was reduced from 8.9% to 6.5%

when, for second-cycle fruit, values from 50 to 65 degree days were subtracted from the accumulated degree days with a base of 15 °C. The lowest cv of 6.5% was found at 60 degree days. Including a lag time of 60 degree days in the heat unit formula decreased the cv by half compared with the calendar-day-count cv.

BLOOMING AND FRUITING SEQUENCES IN MUSKMELON. Based on 17 plants observed in 5 microclimates, 35% of the plants had only one fruit cycle and 65% had two fruit cycles. However, on 156 fruit harvested from these plants, 72% came from the first cycle of fruiting and 28% from the second cycle. Then, modeling fruit from only the first cycle would account for >70% of the yield of muskmelon.

The blooming sequence of productive flowers, that is perfect flowers that will produce a fruit until the full-slip stage, was described. The time at bloom stage of individual flowers was estimated from weekly observations of ovary development in four

Table 3. Time of occurrence of eight phenological stages, expressed as days from bloom stage and heat units (degree-days), and length, diameter, and volume of muskmelon ovaries, expressed as a proportion from final fruit size at full slip (%). Twenty-two fruit from only the first cycle were considered. Heat units were calculated using the maximum temperature accumulation recorded from a meteorological station with a base temperature of 15 °C.

Phenological Stage ^y	Time from bloom stage (d)	Heat units (degree-days)	Length (%)	Diam (%)	Vol (%)
Bud	-2.4 ± 0.2 ^z	-30.6 ± 2.1	7.6 ± 0.2	5.3 ± 0.2	0.020 ± 0.002
Closed	-1.1 ± 0.1	-14.5 ± 1.4	9.4 ± 0.1	6.2 ± 0.1	0.033 ± 0.001
Bloom	0.0 ± 0.0	0.0 ± 0.0	10.2 ± 0.1	6.9 ± 0.1	0.043 ± 0.001
Wilted	1.2 ± 0.1	13.4 ± 0.8	13.1 ± 0.4	8.4 ± 0.2	0.085 ± 0.008
Set	2.9 ± 0.1	31.0 ± 1.5	19.7 ± 0.8	12.5 ± 0.5	0.285 ± 0.034
Unnetted	4.3 ± 0.1	45.0 ± 1.5	30.1 ± 0.7	19.8 ± 0.7	1.14 ± 0.11
Netted	12.0 ± 0.2	140.5 ± 3.5	76.3 ± 1.3	70.8 ± 0.7	37.4 ± 1.2
Full-Slip	38.1 ± 0.3	414.2 ± 3.5	100.0 ± 1.9	100.0 ± 1.3	100.0 ± 4.1

^zEach category represents the beginning of the phenological stage for fruit observed during their growth period.

^yEach datum represents the mean ± SE, $n = 22$.

Fig. 2. Fruit volume, expressed as the proportion of volume at full slip, as a function of (A) day of year (fruit from first and second cycles are shown) and (B) heat accumulation (daily accumulation maximum with a base temperature of 15 °C fruit from only the first cycle are shown). The solid line represents a Richards equation fitted to the 22 fruit of 5 plants.

microclimates and from the dimensions and time of occurrence of the phenological stages from bud to unnetted described in Table 3. The blooming sequence of productive flowers covered a period of 42 d between DY 158 and DY 200. However, each of the two fruit cycles lasted an equal period of 29 d. Each of the four microclimates had plants that started anthesis at separate times. Start of anthesis within each microclimate, defined as the time when 90% of the plants were bearing at least one blooming perfect flower, was DY 154 for CIT, DY 159 for GUT, DY 163 for GUT, and DY 174 for GOO. When the data were presented in terms of days from the start of anthesis, the total blooming period was only 34 d, with each cycle covering an equal period of 19 d (Fig. 3A). One productive flower bloomed 4 d earlier than when 90% of the plants started to bloom. All the productive flowers of the first cycle occurred within 15 d after the start of anthesis, but most (67%) of these flowers appeared during the second week. A small portion (8%) of the second-cycle flowers were present during the second week after the start of anthesis, and the rest of the second-cycle flowers were

approximately normally distributed during the following 2-week period. Then, 71% of the productive flowers appeared during the first 2 weeks after the start of anthesis, 78% during the first 3 weeks, and all of them during a 30-d period after the start of anthesis. Based on a thermal time scale (maximum temperature accumulation with a base temperature of 15 °C), blooming of productive flowers extended over 340 degree days and first-cycle flowers over 180 degree days (Fig. 3B).

Discussion

CONTRASTS BETWEEN AIR AND CANOPY TEMPERATURES FOR HEAT UNIT CALCULATIONS. With canopy temperature, using a base temperature of 11 °C and a maximum-reduced temperature with an UT of 25 °C in an average temperature accumulation formula allowed more precise prediction (cv = 6.9%) of time from anthesis to full slip for muskmelon fruit than using the calendar-day-count method (cv = 12.1%, Table 2). Using air temperature data from the nearby meteorological station resulted in less precision (cv = 8.9%) and required a different heat unit formula (Table 2). As opposed to the temperature in the canopy, temperature recorded from the nearby meteorological station did not precisely reflect the temperature experienced by the fruit or integrate the effect of mulch color on ambient temperature particularly during early plant development when the mulch is not completely covered

by the plant canopy. This resulted in a general and simple formula based solely on maximum temperature accumulation and a base temperature of 15 °C (Table 2). This is in accordance with Perry et al. (1986), who selected a base temperature of 15.5 °C with a maximum-reduced temperature and an upper threshold of 32 °C in a maximum temperature accumulation formula to predict time to harvest of field cucumber grown in North Carolina from meteorological temperature data. Under our northern growing conditions, the meteorological station recorded the highest maximum temperature at 33.8 °C and temperatures above 32 °C for only 4 d (Fig. 1). This might explain why including an upper threshold did not improve the precision of predicting time to maturity.

The base temperature varied depending on the data set used in the calculation. Using canopy temperatures resulted in the selection of an average temperature accumulation formula with a base temperature of 11 °C and a maximum-reduced temperature with an UT of 25 °C (Table 2). Base temperature is usually defined on a physiological basis as the lowest temperature at which plant growth and development will proceed. The appropriate base temperature in a heat unit system may not necessarily coincide with the physiological base temperature, but often results in more accuracy of prediction since it gives the least variation in heat unit summations.

Fig. 3. Distribution in time of blooming flowers that will produce a mature fruit during the first or second fruit cycle, time being expressed as (A) days from start of anthesis and (B) heat units from start of anthesis (maximum accumulation with a base temperature of 15 °C, degree-days). A total of 126 productive ovaries was recorded from 12 plants grown on 4 mulch-rowcover combinations. Start of anthesis was defined as the time when 90% of the plants within one mulch-rowcover combination was bearing at least one blooming perfect flower.

Also, the period from anthesis to fruit maturity covers a period with the highest temperatures during the season, usually with high minimum temperatures. Then, even if the maximum temperatures were often higher than 25 °C, the minimum temperatures sometimes compensated and contributed heat units, especially with a relatively low base temperature value of 11 °C. Further, air temperature at a height of 7.5 cm may often correspond, during hot days, to even higher fruit temperature, which could be detrimental to fruit maturation (Malézieux et al., 1994). Schroeder (1965) reported that, during a sunny day with ambient air temperature at 36 °C, the upper pericarp of a muskmelon fruit was 15 °C warmer than for a shaded fruit and 7.5 °C warmer than ambient air.

In muskmelon, optimal air temperature range for growth was estimated to be 18 to 24 °C (Lorenz and Maynard, 1988). However, developmental response to temperature often differs from the growth response (Dekhuijzen and Verkerke, 1986; Marcelis and Baan Hofman-Eijer, 1993). For example, Marcelis and Baan

Hofman-Eijer (1993) found that the rate of cucumber fruit growth increased from 17.5 to 30 °C, but the developmental rate increased even more resulting in smaller fruit at maturity.

Using temperatures at 7.5 cm above soil level, developmental time from planting to anthesis had a linear response and could be predicted with a base temperature of 7 °C (Jenni et al., 1996). In contrast, fruit development was nonlinear, and time from anthesis to fruit maturity could be predicted with a base temperature of 11 °C and an upper threshold of 25 °C (Table 2). The reproductive phase of development characteristically occurs during the warmer part of our season, whereas the vegetative phase of development tends to occur during the cooler part of the season. Therefore, the base temperature would be different for these two phases not only because they respond differently to temperature, but also because they tend to be exposed to different temperature ranges during the season (Arnold, 1959).

Temperatures at 7.5 cm in the experimental field were systematically higher than temperatures from the meteorological station, in the order of 6.0 °C for the maximum and 1.7 °C for the minimum temperatures (Fig. 1). Including an upper threshold in the experimental field data set may have compensated for the high maximum temperatures recorded, therefore reducing heat unit accumulations. The differences in temperature recorded in the crop canopy and at the meteorological station may be explained in part by the distance of the station from the experimental field, but also because temperature profiles within crop canopies are usually different from those above a crop (Rosenberg et al., 1983). During the day, most of the solar radiation is absorbed near the middle to upper portion of the canopy where there is maximum leaf area. Then, a thermocouple located at a height of 7.5 cm is most likely to register the highest temperatures within the canopy. Above the canopy, the temperature profile generally decreases with height, as reflected by lower maximum temperatures recorded by the meteorological station compared with maximum temperatures registered at a height of 7.5 cm within the canopy (Fig. 1). At night, temperature inversions above plant canopies are frequent. However, the higher minimum temperatures registered at 7.5 cm compared with those from the meteorological station may be a result of some of the outgoing longwave radiation trapped by the canopy when transmitted to the nocturnal sky (Rosenberg et al., 1983; Tanner, 1974).

GROWTH AND DEVELOPMENT OF FIRST- AND SECOND-CYCLE FRUIT. Muskmelon, like many other fruit such as apple (*Malus domestica* Borkh.), tomato (*Lycopersicon esculentum* Mill.), and strawberry (*Fragaria xananassa* Dutch.), exhibits a single sigmoid cumulative growth curve (Bollard, 1970; Gustafson, 1926; McGlasson and Pratt, 1963). The volume of first cycle fruit with various final sizes fitted a common Richards growth curve when volume was expressed as the proportion of final fruit volume at maturity (Fig. 2). However, the fruit from the second cycle had a delayed growth and development, evaluated over the period from anthesis to full slip at 60 degree days, which was not solely explained by the cooler temperature experienced by the second cycle fruit. Others (Bertin, 1995; De Koning, 1989) have reported this delay in growth and development of younger fruit from indeterminate plants. De Koning (1989) observed that truss growth of greenhouse tomatoes may be

delayed in conditions of intense competition for assimilates and starts to grow again after the first trusses reached maturity. Resource availability in the plant appears to remain a major limiting factor for fruit set control (Bertin, 1995; Marcelis, 1992). A commonly accepted explanation for the inhibitory effect of one fruit on another is that fruit constitute strong sinks for assimilates, which draw heavily on plant supplies and inhibit the development of other fruit. Indeed, photosynthetic leaf area was a limiting factor in cucurbits (Pharr et al., 1985), reinforcing a concept of priority for assimilates to older fruit under limited source supply.

PREDICTING TIME TO MATURITY AND YIELD OF MUSKMELONS. Results from this work have useful practical implications for crop management of muskmelon. Number of harvestable fruit and time to maturity can be predicted from simple measurements in the field.

Muskmelon development was expressed in terms of heat units using air temperature from a nearby meteorological station and a maximum temperature accumulation formula with a base temperature of 15 °C (Table 2). When muskmelons reach 4 cm in length (unnetted stage), there is a 99% chance that they will reach maturity (Jenni, 1997). The Unnetted stage is reached 45 degree days after the bloom stage, which corresponded in 1994 to 4.3 d (Table 3). Mature fruit from the first cycle, representing 72% of total yield, originated from flowers blooming during the first 180 degree days ($\approx$ 2 weeks) after the start of anthesis of perfect flowers. Therefore, a grower could go in his/her muskmelon field 225 degree days ($\approx$ 20 d) after the start of anthesis (that is when 90% of the plants bear at least one blooming perfect flower) and count the number of fruit >4 cm to obtain a rapid estimate of close to 75% of the total number of fruit that will reach maturity.

Further, a description of phenological stages from bud to unnetted along with the average developmental time from bloom stage to each of these stages (in degree days, Table 3) permit an evaluation of time to anthesis of individual growing ovaries. Time at full slip of individual fruit can then be calculated from anthesis. Ovaries from the first-cycle fruit, i.e., blooming within 180 degree days after the start of field anthesis, had an average developmental time of 414 degree days. If time to anthesis were estimated to be >180 degree days after the start of field anthesis, it is likely to be a second-cycle fruit and 474 degree days should be considered from anthesis to full slip.

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