Predicting Yield and Development of Muskmelon (*Cucumis melo* L.) under Mulch and Rowcover Management

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Short title:

Predicting Yield and Development of Muskmelon

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Abstract

Field experiments were undertaken to predict the yield of 'Earligold' muskmelon grown with plastic mulches, rowcovers and thermal water tubes. Mulches were either black, photoselective or clear. Rowcover systems included a clear perforated polyethylene, a polypropylene agrotextile, or unperforated polyethylenes (standard or infra-red treated) with a water-filled tube. In all tunnel types, the photoselective mulch had an intermediate effect between clear and black mulch on air and soil temperatures, chilling injury and days to flowering. Plants with a clear mulch and an infrared or standard unperforated tunnel with a thermal tube survived chilling temperatures between 1.6-5.8C for seven days, flowered first, had the heaviest biomass at anthesis and had the highest early yields. Plant dry weight from transplanting to anthesis was predicted from a multiple linear regression based on heat unit formulas using air (base temperature of 14C, maximum threshold of 40C) and soil temperatures (base temperature of 12C). The base temperature for predicting developmental time to anthesis of perfect flowers was 6.8C. In order to study fruit growth, a rapid and non-destructive method for estimating volume of ovaries was established. Fruit phenology was described as six classes for flower development and seven for fruit development. Flower abortion was studied in relation to each class. Plants displayed either one or two fruit growth cycles. The second cycle was triggered as the absolute growth rate of the first cycle fruits decreased. Developmental time of individual fruits was predicted from a heat unit formula with a base temperature of 15C when temperatures were recorded from a meteorological station. Another heat unit formula was proposed for air temperature at 7.5 cm. Fruit growth from the second cycle had a 60-degree day lag. Fruit volume proportion from blooming to maturity of first cycle fruits was described by a common Richards function. Although 65% of the plants produced two fruit cycles, fruits from the first cycle represented 72% of the total yield. Counting the number of developing fruits longer than 4 cm 225 degree days after anthesis gave a rapid estimate of the number of fruits reaching maturity.

Résumé

Des expériences en champ ont été mises sur pied dans le but de prédire les rendements du melon brodé 'Earligold' cultivé avec des paillis plastiques, des mini-tunnels et des tubes d'eau thermiques. Les paillis étaient noirs, clairs ou photosélectifs. Les systèmes de mini-tunnels comprenaient un polyéthylène clair perforé, un agrotextile de polypropylène, ou un polyéthylène non-perforé (standard ou traité infra-rouge) muni d'un tube rempli d'eau. Dans tous les types de tunnels, le paillis photosélectif avait un effet intermédiaire, entre les paillis clair et noir, sur la température de l'air et du sol, les dommages au froid et le nombre de jours à la floraison. Les plantes placées sur paillis clair et sous tunnels non-perforés avec un tube thermique ont survécu des températures allant de 1,6 à 5,8C durant 7 jours consécutifs, ont fleuri les premiers et obtenaient la plus grande biomasse à l'anthèse ainsi que de meilleurs rendements hâtifs. On a pu prédire le poids sec des plantes entre la transplantation et l'anthèse à partir d'une régression linéaire multiple basée sur des formules d'unités thermiques utilisant les températures de l'air (température de base à 14C et seuil critique à 40C), et du sol (température de base à 12C). La température de base sélectionnée pour prédire le temps de développement de la transplantation à l'anthèse était définie à 6.8C. Dans le but d'étudier la croissance du fruit, on a établi une méthode rapide et non-destructive estimant le volume des ovaires. La phénologie du fruit était décrite à partir de six classes pour le développement de la fleur et sept pour le fruit. L'avortement des fruits a été étudié en fonction de chacune de ces classes. Les plantes montraient une mise à fruit à un ou deux cycles de production. Le deuxième cycle de mise à fruit était déclenché alors que le taux de croissance absolu des fruits du premier cycle décroissait. Une formule d'unité thermique avec une température de base à 15C a permis de prédire le temps de développement du fruit, à partir de données de température de l'air provenant d'une station météorologique. Une autre formule de cumul thermique est proposée quand on utilise des données de température à 7,5 cm. La croissance des fruits du deuxième cycle avait un retard de 60 degré-jours par rapport à ceux du premier cycle. La proportion du volume des fruits du premier cycle, à partir de l'anthèse jusqu'à la maturité, est décrite à partir d'une fonction de Richards commune à tous ces fruits. Même si 65% des plantes avaient deux cycles de production, les fruits provenant du premier cycle comprenaient 72% des rendements. Un comptage du nombre de fruits ayant une longueur dépassant 4 cm après 225 degré-jours à partir de l'anthèse permettrait une estimation rapide du nombre de fruits atteignant la maturité.

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Thesis Format

This thesis body consists of a collection of original papers that have been submitted to appropriate scientific journals for publications. Since the manuscript-based structure for the thesis was chosen, the relevant section of regulations as cited in the "Guidelines for Thesis Preparation" from the Faculty of Graduate Studies and Research must apply:

"Candidates have the option of including, as part of the thesis, the text of a paper(s) submitted or to be submitted for publication, or the clearly-duplicated text of a published paper(s). These texts must be bound as an integral part of the thesis.

If this option is chosen, connecting texts that provide logical bridges between the different papers are mandatory. The thesis must be written in such a way that it is more than a mere collection of manuscripts; in other words, results of a series of papers must be integrated.

The thesis must still conform to all other requirements of the "Guidelines for Thesis Preparation". The thesis must include: A Table of Contents, an abstract in English and in French, an introduction which clearly states the rationale and objectives of the study, a comprehensive review of literature, a final conclusion and summary, and a thorough bibliography or reference list.

Additional material must be provided where appropriate (e.g. in appendices) and in sufficient detail to allow a clear and precise judgement to be made of the importance and originality of the research reported in the thesis.

In the case of manuscripts co-authored by the candidate and others, the candidate is required to make an explicit statement in the thesis as to who contributed to such work and to what extent. Supervisors must attest to the accuracy of such statements at the doctoral oral defense. Since the task of the examiners is made more difficult in these cases, it is in the candidate's interest to make perfectly clear the responsibilities of all the authors of the co-authored papers. Under no circumstances can a co-author of any compoent of such a thesis serve as an examiner for that thesis."

In accordance with the above statements, I must mention that Parts 2 to 6 of the thesis were drawn from manuscripts for publication. All five manuscripts are co-authored by Drs. Gaétan Bourgeois, Daniel C. Cloutier and Katrine A. Stewart. The candidate (S. Jenni) performed all the experimental research, statistical analysis and is the primary author of all five manuscripts. Dr. G. Bourgeois and D.C. Cloutier offered supervisory guidance, assistance in the statistical and modeling procedures and reviewed the manuscripts. Dr. Gaétan Bourgeois provided a SAS program that he developed to fit Richards growth functions that was applied to fruit volumes in Parts 4 and 5. Dr. K.A. Stewart provided supervisory guidance and assisted in manuscript preparation.

The Part 2 manuscript titled **a Heat Unit Model to Predict Growth and Development of Muskmelon to Anthesis of Perfect Flowers** was published in the *Journal of the American Society for Horticultural Science* 121(2):274-280.

The Part 3 manuscript titled **Non-destructive Volume Estimation for Growth Analysis of Eastern-type Muskmelon Ovaries** was accepted for publication as a note in *HortScience*.

The Part 4 manuscript titled **Fruit Set, Growth and Development of Muskmelon (*Cucumis Melo* L. var. Reticulatus Naud.) under northeastern climate** has been submitted for publication to the *Canadian Journal of Plant Science.*

The Part 5 manuscript titled **Prediction of Yield and Time to Maturity of Muskmelon Fruits from Weather and Crop Observations** has been submitted for publication to *Journal of the American Society for Horticultural Science*.

The Part 6 manuscript titled **Plastic Mulches in Combination with Rowcovers and Thermal Water Tubes to Prevent Chilling Injury of Muskmelon** has been submitted for publication to the *Journal of the American Society for Horticultural Science*.

Part 1. General introduction

1.1 Plasticulture and muskmelon production

Plasticulture may be defined as a system of growing crops wherein a significant benefit is obtained from using products derived from plastic polymers (Lamont, 1996). Plasticulture in field production includesw the use of plastic mulches, where the plastic film is directly applied to the soil, rowcovers, which cover the whole plant, drip irrigation and artificial windbreaks. Rowcovers consist of either mini-tunnels which are made of plastic sheets supported by wire hoops, or floating rowcovers which are unsupported (Wells and Loy, 1986). Mulches alone or in combination with rowcovers are currently the most widespread plasticulture techniques used in Quebec.

The use of plastic mulches and rowcovers have increased tremendously since the time when they were first used in the field in the 1950's (Emmert, 1955). In 1994, the International Committee for Plastics in Agriculture (ICPA) estimated the surface areas with plastic mulches at 240 000 ha in Europe, 2 000 ha in Africa, 3500 ha in the Near East, 180 000 in America and 3 100 000 ha in Asia and Oceania (Printz, 1996). China has the largest surface area under plastic mulches with 2 870 000 ha. In addition to the gains in yields, water resource management is the major advantage of use of plastic mulches in the warm climates (Mahrer *et al.*, 1984), whereas crop earliness is certainly one of the major advantages of the use of plastics in colder climates (Wells and Loy, 1985). World rowcover use is estimated at 273 000 ha (Printz, 1996). Almost 90% of this amount consists of hoop-supported tunnels, the rest being floating rowcover. Surface area with plasticulture in the southwest region of Montreal increased from 20 hectares in 1983 to 300 hectares in 1988 and is estimated today at about 2 600 hectares (Yelle, pers. comm.).

Research in Quebec has shown gains in yield and earliness from the use of mulches and/or rowcovers for warm-season vegetables like cucumber (Argall and Stewart, 1990), muskmelon (Jenni *et al.*, 1991), tomato (Champagne and Stewart, 1990), sweet corn (Arnold, 1973), as well as from the use of floating rowcovers with cool-season crops such as bean (Kimani, 1988), iceberg lettuce and mini carrot (Jenni and Stewart, 1989), potato

(Michaud *et al.*, 1990) and celery (Jenni and Stewart, 1992). Muskmelons are among the most responsive of all crops to plasticulture because they are sensitive to both low soil and air temperatures and to wind, but are very tolerant of high temperatures (Bonnano and Lamont, 1987; Hemphill and Mansour, 1986; Shales and Sheldrake, 1965; Wells and Loy, 1985; Wittner, 1993). This high-value crop could not be produced commercially in Quebec without the use of plastics (Argall and Stewart, 1988). Using this technology, about 50 growers in Quebec are producing high quality muskmelons for the local market during a period covering from the end of July to September (Anon., 1991). The majority of the imported muskmelon fruits found on Quebec market comes from California, Arizona or Mexico (Fuller and Hall, 1990).

Several advantages have been recognized in the use of mulches/rowcovers. These include:

1) earlier and higher overall yields: due to an increase in soil and air temperature which promotes rapid development and earlier yields (Wells and Loy, 1985);

2) wind protection: rowcovers act as a windbreak and protect plants from the detrimental effect of wind (Guttormsen, 1972);

3) reduced evaporation: because of its impermeability, plastic reduces soil water evaporation loss (Mahrer *et al.*, 1984; Hanlon and Hochmuth, 1989);

4) weed control: black and wavelength selective mulches prevent weed growth by blocking the photosynthetic active radiations (PAR) and allow soil warming by letting the near infra-red radiation (IR) pass through (Loy *et al.*, 1989);

5) reduced fertilizer leaching: excess water runs off the impervious mulch; fertilizer beneath the mulch is not lost by leaching (Locascio *et al.*, 1985);

6) reduced soil compaction: plastic films prevent soil crusting and maintain the aggregate structure of soil particles by breaking the impact of rainfall or by maintaining soil surface moisture (Liptay and Tiessen, 1970; Hemphill and Crabtree, 1988);

7) higher fruit quality: the fruits are not in direct contact with the soil, and as such, stay cleaner and are less subject to rot;

8) pest control: rowcovers may act as a physical barrier against insect infestation (Natwick and Laemmlen, 1989) or reflective mulch may reduce insect populations (Stapleton *et al.*, 1993).

However, there are several disadvantages related to the use of plastic mulches and rowcovers, namely,

1) greater initial cost: in addition to the cost of plastic material, investment is required in some specialized equipments including a bed former, a mulch layer and perhaps a mulch transplanter;

2) greater risks of radiation frosts: risks of frosts may be greater under a clear rowcover during calm, clear nights because it increases the strength of the temperature inversion (Tanner, 1974);

3) removal and disposal: plastics are disposed of routinely by burning or dumping in landfill sites. Use of bio- or photo-degradable plastics has been recognized as an alternative solution for the disposal problem, but they are quite variable in their rate of degradation. Other options are retrieval and recycling or incineration/energy reclamation for the BTUs locked inside the plastic mulch (Hemphill, 1993).

Growers face a choice in determining the combination of a number of plastic mulch and rowcovers available on the market. Mulches may be black, clear or a range of colors which include the wavelength selective characteristics. Tunnels may be perforated or not, and may be clear, white or infra-red opaque. Although the agronomic success of these technologies has been demonstrated for many crops, growers lack management tools in order to maximize the use of this costly, sometimes risky, high-input technology.

Presently, management of crops grown under mulches and rowcovers is mostly based on the knowledge and expertise of the grower. Considerable guesswork is involved in the production of crops using these palsticulture techniques. Predicting yield of a muskmelon crop grown under different combinations of mulches/rowcovers, based on simple information from the microclimate, namely air and soil temperatures, could have important implications concerning the management of plasticulture for this crop in the future. This predictive information could be used for programming sowing dates and scheduling crop harvests, thus eliminating much of the guesswork. This management information would ensure a continuity of supply of appropriate amount of produce to markets and help to plan for labor availability.

In the next section, alternatives in the modeling approaches, in relation to their abilities to predict crop growth and development will be discussed.

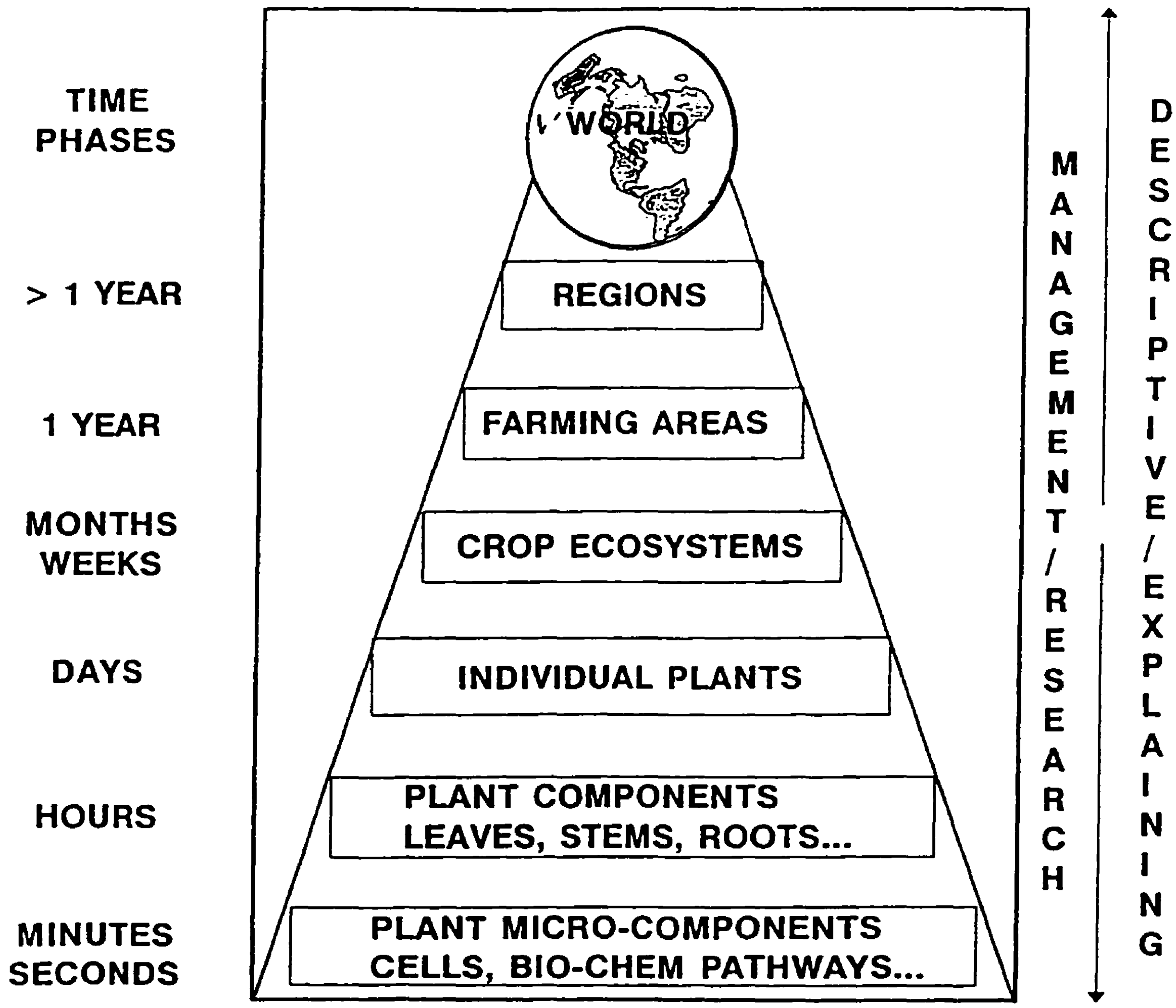
1.2 Basic terminology and modeling approach

Some terms common to system concepts have specialized meanings. Penning de Vries (1983) defined a *system* as a part of reality with strongly interacting elements. A *model* is a simplified representation of a system and *simulation* is the art of building mathematical models and the study of their properties with reference to those of the systems they represent (Rabbinge and de Wit, 1989). Plant physiologists have classified models according to their objectives. According to Krug (1985), models may have different degrees of abstraction levels depending on whether the model serves more as a management tool, or for explanation of the biological process itself. Various nomenclatures are used in the literature (Johnson and Rausser, 1977; Krug, 1985; King *et al.*, 1993). Models qualified as biophysical, explaining, behavioral, mechanistic, explanatory, comprehensive, process or causal, are considered to have a low abstraction level. These models are based on the underlying physiological knowledge which has to be structured and quantified. In contrast, the models qualified as biometric, descriptive, statistic, empiric, demonstrative, regression, predictive or black box, have a high abstraction level. They describe the behavior of the system disregarding the underlying, causal physiological processes.

An important distinction is made between *static* and *dynamic models* (Rabbinge and de Wit, 1989). Static models abstract from time while dynamic models are ones in which time enters in an integral way. Dynamic models often incorporate a concept termed *feedback* which refers to information flows between time periods. Feedbacks are viewed in terms of controls and are essential to models which are truly sequential in nature. Models used for *control* purposes are dynamic models which enable the prediction of crop performance as related to the particular status of the crop at any given moment. Static models are of particular importance with respect to *planning*, but less suitable for control purposes (Challa, 1989)

The choice of type of model also depends on the levels of organization at which the system is defined (Penning de Vries, 1983). These different levels of organization may be classified according to the size of the system (Figure 1.1), for example ranging from molecules, cells, tissues, organs, individual plants, cropping systems, farming areas, to larger ecosystems such as the world (Penning de Vries, 1983; Jones *et al.*, 1987; Liebig, 1989). To each level of organization corresponds a time phase or relaxation time, that is the time to return to an equilibrium state after a sudden disturbance (Penning de Vries, 1983). For long-term processes like crop rotation, planning models are appropriate tools for management purposes (Liebig, 1989). Planning models may also be used where the whole crop is divided into growth phases but control models are needed to accurately describe the time course within the phases, especially if growth processes such as photosynthesis and respiration are included. Models become even more sophisticated at the levels of enzymes, molecules and atoms, but from these levels, the predictive value may decrease in contrast to its explaining capabilities (Liebig, 1989). It is not always clear whether one modeler should use a descriptive or an explanatory approach. Penning de Vries (1983) stated that *'although descriptive models are attractive because of their simple and straightforward relation between yield and one or more environmental variables, they are never accurate and cannot be generalized to other areas, crops or years'*. Another element of importance in the choice of the model is the availability of information required for the model. The more accurate a dynamic model is, the more information is required for initialization and for driving variables (van Ceylon *et al.*, 1976). If these are unavailable, then a regression model may be the best option.

Figure 1.1. Levels of processes in biological and agricultural systems with characteristic time phases (adapted from Penning de Vries, 1983; Jones, Mishoe and Boote, 1987; Liebig, 1989).


TIME PHASES
> 1 YEAR
1 YEAR
MONTHS WEEKS
DAYS
HOURS
MINUTES SECONDS
WORLD
REGIONS
FARMING AREAS
CROP ECOSYSTEMS
INDIVIDUAL PLANTS
PLANT COMPONENTS LEAVES, STEMS, ROOTS...
PLANT MICRO-COMPONENTS CELLS, BIO-CHEM PATHWAYS...
MANAGEMENT/RESEARCH
DESCRIPTIVE/EXPLAINING

1.3 Prediction models in vegetable field crops

Models dealing with yield prediction for production planning are found both for field and greenhouse crops. Models for field crops tend to be more descriptive and are often based on heat units. Models for greenhouse production tend to be more explanatory in nature because data from these controlled environment are more easily available. Greenhouse models have limited adaptability to field crops using mulch/rowcover technologies which offer little control on the environment (temperature, CO_2, light, humidity) and on plant structure (pruning). Therefore, this literature review will focus on existing field prediction models.

1.31 The heat unit approach

The heat unit system has been widely adapted by the canning industry, particularly as a means of scheduling planting dates to insure a regular flow of raw materials at an optimal stage of maturity to the cannery. Early work was done on pea (Boswell, 1929) and sweet corn (Maroon and Culpepper, 1932) and later on spinach (Boswell, 1935), asparagus (Culpepper and Moon, 1939), lettuce (Madariaga and Knott, 1951), tomato (Austin and Ries, 1965), collard (Dufault *et al.*, 1989), cucumbers (Perry and Wehner, 1990; Perry *et al.*, 1986) and potato (Arazi *et al.*, 1993). Crops other than vegetables have made use of the heat unit system for the prediction of growth and development, including fruit, ornamental, fiber, grassland and cereal crops (Bootsma, 1984; Fry, 1983; Garcia-Huidobro *et al.*, 1982 a &b; Johnson and Lasko, 1985; Karlson *et al.*, 1990; Malézieux *et al.*, 1994). Further applications of the heat unit approach have been used for scheduling pest management programs for insect, disease and weed control (McGriffen and Masiunas, 1992; Johnson, 1991; Ahmad, 1988). The system has also been used in the selection of suitable farming areas and of appropriate crop varieties for these areas (Cross and Zuber, 1972; Dodd, 1991). The heat unit system has been widely adopted because it satisfies practical needs, rather than for its accuracy or its theoretical soundness. However, researchers applying this system have made many refinements in the methodology.

There are basically two approaches found in the literature for modeling plant development using the heat unit system. The simplest one assumes that rate of development is linearly related to temperature. Another approach considers a curvilinear relationship between rate of development and temperature, and involves the fitting of a series of empiric formulas of heat units often incorporating lower and/or upper temperature thresholds. The best formula is determined using regression techniques to identify the method which is the most accurate in predicting a particular developmental stage. Further developments of the heat unit system made inclusion of other environmental variables such as soil moisture or day length.

1.311 The linear heat unit system

The most common method of calculating heat units is the daily mean method, in which a day is the time unit and each degree above a base temperature has a linear effect on plant growth and on the accumulation of heat units (Arnold, 1959 and 1960). This can be expressed as:

$$\theta = \Sigma\ (TMAX + TMIN)/2 - Tb$$

where TMAX is the daily maximum, TMIN the daily minimum temperature, Tb is the base temperature (Celsius) and θ is the thermal time (Celsius degree-day). By this method, negative values are ignored and the minimum daily accumulation is zero. In all predictive methods, it is assumed that the plant must accumulate a certain number of heat units in order to complete a developmental stage.

The x-intercept or development rate method is an alternative and a simple method of determining the base temperature of a particular crop (Arnold, 1959; Monteith, 1977). This method is based on the assumption that the rate of development varies linearly with temperature between a minimum and an optimum:

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

where t is the time required to complete a developmental process (days); T is the prevailing temperature (Celsius). Therefore, by plotting on the y axis the rate of development (1/t) and on the x axis the prevailing temperature during that period, a regression line can be drawn to determine the parameters Tb (base temperature) as the intercept of the regression line with the x 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 provided that no temperatures above an optimum occur (Munoz *et al.*, 1986). These data are usually readily obtained from most climatological records. Although the x-intercept method has been statistically criticized because it extrapolates a regression model (Yang *et al.*, 1995), this method is simple, analytical and widely used (Monteith, 1977; Garcia-Huidobro *et al.*, 1982b; Munoz *et al.*, 1986).

Wang (1960) indicated a number of non random errors associated with the use of the linear heat unit system:

1) Growth and development rates of plants do not change linearly with temperature.

2) Plants respond differently to the same environmental factor during the different stages of their life cycles (Brown and Chapman, 1960).

3) Variables other than temperature (e.g. soil moisture, vapor pressure deficit, solar radiation, wind and duration of light) may influence the rates.

4) The base temperature differs among varieties (Hoover, 1955).

5) Substantial errors may occur when lower and upper threshold temperatures are not determined correctly or when they shift with plant aging.

6) Small inaccuracies in temperature measurements may result in substantial error when accumulated over an extended period.

7) Temperatures measured at a distance from the field may introduce large heat units errors over time. Katz (1952) suggested that weather data should be collected at plant height.

8) The time intervals used may differ from one method of heat unit calculation to another.

Refinements to the basic linear heat unit system aiming to reduce these non random errors are presented below.

1.312 Non linear heat unit systems

The linear heat unit system, which presumes that plants accumulate a certain number of heat units in order to complete a given developmental stage, has given variable results. This system worked well in England (Gray *et al.*, 1980), where daily mean temperatures ranged from 10 to 17C, but not in California (Austin and Ries, 1965; Warnock and Issacs, 1969; Warnock, 1970), or in Israel (Wolf el al., 1986) where the temperature range is 15 to 30C. Working with lettuce, Madariaga and Knott (1951) introduced the idea of a temperature ceiling, considering daily maxima that exceeded 21C as being 21C before summing the heat unit. Gilmore and Roger (1958) used a so-called 'heat stress system' in corn where the number of degrees by which the daily maximum exceeding the ceiling was subtracted from the daily mean temperature. An advantage of this method was that it tended to compensate for the quadratic nature of the development rate curve in the high temperatures. Then, if we assume an optimum temperature of 30C, a temperature of 35C might be equivalent to a temperature of 25C in terms of growth for a particular day. Many other formulas have been developed using combinations of upper and/or lower threshold to take into account the non-linearity of the development rate curve related to temperature. Brown (1975) developed a formula that expressed the relationship between temperature and the sum of heat units for corn development until ripening. This relationship is a quadratic function, with an optimum at 30C and a minimum base temperature of 10C, below which no heat accumulation occurs. In Brown's model, heat units are calculated separately during the day and the night.

1.313 Including other variables

Madariaga and Knott (1951) used heat unit summations multiplied by day length to predict the time to maturity for head lettuce planted over a nine month period in the Salinas and the Imperial Valleys of California. This procedure has been also used to compensate for the differences in growth over different seasons for snap beans (Guyer and Kramer, 1952). Wolf *et al.* (1986) included soil moisture stress indices based on tensiometer readings working on a tomato model for Israel.

1.314 Other heat unit related approaches

McKinion *et al.* (1975) developed an alternative concept of the 'physiological day'. For cotton, one physiological day was equivalent to a calendar day with a constant temperature of 26C. In this system, heat accumulation is calculated separately for the day and the night and is weighted according to day and night length, respectively. Physiological days were also used in a prediction model for processing tomatoes in Israel (Wolf *et al.*, 1986). The input data were latitude, daily minimum and maximum temperature, planting date, soil moisture and plant stage. Prediction of the harvesting date on the basis of data from 44 fields showed a mean accuracy range of 3-4 days as compared with a 9-day range when a heat unit based on daily means was used. The authors did not include any upper thresholds in their method.

1.315 Heat unit and rowcovers

Hadley *et al.* (1993) predicted emergence and vegetative development of iceberg lettuce, carrot and potato grown under floating rowcovers based on a linear heat unit system. Under the United Kingdom climate, they found that dry weight of iceberg lettuce, root diameter of carrot and ground cover of potatoes were correlated with the number of degree-days after planting. However, yield of potatoes could not be predicted using degree-days alone. Light interception was found to be a major contributing factor for yield prediction.

Hemphill (1989) correlated yields of tomato, sweet corn, cucumber and muskmelon with mean temperature and heat unit accumulation under several types of plant protection devices including plastic mulches and rowcovers. Although results were quite variable, he found strong correlations between early yields and the standard heat unit formula (base temperature of 10C), particularly for heat tolerant crops like cucurbits. Introducing a maximum threshold or modifying the base temperature did not improve the fit.

Wolfe *et al.* (1989) used eight modified heat unit models to evaluate early and total yields of tomato and cucumber under several mulch/rowcover materials. Formulas included upper thresholds (30, 35, 40C), lower thresholds (5, 10C), base temperatures (5, 10C), air and/or soil temperatures during rowcover placement and adjustments for PAR transmission through the rowcovers. Although tomato yields could not be accurately predicted using this approach, the authors found a positive linear relationship between the simplest standard formula of cumulative degree-day and cucumber biomass, as well as early and total yield. Early and total yield response could be predicted by information on temperature during the early stage, i.e., during rowcover placement. However, no information on yield distribution was provided.

1.32 Non-temperature related approaches

Models predicting harvest dates of once-over harvested field cucumber exist based on data recorded at a time close to optimum harvest. Holtman *et al.* (1974) developed a simple model to assist the grower in making decisions as to the most profitable date for once-over mechanical harvest of pickling cucumber. This model predicted the fruit size distribution based on the number of fruit per grade class for a period of five days prior to the considered optimum harvest using an empirical function that did not consider climatic conditions. Chen *et al.* (1975) developed models for harvesting pickling cucumbers for both once-over and multiple harvesting. Inputs included average weight per fruit, sale price as well as average time required to advance from one grade to the next, plant population, fruit arrival probability, recovery efficiency of the harvester and sample size. They concluded that the multiple harvesting model showed promise as a valuable tool in scheduling operations, although limited knowledge and data of the physiological aspect of cucumber growth limited the validity of the model. Later versions of the model included the effects of planting interval, acreage and risks associated with the day-to-day weather uncertainty that could limit harvest work (Chen *et al.*, 1976; Chen, 1979).

An agricultural robot for harvesting muskmelon has been recently developed (Edan and Miles, 1993). A model testing the performance of the robot was based on total harvest as the machine must approach all the fruits for ripeness detection. Although it would have been a more valid simulation, the authors did not use only ripened fruits as input for their model because no data on the ripeness distribution of muskmelons during the season was available.

In 1992, Sullivan *et al.* developed an expert system for integrated production management in muskmelon. This system included production, pest management and economic aspects which they felt would be of use in a decision making process. Their system objective was to enable the grower to schedule for the earliest planting with the least risk of frost, taking into consideration the various constraints of production. However, they did not stress the underlying physiological and developmental aspects that lead to decision making.

1.33 Micrometeorological models

A recent model was developed to predict soil temperatures under plastic mulches (Wu *et al.*, 1995). The model required data usually available from meteorological stations (hourly measurements of global radiation, air temperature, dew point, wind speed and rainfall) and predicted soil temperatures within 2C. Plants were not taken into account in this model, as its primary objective was to evaluate the potential application for soil solarization.

An explanatory model describing mulch/mini-tunnel microclimate was developed by Albright, Wolfe and Novak (1989). This time dependent model used exterior air temperature and solar radiation as inputs and tunnel air and soil temperatures as outputs. Parameters of this model included thermal conductivities of soil and rowcover, convective heat transfer coefficients of soil and rowcover, long and short wave radiation of soil and rowcover, tunnel dimensions, air exchange rates, perimeter heat loss factor, soil volumetric heat capacitance and initial temperatures at 10 levels throughout the plasticulture system. In order to use this model, values for each of these parameters should be set for each of the plasticulture system considered. Under test, this model showed that minimum air temperature could be predicted within 2C, and maximum air temperature and soil temperatures could be overestimated by as much as 10C.

1.4 Thesis objectives

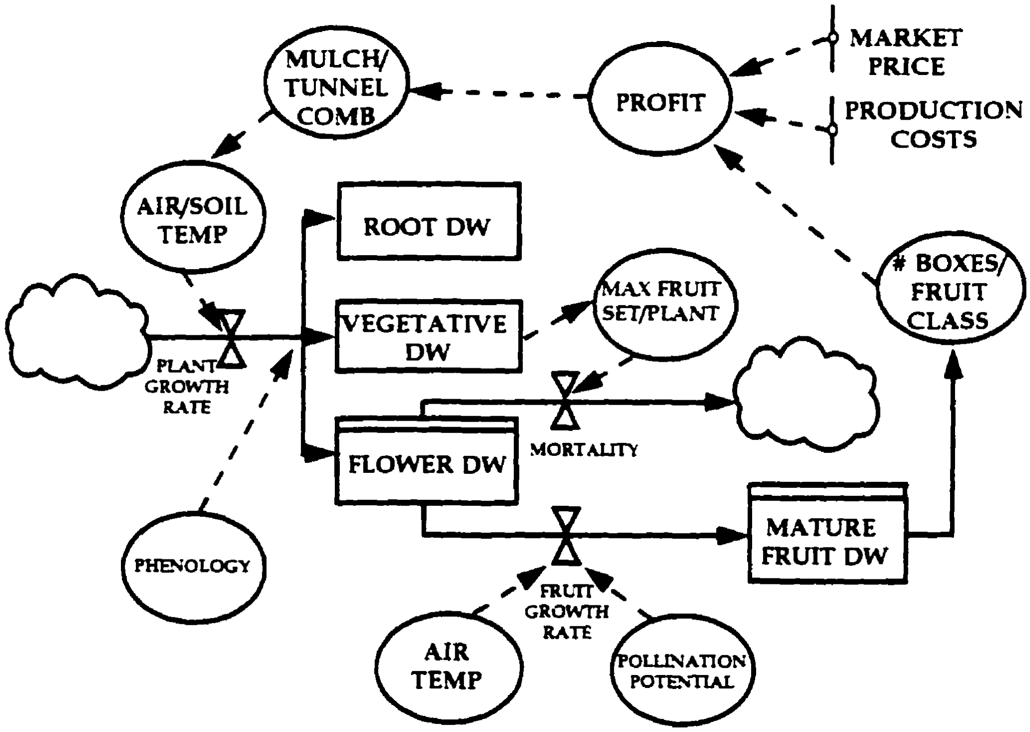
1.41 Conceptualization of the system: a relational diagram

In order to represent the components in the system and to summarize their relationships, models are often illustrated by relational diagrams according to the method developed by Forrester (1961). A relational diagram of the model under study is presented in Figure 1.2. State variables are represented by rectangles and the flow of material by solid arrows. The rate of these flow are represented by the valve symbol. Sources and sinks are visualized by cloud-like forms and represent the environment of the system. It is assumed that flow can occur from a source in the environment into the system or from the system into a sink in the environment without affecting the environment (Jones *et al.*, 1987). Auxiliary variables are shown by circles and represent factors (input and parameters) that influence the rates. Dashed lines represent information flow. Selected variables affecting muskmelon yields were included in the relational diagram.

The system may be divided into 2 parts, a physiological part and an economic part. Only the physiological part will be dealt with in this thesis. The fruit maturity process in muskmelon can be conveniently described by two phases of development: the period from transplanting to first perfect flowers, and the period from perfect flowering to first ripe fruits (Bohn and Davis, 1957; Loy and Wells, 1975).

During the first phase, a muskmelon transplant will grow as a plant which can be subdivided into root dry weight, vegetative dry weight (leaves and stems) and flower dry weight according to a plant growth rate that will be a function of air and soil temperatures found under the various mulch/rowcover combinations. The driving variables, air and soil temperatures, characterize the effect of outside environmental conditions on the system in combination with the effect of the mulches/rowcovers. These driving variables will be monitored continuously from transplanting of the muskmelon crop to maturity. Although root dry weight will not be measured during the field experiments, this state variable is included in the relational diagram for reasons of completeness. Muskmelon plants grown with trickle irrigation have shown no significant differences with respect to root weight and vertical and horizontal root lengths when grown under clear mulch, black mulch or

Figure 1.2. Relational diagram of a muskmelon production system as affected by mulches and rowcovers. Symbols according to Forrester (1961).


MULCH/
TUNNEL
COMB
PROFIT
MARKET
PRICE
PRODUCTION
COSTS
AIR/SOIL
TEMP
ROOT DW
VEGETATIVE
DW
MAX FRUIT
SET/PLANT
BOXES/
FRUIT
CLASS
PLANT
GROWTH
RATE
FLOWER DW
MORTALITY
MATURE
FRUIT DW
PHENOLOGY
FRUIT
GROWTH
RATE
AIR
TEMP
POLLINATION
POTENTIAL

bare soil (Battikhi and Ghawi, 1987). This model will assume no differences in root growth between treatments.

During the second phase of muskmelon development, the number of perfect flowers that will abort depends on a mortality rate that may be a function of a maximum fruit set per plant. This latter auxiliary variable varies with the total above ground biomass produced under each microclimate. Some of the flowers develop into mature fruits according to a fruit growth rate related to air temperature (after the removal of the rowcover) and to pollination potential. Bees act as pollinators for muskmelon because the pollen is too heavy to be carried by wind (Bohn and Davis, 1964). Although bees may be active at temperatures of 12-14C early in the spring, pollen collection tends to increase with temperatures between 10 and 30C (Free, 1993). Pollination potential will vary with the mulch/rowcover combination. Indeed, observations from the field have shown that with some treatments flowering occurs so early in the spring that climatic conditions at that time are not always favorable to bee pollination. This condition may result in a large number of early but small fruits. The state variable fruit dry weight is shown with an additional line on top of the rectangular box to indicate that yield of muskmelon has successive harvests along the season.

The final part of the diagram shows the economic aspect of the model and will not be covered by this thesis. The weight of mature fruits can be translated into number of boxes per fruit class according to the Quebec classification (Table 1.1). The market value of the fruit will depend on the grade size. A measure of profit may be obtained from each mulch/rowcover combination according to market price of each grade, timing of arrival on the market, harvest costs, and production costs associated with each systems (Saint-Pierre and Sullivan, 1993). The optimum combinations of mulch/rowcover may then be determined according to additional returns and continuity of supply.

Table 1.1. Classification of muskmelon fruits for Quebec market according to a number of fruits per box measuring 30 cm X 35 cm X 43.5 cm.

Grade (Fruits/box)	Average Fruit Weight (g)
23	< 900
18	900 - 1200
15	1200 - 1500
12	1500 - 1800
9	1800 - 2100
8	> 2100

1.42 Statement of objectives

Physiological aspects of the model described in the previous section will be addressed in this thesis. The specific objectives of the study were to:

1) evaluate the effect of unperforated mini-tunnels with thermal tube and perforated mini-tunnel combined with three plastic mulch types (clear, photoselective and black) on growth, development and yield of muskmelon.

2) define a heat unit model that could accurately predict vegetative growth to anthesis of muskmelon cultivated under various mulches and rowcovers.

3) predict developmental time from transplanting to anthesis of perfect flowers and from anthesis to fruit maturity for muskmelon.

4) establish a rapid and non-destructive method for measuring growth of muskmelon ovaries.

5) define a reference set of phenological stages for flower and fruit development specific to muskmelon.

6) study fruit set, floral/fruit abortion, cycles and fruiting behavior of muskmelon in our northeastern climate.

7) define a simple relationship for fruit growth with clear initiation and termination parameters.

8) develop a simple technique for predicting quantity and timing of muskmelon yield.

Introduction to Part 2

To predict more precisely yield of muskmelon grown under various mulch and rowcover combinations, fruit maturity may be divided into two developmental phases: from planting to anthesis of perfect flowers, and 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 the 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 within 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.

In the next section, a heat unit model that predicts growth and development of muskmelon to anthesis of perfect flowers is presented. This model is based on simple variables, namely air and soil temperature recorded under a range of mulches and rowcover systems.

Part 2: A heat unit model to predict growth and development of muskmelon to anthesis of perfect flowers

2.1 Summary

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% 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.

2.2 Introduction

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).

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 greater than 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 mulch 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.

2.3 Materials and methods

2.31 Experimental data

'Earligold' muskmelon 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 Inc., 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, St-Rémi, Qué.), a spunbonded polypropylene (Rotop, Plastitech, St-Rémi, Qué.) 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 a 8-m-long X 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 non perforated tunnel/ thermal tube (CUT), 8) photoselective green mulch/ clear non perforated tunnel/ thermal tube (GUT), 9) black mulch/ clear non perforated tunnel/ thermal tube (BUT), 10) clear mulch/ infra-red non perforated 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-naphtalenyl-amino)carbonyl]benzoic acid) was applied on clear mulch plots according to the 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 meters 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 for the latter 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 the spring of 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.

2.32 Heat unit models

Although heat unit systems have been used mostly to predict rates of development (Monteith, 1977), they have 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.

2.321 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 2.1. 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, 10, 12 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 formula (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.

2.322 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).

2.4 Results

2.41 Description of microclimates

Table 2.2 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 infra-red treated tunnel increased night temperature more than did the standard polyethylene: CUT had one 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 4C (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 in 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.

2.42 Predicting growth before anthesis

2.421 Air-based heat unit formulas

Figure 2.1 shows the relationship between the standard heat unit accumulation with base temperatures of 5, 10 and 15C and dry weight of muskmelon plants 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 400-450 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 2.2). Increasing the base temperature from 5C to 10C 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 DD), 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 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 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.

2.422 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 a 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.

2.423 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 2.3. 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 temperatures 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% of the variation in plant dry weight. The equation shown graphically in Figure 2.2 is:

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

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 12C (Table 2.1).

2.43 Predicting time to anthesis

Table 2.4 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 Figure 2.3 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.

2.5 Discussion

Many authors have used different minimum and maximum thresholds in attempts to obtain straight line relationships 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. 2.1).

Optimal air temperature range for muskmelon has been estimated to be 18 to 24C (Lorenz and Maynard, 1988). However, tolerance in excess of 30C has been reported (Wien and Bell, 1981; Wells and Loy, 1985; Hemphill and Mansour, 1986). 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 13.3-19.5% to 7.9-13.3% when using the heat unit formula as compared 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 two years of data for 11 mulch and rowcover combinations, 86% 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 temperature which tended to vary more over replicates than air temperature due to soil heterogeneity.

No significant interactions were found between air and soil temperatures as mulch type affected soil temperature 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. 2.3). 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 which 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 temperature beyond 40C 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.

Table 2.1. Selected heat unit formulas (in degree days) tested to predict plant dry weight before anthesis of muskmelon plants grown under various mulches and rowcovers. 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 IF MX ≤ UT; MXL = UT IF MX > UT

Maximum reduced on average accumulation

F4 = (MXR + MN)/2 - BT

MXR = MX IF MX ≤ UT; MXR = UT - (MX - UT) IF MX > UT

Minimum-limited on average accumulation

F5= (MX + MNL)/2 - BT

MNL = MN IF MN ≥ LT; MNL = LT IF MN < LT

Minimum-reduced on average accumulation

F6 = (MX + MNR)/2 - BT

MNR = MN IF MN ≥ LT; MNR = LT - (LT - MN) IF MN < LT

Air minimum-stress factor on average accumulation

F7 = (MX + MN) / 2 - BT IF PREVMN > LT;

F7 = 1/2 [∑(MX + MN) / 2 - BT] IF PREVMN ≤ LT

Table 2.2. Air temperatures at 7.5 cm and time to anthesis of a muskmelon crop grown under mulch and rowcover.

Mulch/row cover/thermal tube[z]		CIT	CAO	CPO	GPO	BPO	COO	GOO	BOO	CUT	GUT	BUT
Number of days <2 C	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 <4 C	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 <6 C	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 <10 C	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 >35 C	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 >40 C	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 >45 C	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 June	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

[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).

Table 2.3. Multiple regression equations predicting dry weight (DW on a ln scale) of muskmelon plants before anthesis of perfect flowers as a function of heat unit formula based on air and soil temperatures. All terms are significant at the 0.05 level.

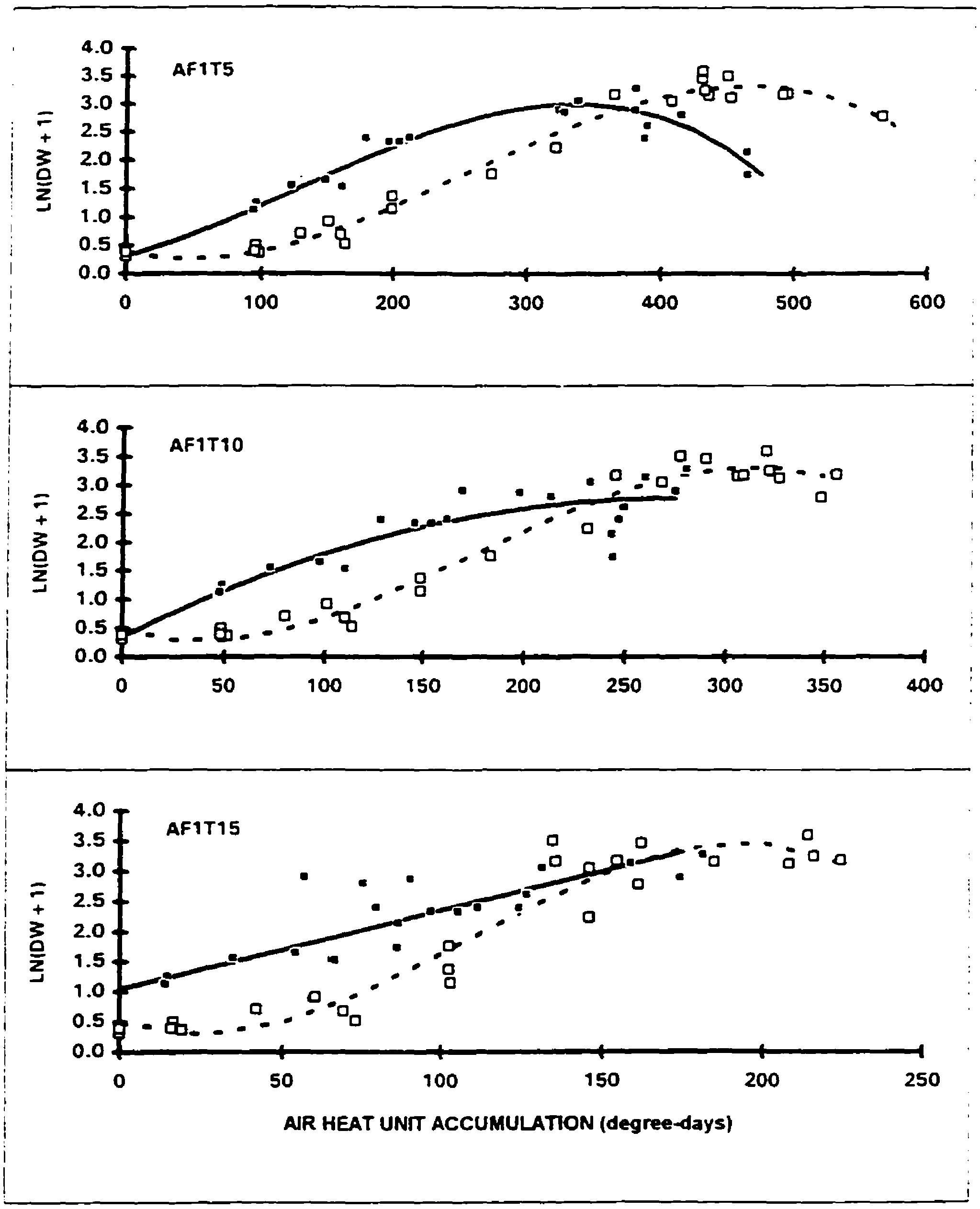
Equation[z]	Adj R^2	R^2	CV (%)
Ln(DW) = a + b (AF1T10) + c (SF1T12)	0.831	0.842	21.0
Ln(DW) = a + b (AF4T13U40) + c (AF4T13U40)^2 + d (SF1T12)	0.844	0.857	20.2
Ln(DW) = a + b (AF4T14U40) +c (SF1T12)	0.855	0.864	19.5
Ln(DW) = a + b (AF4T15U40) + c (AF4T15U40)^3 +d (SF1T12)	0.860	0.873	19.1

[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.

Table 2.4. 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 $1/t = a + b\,T$.

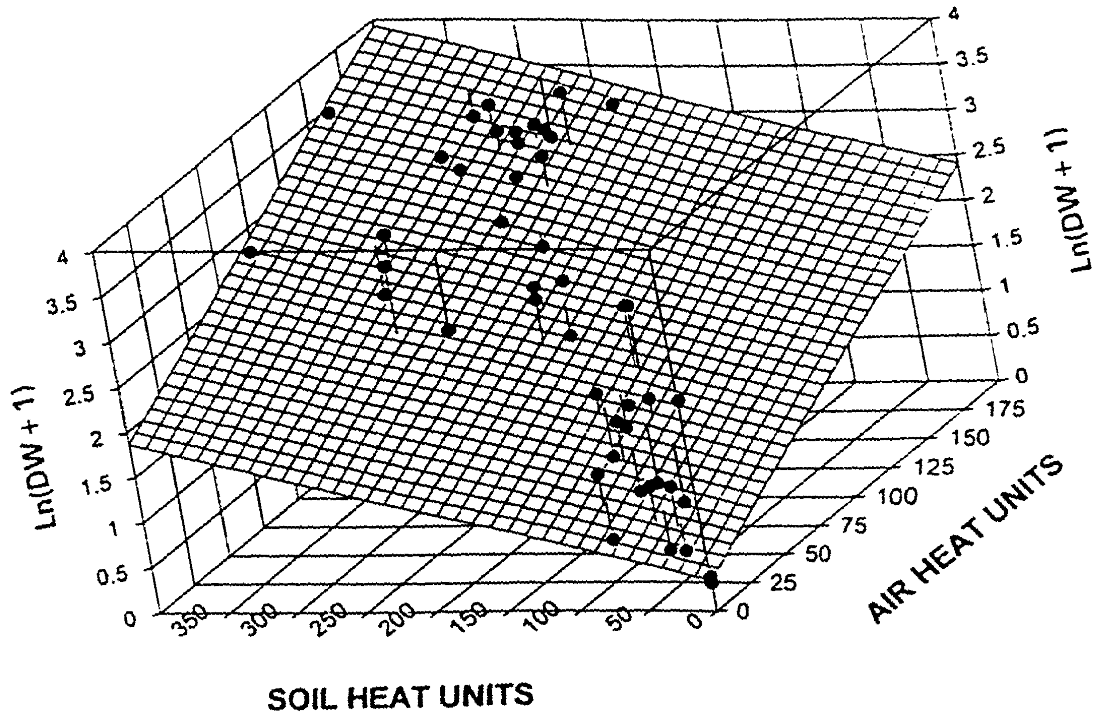
Year	Parameter	Estimate	SE	Base temperature	Thermal time	r^2 (n=11)
1993	a	-2.0124	0.5955	6.7	335	0.912
	b	0.2982	0.0308			
1994	a	-1.7510	0.9895	6.9	392	0.709
	b	0.2553	0.0469			

Figure 2.1. Relationship between air heat unit accumulation (F1 in Table 1, in degree days) with base temperatures of 5 C (AF1T5), 10 C (AF1T10) and 15 C (AF1T15) and dry weight (DW, in grams) of muskmelon plants at transplanting, 10 days after transplanting and at anthesis during 1993 (■) and 1994 (□).



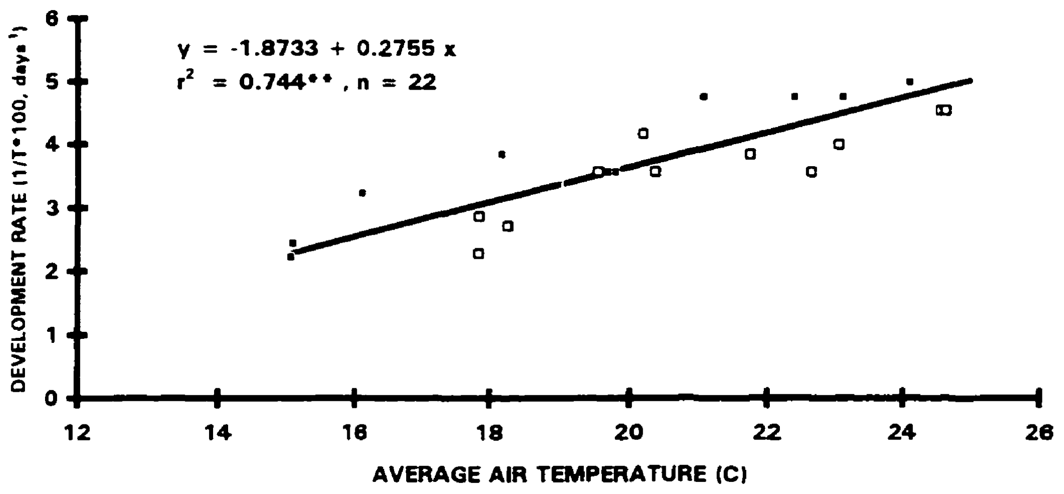
AF1T5
AF1T10
AF1T15
LN(DW + 1)
AIR HEAT UNIT ACCUMULATION (degree-days)

Figure 2.2. Plant dry weight (in grams) before anthesis of pistillate flowers as a function of accumulated air heat units (in degree days) with a base temperature of 14C and a maximum reduced of 40C (AF4T14U40), and as a function of accumulated soil heat units (in degree days) with a base temperature of 12C (SF1T12). See Table 2.1 for F1 and F4 formulations. The equation is $z = 0.336 + 0.0104\ x + 0.00382\ y$; adj $R^2 = 0.855$; n=47.



Ln(DW + 1)
4
3.5
3
2.5
2
1.5
1
0.5
0
Ln(DW + 1)
350
300
250
200
150
100
50
0
SOIL HEAT UNITS
175
150
125
100
75
50
25
0
AIR HEAT UNITS

Figure 2.3. Rate of muskmelon plant development to anthesis (1/TX100) regressed on the average air temperature prevailing under various mulch and row cover combinations. Data are shown for two growing seasons: 1993 (■) and 1994 (□).



y = -1.8733 + 0.2755 x
r² = 0.744** , n = 22
DEVELOPMENT RATE (1/T*100, days⁻¹)
0
1
2
3
4
5
6
12
14
16
18
20
22
24
26
AVERAGE AIR TEMPERATURE (C)

Introduction to Part 3

A necessary step in order to study fruit growth is to have a rapid, accurate and nondestructive method of repeatedly measuring the fruit during its development. Fruit growth may be measured in terms of size (length, diameter, volume) or weight (Gustafson, 1926). When growth measurements of a large number of fruits grown under field conditions are required, direct measurements of weight or volume by water displacement, are simply not practical nor precise. This is particularly true during early ovary development when the corolla is still attached. In the next section, a rapid and non-destructive method for estimating volume of muskmelon ovaries is presented, based on an early formula developed for mature fruits (Currence *et al.*, 1944).

Part 3. Nondestructive Volume Estimation for Growth Analysis of Eastern-Type Muskmelon Ovaries

3.1 Introduction

Fruit volume is important for studies of growth and development of muskmelon (*Cucumis melo* L.) in relation to environmental factors and management practices. Volumes measured by water displacement are precise. However, this method is time-consuming, possibly damaging for the ovaries due to repeated measures over time, and impractical, particularly for measuring many ovaries under field conditions. A nondestructive method was adapted to precisely and rapidly evaluate ovary volume at various phenological stages. This method could be used to study growth and development of eastern-type muskmelon ovaries from anthesis to fruit maturity.

Fruit volume of muskmelon has been estimated from their equatorial diameter by a 4th order polynomial regression (McGlasson and Pratt, 1963) or from their polar and equatorial diameters taking into account fruit geometry (Currence *et al.*, 1944). McGlasson and Pratt's equation was developed for fruit within a diameter range of 2.8 to 14.7 cm and cannot be used outside this range. Although Currence *et al.* (1944) developed their formula from fruit ranging from 8 to 20 cm in diameter and 9 to 23 cm in length, these authors took into account the departure of the shape of the fruit from a sphere or an ellipsoid and used a wide range of cultivars. In our work, we propose to extend the applicability of Currence *et al.*'s formula to growing ovaries. Our objective was to test Currence *et al.*'s model for small growing ovaries of eastern-type muskmelon outside the range for which it was originally developed, that is, for fruit 0.6 to 17.1 cm in diameter and 1.1 to 18.6 cm long. The volume calculated from the length and diameter of fruit at various phenological stages was compared with the volume measured by water displacement.

3.2 Materials and methods

Three week old 'Earligold' muskmelon transplants were planted 1 June 1994 into a sandy loam field covered with 1.2 m wide black plastic mulch. Water was supplied via drip irrigation lines. Nitrogen was applied at 100 $kg.ha^{-1}$ and other nutrients were applied according to soil tests and recommendations (Conseil des Productions Végétales du Québec, 1994). Insect and disease control followed Quebec recommendations. Weeds were controlled manually between the rows. The experiment had three replications of three 8m-rows with only the center row being used experimentally. Plants were spaced at 0.7 m within and 2.0 m between rows.

Once a week, one plant in each of the three replications was randomly sampled and cut at the soil level. All perfect flowers and fruit were cut at the base of the pedicel. Polar and equatorial diameters of inferior ovaries were measured using a digital caliper. After the calyx and the corolla were removed, the volume of the ovary or fruit was measured by immersion in a graduated cylinder. In total, 167 ovaries at various phenological stages were measured over 6 weeks. Only one polar diameter was measured because it was very uniform for young immature fruit; this was not true for more mature fruits, which might account for a greater variation in predicting values when larger fruit volumes were estimated. Ovary volume was calculated from polar and equatorial diameters according to formula developed by Currrence *et al.* (1944):

$$Y = K\,D^2\,L / 1000$$

where: $K = 0.1528\ (D/L) + 0.4152,\ \text{if}\ (D/L) \leq 1$

$K = -0.2204\ (D/L) + 0.7872,\ \text{if}\ (D/L) > 1$

and Y is fruit volume (cm^3), K, a shape factor, D, fruit diameter (mm) and L, fruit length (mm).

3.3 Results and discussion

Most of the range between 0.5 and 17 cm in ovary diameter and 1 to 19 cm in ovary length was covered, with a particular emphasis of size around the time of anthesis, when it averaged 0.9 cm in diameter and 1.5 cm in length (Fig. 3.1). A majority (90%) of the ovaries were oval shape, with a length/diameter > 1.

Simple linear regression analysis was performed (SAS, 1986, v. 6.09) between the volume of growing muskmelon ovaries measured by water displacement (actual volume) and the volume estimated from ovary length and diameter (Fig. 3.2). The assumption that predicted value at fruit volume 0 cm^3 was 0 cm^3 was confirmed, as the intercept of the model was not significantly different from zero at $P \leq 0.05$. A second analysis with the intercept fixed at zero resulted in a coefficient of variability of 8.7%, a coefficient of determination of 99.7% and a slope of 0.984. Although the slope was close in value to 1.000, a t test indicated that the slope was significantly different from 1.000 at $P \leq 0.001$. Therefore, although the prediction of fruit volume using Currence *et al.*'s model (1944) is accurate for mature fruit, a slight, although significant, correction is suggested to evaluate volume of growing ovaries from eastern-type muskmelon. The cultivar used in this experiment might have accounted for this difference, because eastern types tend to be more oval than western types.

3.4 Conclusion

Calculated fruit volume from polar and equatorial diameters provided a good estimate of fruit volume measured by water displacement. Although the equation was originally developed for large fruit, it can also be used for developing ovaries. Currence *et al.*'s equation was developed using eastern, western, and honeydew types of melons, but it can be easily adapted to specific needs. We suggest the use $Y = 0.984\ K\ D^2\ L / 1000$ for ovaries of eastern-type muskmelon, such as 'Earligold', that are 0.5 to 17 cm in diameter and 1 to 18 cm long. This equation allows for rapid, nondestructive, and accurate estimation of growing ovary volume by measuring length and diameter directly in the field.

Figure 3.1. Frequency distributions of the (**A**) diameter (D, mm), (**B**) length (L, mm) and (**C**) shape (expessed as L/D) of 167 muskmelon ovaries.

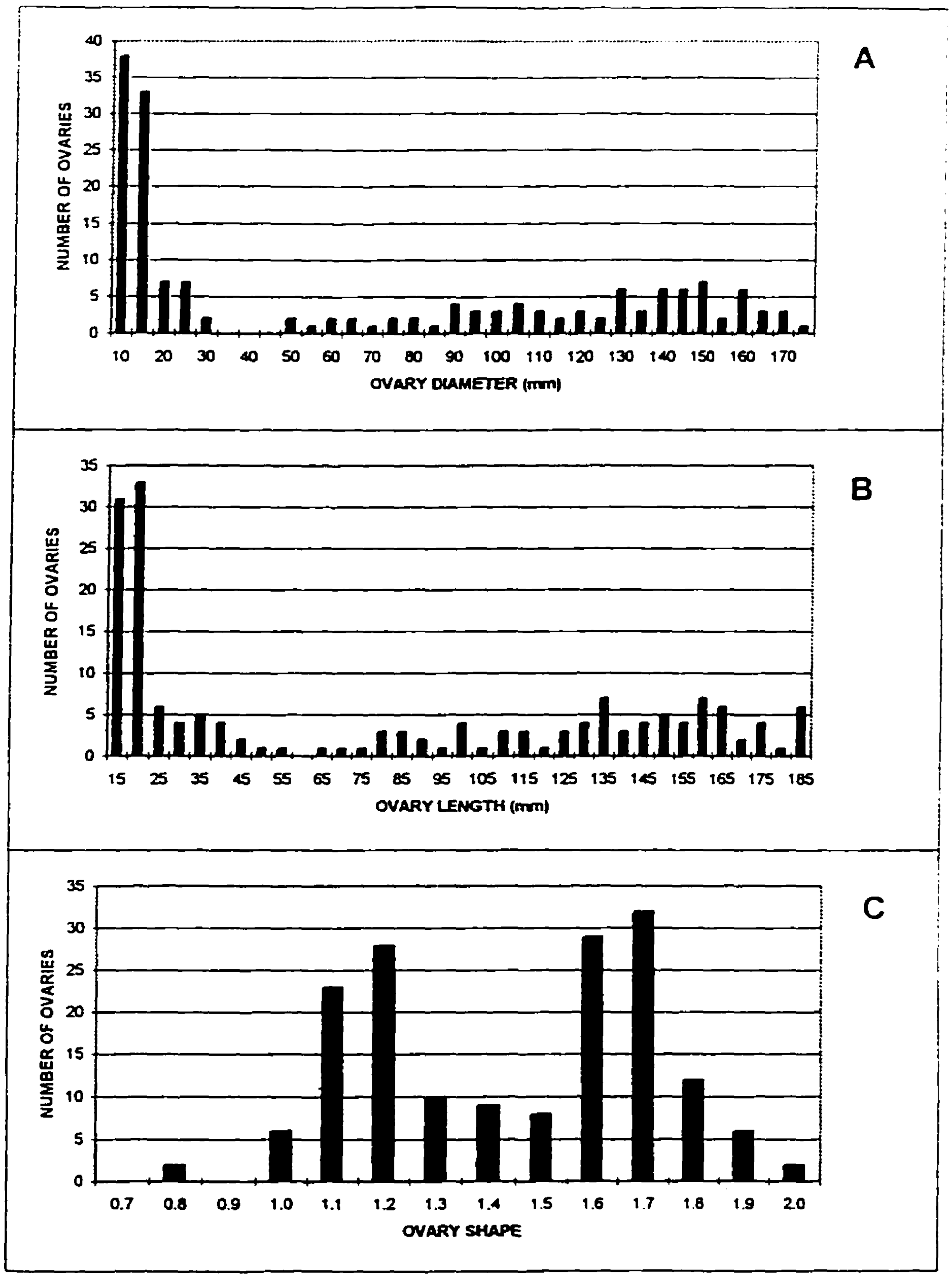
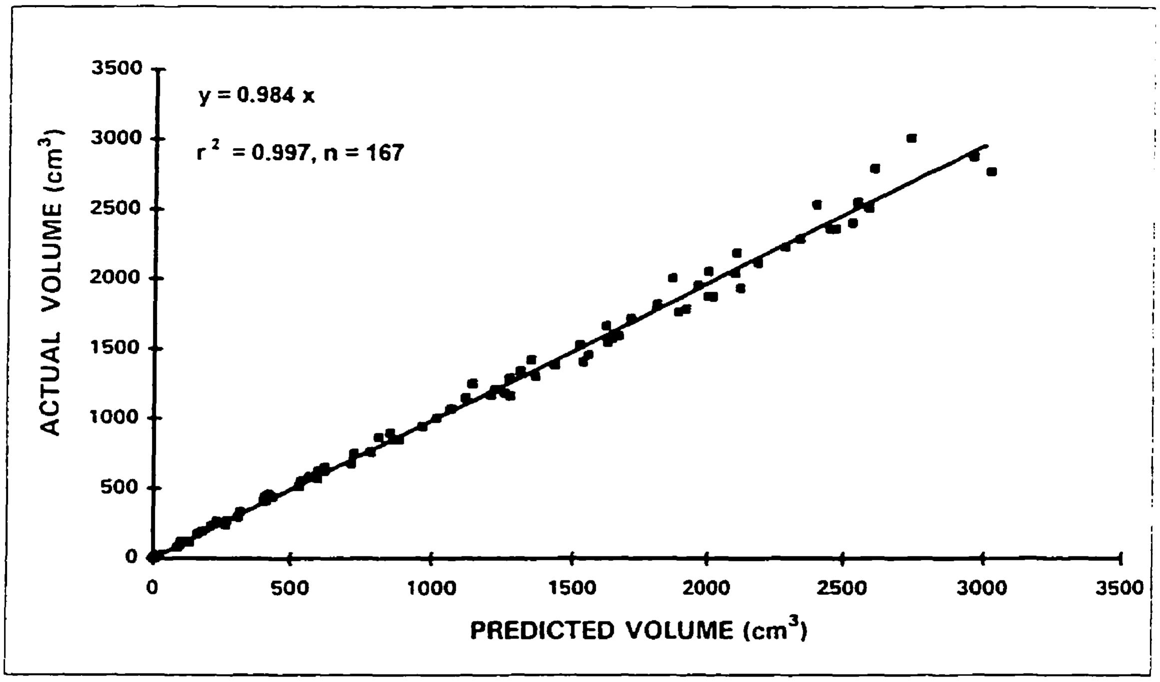

A
NUMBER OF OVARIES
0 5 10 15 20 25 30 35 40
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170
OVARY DIAMETER (mm)
B
NUMBER OF OVARIES
0 5 10 15 20 25 30 35
15 25 35 45 55 65 75 85 95 105 115 125 135 145 155 165 175 185
OVARY LENGTH (mm)
C
NUMBER OF OVARIES
0 5 10 15 20 25 30 35
0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
OVARY SHAPE

Figure 3.2. Relationship between the volume (cm^3) of muskmelon ovaries measured by water displacement and the calculated volume (cm^3) using the formula of Currence *et al.* (1944).



y = 0.984 x
r² = 0.997, n = 167
ACTUAL VOLUME (cm³)
PREDICTED VOLUME (cm³)
3500
3000
2500
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
3000
3500

Introduction to Part 4

Another step towards predicting yield of muskmelon under plasticulture techniques is to have a clear understanding of the fruiting dynamic of the plant, particularly in relation to fruit phenology. Therefore, a detailed description of the stages of development of the fruit, from early flower development to fruit maturity, is a basic requirement to develop such a model. The next section classifies muskmelon flowering into six stages and fruiting into seven stages. Abortion is quantified according to flower and fruit phenology. Fruit set, fruit cycles and fruit growth are described for muskmelon grown under a northeastern climate.

Part 4. Fruit set, growth and development of muskmelon (*Cucumis melo* L.) under northeastern climate

4.1 Summary

Six phenological classes for flower development and seven classes for fruit development are described for muskmelon. In a case study, only 13% of the perfect flowers reached maturity (Full-slip). Ninety six percent of the perfect flowers bloomed for only one day. Ovaries had an equal chance of aborting before or after the Bloom stage. Less than 1% of the fruit aborted after the Unnetted stage, that is when fruits grew longer than 4 cm. Therefore, evaluating yield potential by counting ovaries at this stage gives a good estimate. Length and diameter of fruits at Full-slip were directly proportional to those at the Netted stage, but fruit diameter was more variable than fruit length. There was no relationship between fruit dimensions at Full-slip and those at stages earlier than Netted. Fruit growth, expressed by fruit volume as a function of days, was described by the Richards function with coefficients of determination varying between 0.97 and 0.99. Plants displayed either single or double fruit growth cycles. The second fruit cycle was triggered as the absolute growth rate of the fruits in the first cycle decreased.

4.2 Introduction

Muskmelons are generally produced commercially in northern climates only with the use of plastics sheets. Various polyethylene mulches and row covers are used by growers and each combination of materials can result in different maturation times and yields (Loy and Wells 1975; Argall and Stewart 1989). Prediction models can be valuable tools to help growers in planning production schedules. A heat unit model was determined to predict plant biomass and time to anthesis for muskmelon grown under various mulch and row covers (Part 2). After anthesis, row covers were removed to permit insect pollination and fruit set. An important aspect to develop a prediction model for yield of this crop is to have a clear understanding of the growth and phenology of the fruit.

Gustafson (1926) was probably the first to describe muskmelon fruit growth with a sigmoid growth curve. In California, Davis *et al.* (1967) described fruit diameter as a logarithmic function of time using fruits of 5.1-7.6 cm in length as a starting point. This length was reached between 5 and 7 days after anthesis and, therefore, earlier stages close to anthesis were not included. Leeper (1951) predicted the maturity date of 'Rio-Sweet' muskmelon based on the start of fruit netting. In 31 fruits studied, maturity occurred within 21 to 25 days after the onset of netting. However, McGlasson and Pratt (1963) did not find that this parameter was a precise indicator of fruit age. They divided fruit growth into three stages. During the first stage, a 10 day period post anthesis, fruit volume increased exponentially, similar to that of other cucurbits (Sinnott 1945). The second, 10 to 20 days post anthesis, marked the appearance of netting and was described with a constant rate of growth. The final, 20 days post-anthesis to maturity was characterized by a slower rate of growth. During this last stage, muskmelon fruits underwent a metabolic transition marked by both physical and metabolical changes such as intense netting of the exocarp, mesocarp softening and the onset of sucrose accumulation (Bianco and Pratt 1977; Lester and Dunlap 1985).

A description of phenological classes of fruit growth after anthesis has been reported by Pratt, Goeschl and Martin (1977) for 'Honey Dew' melons (*Cucumis melo* var. *'inodorus'* Naud.). However, a description of flowering and fruiting stages for the netted muskmelon (*Cucumis melo* var. *'reticulatus'* Naud.) is lacking. Several scales, among which the BASF, Bayer, Ciba-Geigy and Hoechst, also referred to as the BBCH scale, have been developed to identify developmental stages that were similar for a range of crops (Lancashire *et al.*, 1991). Reference to these codes avoids ambiguities and provides a standard description of muskmelon ovary/fruit development common to other species.

The overall objective of this study was to characterize growth and development of muskmelon fruit, particularly during the early stages of fruit development. More specific objectives were: 1) to describe a reference set of phenological stages for flower and fruit development specific to muskmelon and relate these stages to the standards of the BBCH scale, 2) to study fruit set as well as floral and fruit abortion, and 3) to define a simple relationship for fruit growth with clear initiation and termination parameters.

4.3 Materials and methods

'Earligold' Muskmelon was seeded in a commercial peat-lite medium in a greenhouse in 61 mm X 60 mm X 58 mm plastic cell pots. On June 1, 1994, transplants were set into a sandy loam field that had 1.2 m wide black polyethylene mulch layed and equipped with drip irrigation. Nitrogen was applied at a rate of 100 kg/ha and incorporated by rototilling prior to laying the mulch. Additional fertilizers and pest control followed Quebec recommendations (C.P.V.Q. 1994). Weed control between the mulched rows was performed manually.

The experimental field consisted of three rows of 24 m in length. Plants were spaced at 0.7 m within and 2.0 m between rows. On July 8, all ovaries which had developed beyond the Bloom stage were removed from five plants, randomly selected from the centre row. The remaining perfect flowers were tagged daily as they appeared. The length and the diameter of the inferior ovary and subsequent fruit were recorded from tagging to Full-Slip, or until the fruit aborted. Phenological classes were developed from daily observations of the fruits. On July 21, the number of secondary branches, tertiary branches, spurs (4th order branches) and leaves longer than 1 cm were recorded on each plant.

Volume of all growing fruits reaching Full-Slip was calculated from polar and equatorial diameters using an adjusted formula based on work by Currence *et al.* (1944). The following equations were used (Part 3):

$$Y = 0.984\,K\,D^2\,L / 1000$$

where:

$$K = 0.1528\,(D/L) + 0.4152, \text{ if } (D/L) \leq 1$$

$$K = -0.2204\,(D/L) + 0.7872, \text{ if } (D/L) > 1$$

The parameter D is the fruit diameter (mm), L the fruit length (mm), K a shape factor and Y the fruit volume (cm^3).

Richards growth functions (Richards 1959) were fitted to the growth curves of fruit volume using a SAS program developed by one of the authors (Bourgeois unpublished). The fruit volume Y (in cm^3), was expressed as a function of time X (in days). Two equations were tested according to the range of the shape parameter m:

1) for $0 \leq m < 1$ and $m > 1$, $$Y = Y_{max} R^{1/(1-m)}, \text{ with } R = 1 - (Y_0^{(1-m)} - 1)\, e^{-kX}$$

2) for m = 1 (Gompertz equation), $$Y = Y_{max} e^{\ln(Y_0) e^{-kX}}$$

with Y_0, being the ovary volume at the Bloom stage (cm^3) and Y_{max}, the fruit volume at the Full-Slip stage (cm^3). The parameter k was defined as a rate constant determining the proportion of the final size where the inflexion point occurs and m, a shape parameter determining the spread of the curve along the time axis. At m=1, the Gompertz equation was used because an impossible solution is obtained when employing a Richards equation. When m approaches one in the Richards equation, the Gompertz is mathematically obtained (Madden, 1980). The two parameters of the growth curve, k and m were estimated by the non linear regression procedure available in SAS (SAS, Institute 1988). Selection of Richards equations were based on the least square method and on its ability to predict the volume at maturity (Y_{max}). The derivative of these selected growth curve equations were then used to estimate absolute growth rate of individual fruits.

4.4 Results

A description of the ovary developmental stages from the appearance of perfect flowers to the production of Overripe fruit is presented in Table 4.1 and in Figure 4.1. Six floral and seven fruit stages were determined. Each stage was assigned a code according to the BBCH scale (Lancashire *et al.*, 1991).

The date of the onset of most phenological classes was clearly identified in the field, with the exception of the Unripe stage. The Unripe stage started when the fruit was fully netted. However, the final netting capacity of a fruit was variable. This stage was more difficult to predict precisely, particularly for fruits which had a poor final quality of netting.

Of the 199 labeled flowers, only 13% reached the Full-Slip stage. About the same proportion of ovaries aborted before and after the Bloom stage (Table 4.2). Most flowers aborted at the Pre-Bud (25%) or the Set stage (26%). Less than 1% of the fruit aborted at the Unnetted stage and no fruit aborted after this stage.

The time from Bloom to Full-Slip was measured for 26 fruits on five plants. This period varied from 35 to 60 days during which the volume increased approximately 2500 fold (Table 4.3). The initial flowering stages were of relatively short duration (Table 4.2). The Bud and Closed stages lasted one or two days, the Bloom stage one day (96%), and the Wilted and Set stages one to three days. Some ovaries remained at the Set stage for more than 3 days, but all of them subsequently aborted. The Bloom stage was the most stable of the growth stages from Pre-Bud to Set as ovary diameter, length and volume had the smallest coefficient of variation at this stage (data not shown). Therefore, ovary volume at Bloom stage was used as a starting point in order to fit growth curves to fruit volume during the season. Ovary dimensions are presented in Table 4.3 at the onset of stages from Bud to Full-Slip. At Bloom stage, ovaries measured 9.4 ± 0.1 mm in diameter, 15.1 ± 0.3 mm in length and 0.67 ± 0.03 cm^3 in volume. Earlier appearing ovaries were longer and wider than later blooming ovaries on the same plant. No significant relationships were found between length and diameter of ovaries at early stages (Bloom, Wilted and Set) and those at maturity (data not shown). However, fruit length at Full-Slip was significantly related ($P\leq0.01$) to length at the beginning of the Netted stage (Fig. 4.2). The relationship between diameter of fruits at Full-Slip and Netted stages were also significant ($P\leq0.05$), but the variation was greater for this parameter than for length. This suggests that once a fruit has reached the Netted stage, it will tend to grow more uniformly in length than in diameter.

Fruit volume, expressed as a function of days, could be described by a Richards function from the Bloom to Full-Slip stage (Fig. 4.3a). The fitted curves accounted for 97 to 99% of the variation in each fruit volume. It took between 35 to 60 days to go from Bloom to Full-Slip stage. The earlier the flower bloomed on a plant, the shorter the time it took to develop into a mature fruit. Fitting Richards growth functions resulted in m values varying between 0.70 and 1.00, and k values between 0.10 and 0.15. No trends could be detected between these values and the blooming sequence of perfect flowers.

Plants displayed either one or two fruit growth cycles. Plants which set 5 perfect flowers within 3 days (plants #2, #4 and #5) had only a single fruit cycle. Plants which set only 3-4 perfect flowers within a 1 to 2 day period (plant #1 and #3) had a second cycle. First cycle fruits matured within 35-40 days, whereas second cycle fruits took 49 to 60 days to mature.

A typical example of the latter is presented in Figure 4.3. During the initial cycle, four flowers opened simultaneously and all subsequent fruits reached the Full-Slip stage within a two-day period. At the point where the absolute growth rate (AGR) of these fruits reached a maximum, a second set of two flowers opened and developed (Fig. 4.3b). Fruit load seemed more related to the number of tertiary branches rather than the number of spurs (fourth order branches) or total number of leaves produced (Fig.4.4). Indeed, plants with two fruit cycles had 30-48% more tertiary branches compared with those having only one fruit cycle. It should be noted that the main stem of plant #5 was damaged after the sixth node. Consequently, the plant compensated by producing a larger number of spurs and leaves.

4.5 Discussion

Most cultivated cucurbitaceae are indeterminate plants that exhibit periodic fruit set. Developing fruits inhibit growth and development of other parts of the plant, resulting in reduced shoot and root growth, senescence of flowers before anthesis and prevention of growth of fruits fertilized after the first developing fruits (Rosa 1925; Mann and Robinson 1950; McGlasson and Pratt 1963; van der Vlugt 1987). In California, Rosa (1925) found that muskmelon set fruit in 2 or 3 recurring periods or cycles depending on the length of the season. Under the shorter growing season of southern Quebec, muskmelon plants grown on plastic mulch produced 1 to 2 fruit cycles. If a second cycle was present, it appeared to be triggered when the AGR of the first cycle fruits attained a maximum (Fig. 3b).

Failure to set fruit can be caused by a number of factors occurring at specific stages. Prior to anthesis, flowers may abort due to competition for assimilates with the vegetative apex and earlier flowers (Bertin 1995). In this study, 54% of the total number of perfect flowers that aborted did so between initiation and anthesis (Table 4.2).

Melon flowers may fail to set due to inadequate pollination (Bohn and Davis 1964). Although perfect flowers of muskmelon are self-fertile, the pollen is sticky and tends to adhere to the anthers after dehiscence so that self-pollination is unlikely to occur (Rosa 1925; McGregor and Todd 1952; Free 1993). Production of a marketable fruit requires the successful fertilization of 400 to 600 ovules (McGregor and Todd 1952). Consequently, insect-vectored pollination is critical.

After fertilization, fruit may stop growing immediately, have a lag period and then a rapid growth (Table 4.2) or immediate rapid growth (Fig. 4.3b). In this study, 13% of ovaries that aborted occurred immediately past anthesis, i.e. at the Wilted stage. Ninety six percent of the ovaries grew rapidly moving from Wilted through Set stage in 1 or 2 days and the remainder were delayed. The Set stage period mostly lasted 1 to 3 days, and the 4% of the ovaries that lasted more than 3 days at this stage did not produce a mature fruit. The Set stage was the last stage where major abortion was noted. Indeed, 99.4 % of all ovaries that had to abort did so prior to this stage.

Sink demand in cucurbits continuously alternates between high periods with many growing fruits and low periods with few growing fruits. As a result, Schapendonk and Brouwer (1984) found periods of assimilate deficiency following periods of assimilate surplus. Marcelis (1992) studied the distribution between the vegetative and fruiting parts of greenhouse cucumber. He concluded that the proportional dry matter distribution to the fruits was positively correlated with fruit load in terms of weight and number. He attibuted this to the increase in potential sink capacity as the fruit matured. In cucumber, fruit abortion was linked to the availability of assimilates 10 days after anthesis. In this experiment, fruit abortion was minimal (less than 1%) after a period of 4.5 days when the ovary had reached a length of 4 cm, i.e. the Unnetted stage (Table 4.3). This risk period is shorter than the 10 days used to measure fruit set by McGlasson and Pratt (1963), or the length of 5.1-7.6 cm attained within 5-7 days as suggested by Davis *et al.* (1967).

Assimilates are available to the muskmelon fruit most importantly from nearby leaves, thus depleting carbohydrate supply for that part of the plant (Hughes *et al.*, 1983). Consequently, a leaf near a fruit will be source-limited, whereas a leaf at a distance from the fruit will be sink-limited during later fruit growth. Any perfect melon flower subsequently pollinated in the vicinity of a developing fruit will abort because of assimilate shortage. A fruit set is then possible only when a perfect flower is formed at a distance where the leaves are not under the influence of an older competing sink. Furthermore, Schapendonk and Brouwer (1984) proposed that fruit abortion in cucumber was not solely due to a shortage of assimilates, but also to dominance of competing fruits. Single fruits with a limited assimilate supply due to defoliation had a reduced growth rate, but did not abort. The authors suggested that the dominance of older fruit was of great significance, regulating fruit abortion of younger fruits in the lower axils.

From a management point of view, the benefit of a second fruit cycle is questionable. Breeding efforts have resulted in the development of cultivars with a more concentrated fruiting and yield in order to reduce harvesting costs of the crop (Paris *et al.* 1986). Birdnest type or "short internode" varieties allows for better control of yield and timing of harvests. On the other hand, growers may find it economically advantageous to have a two-cycle fruiting system in order to obtain better uniformity of yield over a longer period of time. In this regard, pruning the plant which may favor multiple branching of spurs and a large number of smaller leaves, may not be advisable. Rather, the development of a plant structure with a high number of tertiary branches would promote a second fruit cycle (Fig. 4.4).

Perfect flowers are usually born singly on small fruiting spurs arising from the main, secondary or tertiary branches (Rosa 1925; McGlasson and Pratt 1963). However, a greater number of spurs and potentially a greater number of perfect flowers does not necessary translate into a second fruit cycle. Assimilate availability is probably more a limiting factor in promoting subsequent fruit sets rather than the presence of perfect flowers. In this experiment, plants which set a higher number of fruits (5 with plants #2,

#4 and #5) within 1-3 days tended to have one fruit cycle, whereas plants with a lower number of fruit set (3-4 with plants #1 and #3) tended to have a second fruit cycle. This is in accordance with Paris *et al.* (1986) who suggested that the larger number of young fruits developing simultaneously in birdnest-type cultivars tended to pose a drain on the total resources of the plant, thereby preventing development of subsequent fruit sets.

Muskmelon fruit growth followed a simple sigmoid curve similar to that of other crops (Bollard 1970). Fruit volume, expressed as a function of days, was described by the Richards function from the Bloom to Full-Slip stage with a coefficient of determination ranging from 0.97 to 0.99 (Fig. 4.3a). The longer time period required for maturation of the second cycle fruits may have been related to plant aging and lower temperatures.

Fruit size prior to the Netted stage was not related to fruit size at Full-Slip and cannot be used for yield prediction purposes. Only fruit dimensions at the Netted stage could give an indication of fruit size at maturity, although fruit diameter was more variable than fruit length (Fig. 4.2). On average, the Netted stage appeared on the 12th day of the 40-day period necessary for fruit maturation from Bloom stage to Full-Slip, and the fruits at this stage attained 37% of final volume (Table 4.3). Fruits tended to get rounder as they matured, as indicated by the steeper slope of the fruit diameter compared with the slope of the fruit length (Fig. 4.2). This agrees with Davis *et al.* (1967) who found that fruit shape (length/diameter) decreased with time. However, they also found that final fruit shape was not correlated with the shape of immature fruits until the fourth week after anthesis over a six week period for fruit growth.

The fact that less than 1 % of the ovaries aborted after the Unnetted stage has a most interesting practical implication. It suggests that more than 99% of all ovaries longer that 4 cm will produce a mature fruit. Therefore, determination of number of melon ovaries with a length greater than 4 cm could give the grower a rapid estimate of the yield potential of the crop.

Table 4.1. Phenological classes evaluating flower and fruit development of muskmelon and codes according to the BBCH scale (Lancashire *et al.*, 1991). The description is based on an ovary that will develop into a mature fruit.

Stage	Description	BBCH scale
FLOWER		
A) IMMATURE	Distinct inferior ovary, corolla not visible and calyx closed.	51
B) PRE-BUD	Corolla visible but shorter than calyx.	54
C) BUD	Corolla longer than calyx, individual petals not completely expanded nor easily distinguished.	56
D) CLOSED	Petals fully formed but closed.	59
E) BLOOM	Petals fully open.	65
F) WILTED	Petals wilted but not dried and still fully colored.	66
FRUIT		
G) SET	Corolla and calyx dull yellow or brown, drying, often attached to the fruit, hairy dark green fruit, length less than 4 cm.	68
H) UNNETTED	Fruit length greater than 4 cm, hairy during most of this stage. Visible ribs, brown dried corolla and calyx may still be attached.	70
I) NETTED	Appearance of epidermal cracks on skin, hairless.	74
J) UNRIPE	Fully netted, green skin appearing between the epidermal cracks, blossom end of the fruit hard.	79
K) HALF-SLIP	Appearance of abscission layer at the peduncle/fruit interface, fruit can be detached with pressure, portion of stem remaining in stem cavity, blossom end of the fruit starts to soften, good commercial harvest maturity for shipment.	87
L) FULL-SLIP	Fruit detached cleanly without pressure, blossom end of the fruit soft, characteristic aroma, slight yellowing, optimal edible stage, harvested commercially for local markets.	89
M) OVERRIPE	Fruit yellow, very soft, very strong aroma.	90

Table 4.2. Percentage of muskmelon ovaries lasting 1, 2 or 3 days from Bud to Set stage and aborting at seven phenological stages.

Phenological Stage	Duration of Stage 1 Day (%)	2 Days (%)	3 Days (%)	Aborted Ovaries[z] (%)
PRE-BUD	-	-	-	25.4
BUD	82.4	17.6	0.0	13.2
CLOSED	87.5	12.5	0.0	4.6
BLOOM	96.2	3.8	0.0	3.6
WILTED	48.0	48.8	4.0	13.2
SET	57.8	30.8	7.7	26.4
UNNETTED	-	-	-	0.5

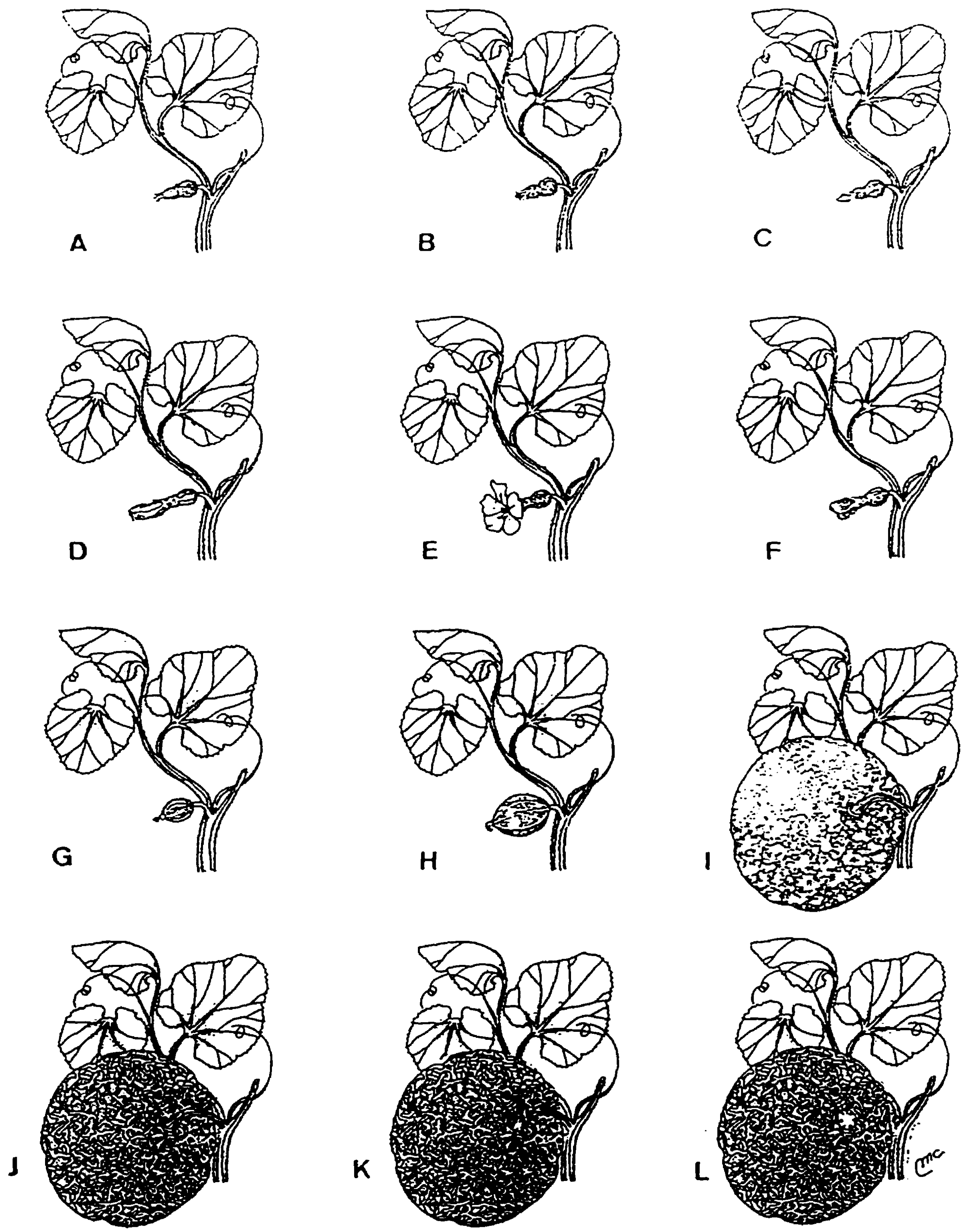
[z] Only 13.2% of the 197 ovaries reached the Full-Slip stage. No fruit abortion occurred after the Unnetted stage.

Table 4.3. Time (days from Bloom stage) of occurrence of eight phenological stages and dimensions in terms of length (mm), diameter (mm) and volume (cm^3) of muskmelon ovaries. Fruits from both first and second cycle are included in the calculations.

Phenological Stage	Time From Bloom Stage[z] (days)	Length[z] (mm)	Diameter[z] (mm)	Volume[z] (cm^3)
BUD	-2.3 ± 0.1	11.6 ± 0.2	7.3 ± 0.2	0.32 ± 0.02
CLOSED	-1.1 ± 0.1	13.9 ± 0.3	8.5 ± 0.1	0.50 ± 0.02
BLOOM	0.0 ± 0.0	15.1 ± 0.3	9.4 ± 0.1	0.67 ± 0.03
WILTED	1.2 ± 0.1	19.5 ± 0.6	11.6 ± 0.3	1.28 ± 0.13
SET	2.9 ± 0.1	29.7 ± 1.1	17.6 ± 0.6	4.77 ± 0.51
UNNETTED	4.5 ± 0.2	45.8 ± 0.9	28.3 ± 0.9	19.5 ± 1.7
NETTED	12.1 ± 0.2	115.6 ± 1.7	99.0 ± 0.9	613 ± 18
FULL-SLIP	39.5 ± 1.0	152.5 ± 2.8	141 ± 2.0	1675 ± 71

[z] Each datum represents the mean ± SE.

Figure 4.1. Diagram of the developmental stages of muskmelon (*Cucumis melo* L.) flower and fruit. For flower: (**A**) Immature, (**B**) Pre-Bud, (**C**) Bud, (**D**) Closed, (**E**) Bloom, (**F**) Wilted. For fruit:(**G**) Set, (**H**) Unnetted, (**I**) Netted, (**J**) Unripe, (**K**) Half-Slip and (**L**) Full-Slip.


A
B
C
D
E
F
G
H
I
J
K
L

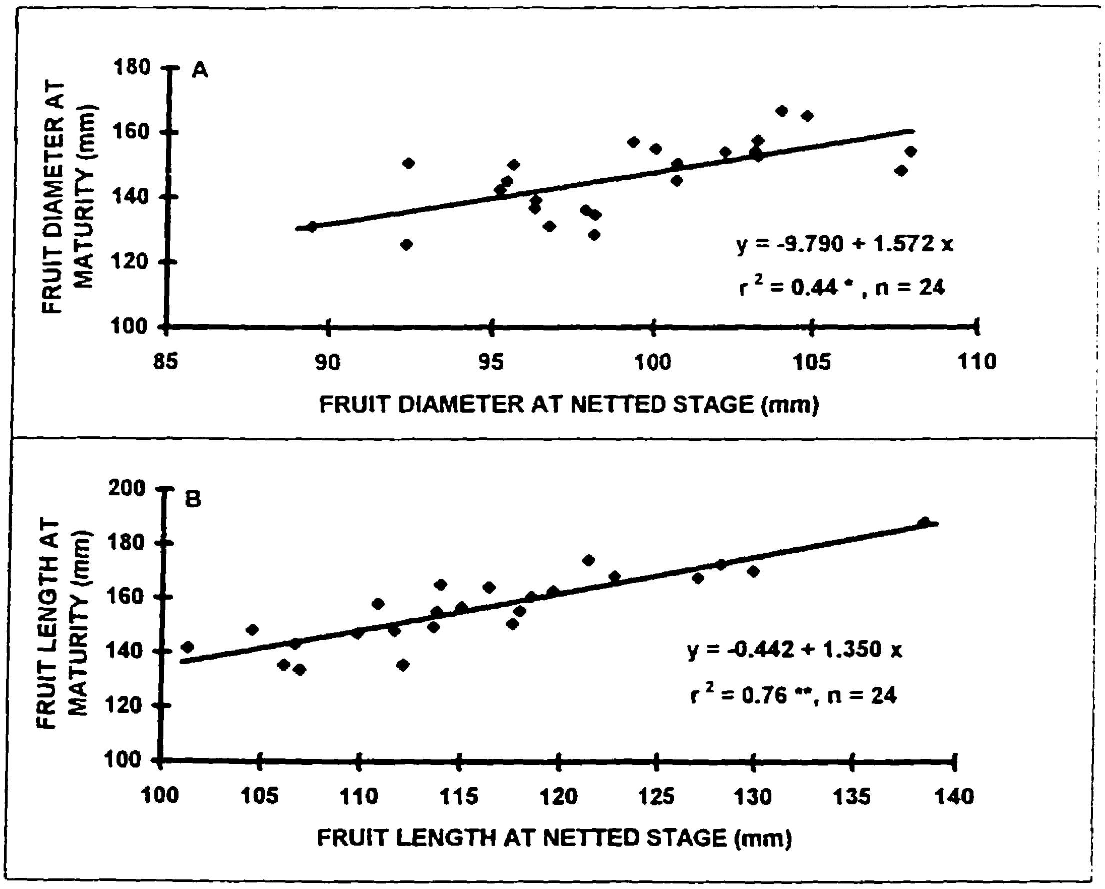

A
FRUIT DIAMETER AT MATURITY (mm)
180
160
140
120
100
85
90
95
100
105
110
FRUIT DIAMETER AT NETTED STAGE (mm)
y = -9.790 + 1.572 x
r 2 = 0.44 * , n = 24
B
FRUIT LENGTH AT MATURITY (mm)
200
180
160
140
120
100
100
105
110
115
120
125
130
135
140
FRUIT LENGTH AT NETTED STAGE (mm)
y = -0.442 + 1.350 x
r 2 = 0.76 **, n = 24

Figure 4.2. Relationship between fruit dimension at Full-Slip and its dimensions at the beginning of the Netted stage; (**A**) length (mm) and (**B**) diameter (mm).

Figure 4.3. (**A**) Volume (cm^3) and (**B**) absolute growth rate (AGR, $cm^3\ day^{-1}$) of fruits for a typical muskmelon plant with a double cycle. Each curve represents a fruit from Bloom stage to Full-Slip stage. The number of the fruits indicates order of appearance of the Bloom stage.

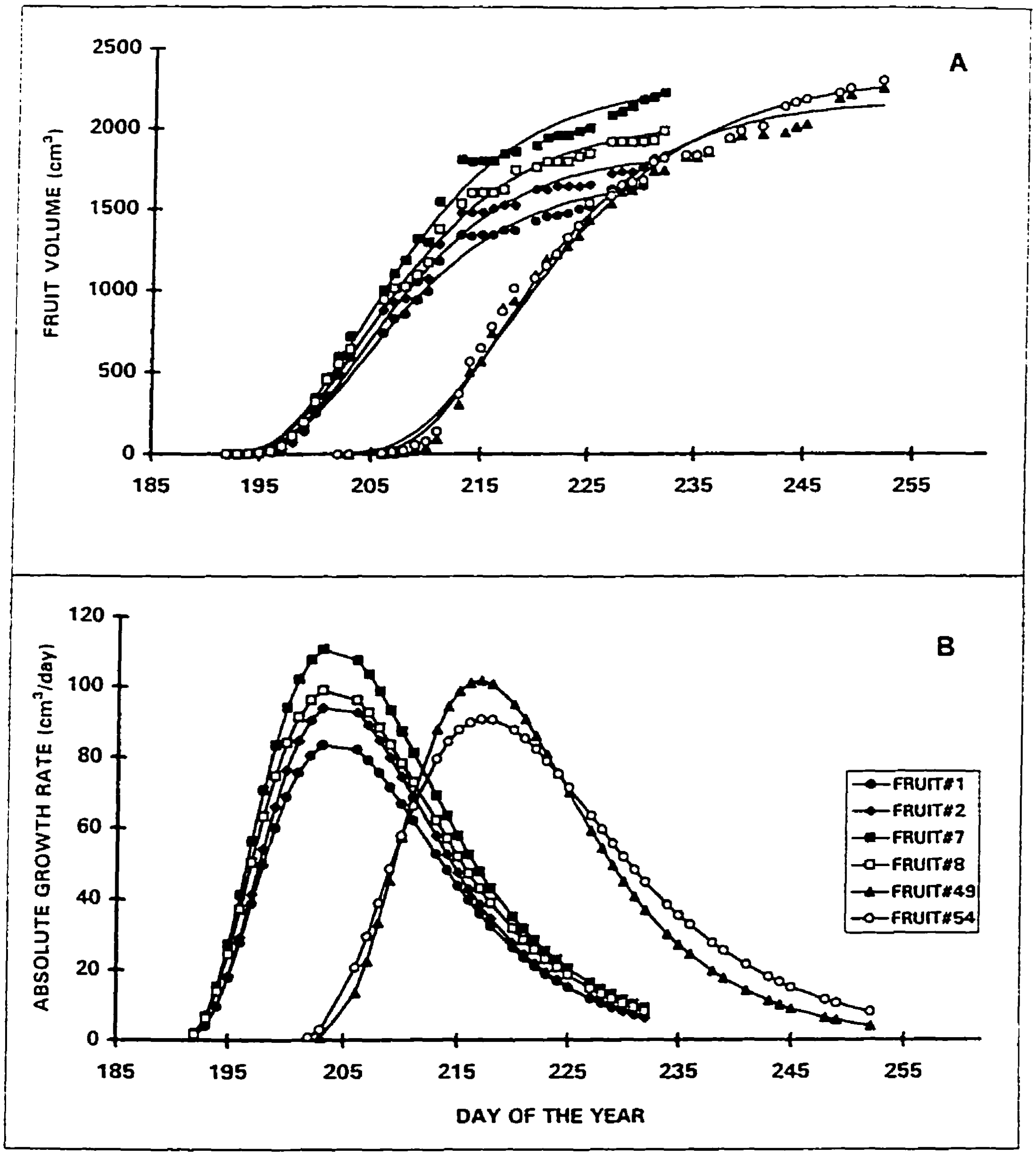
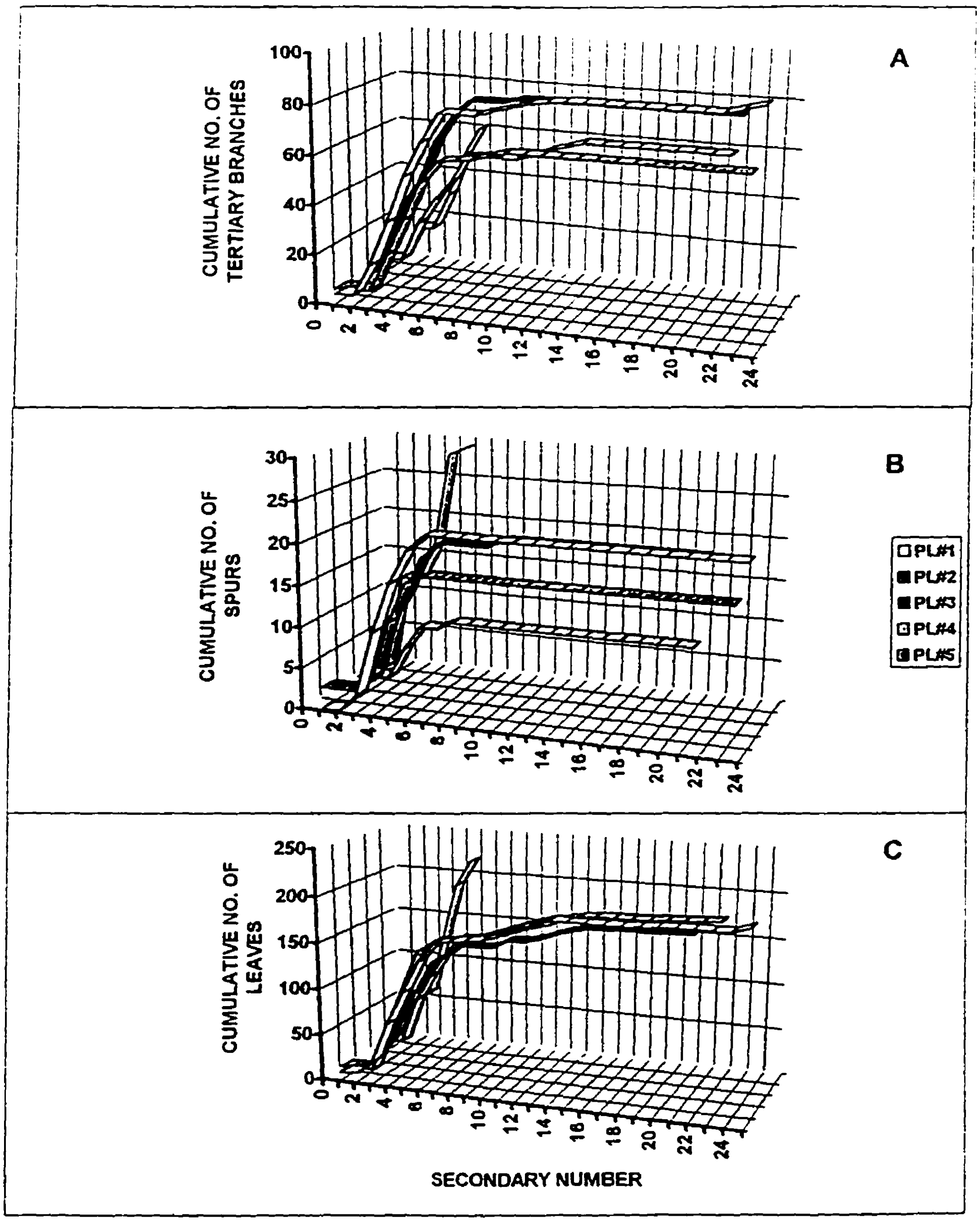

A
FRUIT VOLUME (cm³)
2500
2000
1500
1000
500
0
185
195
205
215
225
235
245
255
B
ABSOLUTE GROWTH RATE (cm³/day)
120
100
80
60
40
20
0
FRUIT#1
FRUIT#2
FRUIT#7
FRUIT#8
FRUIT#49
FRUIT#54
DAY OF THE YEAR

Figure 4.4. Cumulative number of (**A**) tertiary branches, (**B**) spurs and (**C**) leaves produced on each secondary branch of five muskmelon plants (PL).


A
CUMULATIVE NO. OF TERTIARY BRANCHES
0
20
40
60
80
100
B
CUMULATIVE NO. OF SPURS
0
5
10
15
20
25
30
PL#1
PL#2
PL#3
PL#4
PL#5
C
CUMULATIVE NO. OF LEAVES
0
50
100
150
200
250
0 2 4 6 8 10 12 14 16 18 20 22 24
SECONDARY NUMBER

Introduction to Part 5

Time from transplanting to first anthesis of perfect flowers can be predicted for muskmelon grown under various mulches and rowcovers (Part 2). However, this crop has an extended period of flowering followed by periods of fruit set and abortion (Part 4). Further, the fruit has a specific maturity stage for optimum quality. As a result, maturing fruits will require multiple harvests.

Because muskmelon produce mature fruits over a period of time, predicting time and yield from the start of anthesis to first mature fruits will provide only limited information on potential yield. Therefore, investigating the fruiting behavior of muskmelon in terms of the relative importance of first and second cycle fruits, and their timing of flowering and maturity, is crucial. This aspect will be covered in the following part.

Further, two heat unit systems for individual fruits are presented, depending on the temperature data set available. Finally, a simple way to predict yield and maturity of muskmelon is proposed, based on this information.

Part 5. Prediction of Yield and Time to Maturity of Muskmelon Fruits from Weather and Crop Observations

5.1 Summary

A simple method to predict time from anthesis of perfect flowers to fruit maturity (Full-Slip) and yield is presented here for muskmelon grown in a northern climate. Developmental time for individual muskmelon fruits from anthesis to Full-Slip could be predicted from different heat unit formulas depending on the temperature data set used. When temperature at a height of 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 11C and an upper threshold of 25C. 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 15C. This latter method was improved by including a 60-degree-day lag for second cycle fruits. The proportion of fruit volume from Full-Slip of 22 fruits 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, fruits from the first cycle represented 72% of total yield, both in terms of number and weight. The blooming period of productive flowers lasted 34 days, each cycle overlapping and covering an equal period of 19 days. A counting of the number of developing fruits longer than 4 cm after 225 degree days from the start of anthesis (when 90% of the plants have at least one blooming perfect flower) could give a rapid estimate of the number of fruits that will reach maturity.

5.2 Introduction

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 under various locations and years are used to define base temperatures (Dufault *et al.*, 1989; Munoz *et al.*, 1986 ; Perry *et al.*, 1986). Another way is to alter the microclimate around the plants, for example with the use of plastic mulches and rowcovers, in order to modify plant development within a production year (Hemphill, 1989; Wolfe *et al.*, 1989). 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 (Part 2). A second logical step is to predict time from anthesis to fruit maturity.

Most of the heat unit systems have been developed for crops with a unique commercial harvest such as sweet corn (Magoon and Culpepper, 1932), spinach (Boswell, 1935), lettuce (Madariaga and Knott, 1951), collard (Dufault *et al.*, 1989) and mechanically harvested peas (Boswell, 1929) and cucumbers (Perry *et al.*, 1986). However, muskmelon has multiple harvests. The plant produces a number of fruits, each of which progressively ripen over several weeks. It is an indeterminate vining crop which tends to produce fruits 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). Fruits from the second cycle are produced in the cooler part of the growing season and fruit maturation usually takes longer. We define in this paper a heat unit system based on data from individual fruits on plants that had reached anthesis at different times within a growing season because they were grown under various mulches and rowcovers.

The objectives of this study were: 1) to investigate the fruiting behavior of muskmelon grown under various microclimates using mulches and rowcovers, 2) to determine a heat unit system that would predict time from anthesis of perfect flowers to Full-Slip for first and second cycle fruits, and 3) to develop a simple technique for predicting quantity and timing of muskmelon yield.

5.3 Materials and methods

'Earligold' muskmelon seeds were placed into 61 mm X 60 mm X 58 mm plastic cell pots filled with a moist commercial peatmoss medium and were allowed to grow in a greenhouse for a period of three to four weeks. The experimental field was located at the Horticulture Research Center at Macdonald Campus in Ste-Anne-de-Bellevue (45° 24' 30" Lat., 73° 56' 10" Long.). The soil was a sandy loam fertilized with nitrogen applied at a rate of 100 kg/ha and rototilled prior to laying the mulch. Other fertilizer elements were applied according to soil test (Conseil des Productions Végétales du Québec, 1994). At least one week prior to planting, a drip irrigation line and either a green photoselective (IRT-76, AEP Industries, Moonachie, N.J.), a black embossed or a clear polyethylene mulch (Plastitech, St-Rémi, Qué.) 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) was applied on clear mulch plots according to manufacturer's recommendations. Weed control between the rows was performed by hoeing and rototilling.

5.31 Experiment 1: Monitoring fruit growth and development daily on five plants.

On 1 June 1994, four-week old muskmelon transplants were planted in three eight-meter rows covered with a black mulch. Only the center row was used experimentally. On 8 July 1994, all fruits which had developed beyond the Bloom stage were removed on five randomly selected plants. The remaining perfect flowers were labeled daily. The length and the diameter of the inferior ovary and subsequently the fruit were recorded from tagging to fruit maturity (Full-Slip), or until the fruit aborted. Phenological stage of the developing ovary was recorded daily according to the classification presented in Part 4. In total, 199 flowers were labeled on these five plants.

5.32 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 in a randomized complete block design with three replicates. Four treatments were defined to expose the plants to different heat units: 1) a green photoselective mulch with no rowcover (GOO); 2) a green photoselective mulch with a perforated polyethylene mini-tunnel (500 holes/m^2; Plastitech, St-Rémi, Qué.) and no thermal tube (GPO); 3) a green photoselective 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, CA) and a thermal tube (CIT). Each unperforated polyethylene tunnel contained a 8-m-long X 0.32-m-diameter clear polyethylene tube filled with 250 liters of water (thermal tube). All rowcovers were stretched over 80-cm-long wire hoops (#10 gauge) spaced at every 87.5 cm along the plot. 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, diameter of the ovary as well as the phenological stage (Part 4) were recorded weekly from labeling time to Full-Slip or until the fruit aborted. A total of 1220 perfect flowers were labeled on 12 plants. Volume of all growing fruits reaching Full-Slip was calculated from polar and equatorial diameters using an adjusted formula based on work by Currence *et al.* in 1944 (Part 3). Richards growth functions (Richards, 1959) were fitted to the growth curves of fruit volume using a SAS program developed by one of us (Bourgeois).

Replicated air temperature data were recorded hourly from copper-constantan thermocouples placed in the middle of each plot and connected to a CR-10 datalogger (Campbell Scientific Canada, Edmonton, AL) installed in Stevenson shelters. Thermocouples used to measure air temperature 7.5 cm above ground were placed in white painted plastic tubes of 15 cm in length and 3.3 cm in diameter to protect the sensors from direct solar radiation. Alternative air temperature data were obtained from the meteorological station on Macdonald Campus located 2 km from the experimental field.

5.33 Predicting time from anthesis to Full-Slip.

The number of days from Bloom stage to Full-Slip of 55 fruits from both first and second cycles was compared with accumulated heat units. Fruits from both experiments 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 air temperature recorded from the meteorological station. Two basic equations (GDD1 and GDD2, in degree days) were evaluated, namely the average temperature accumulation:

$$GDD1 = (MX + MN) / 2 - BT$$

and the maximum temperature accumulation:

$$GDD2 = MX - BT,$$

where BT is the base temperature (C), MX, the maximum temperature (C) and MN, the minimum 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 (MX_a) in two ways:

For maximum-limited formulas:

$$MX = MX_a \text{ if } MX_a \leq UT; \quad MX = UT \text{ if } MX_a > UT$$

For maximum-reduced formulas:

$$MX = MX_a \text{ if } MX_a \leq UT; \quad MX = UT - (MX_a - UT) \text{ if } MX_a > UT$$

Base temperatures tested included 6, 10, 14 and 18C and upper thresholds, 28, 32 and 36C. 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).

5.4 Results

5.41 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 5.1 using two sets of air temperature data, either at a height of 7.5 cm in each experimental plot, or at a height of 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 14C and maximum reduced with an upper threshold of 28C. This combination reduced the CV to 7.5% compared with 14.0% when days from anthesis to Full-Slip was used (Table 5.1). However, when fruits 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). In order to determine whether the CV could be reduced further, smaller intervals of 0.5C for BT and UT were tested for the average temperature accumulation formula. Using a base temperature of 11C and an UT of 25C reduced the CV to 6.9% (Table 5.2).

The same process for determining an optimal heat unit formula was performed using the set of air temperature data from the meteorological station. In this case, including an upper threshold in the heat unit formula did not reduce the CV (Table 5.1). 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 0.5C increments of base temperature values between 13 and 16C (Table 5.2). 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 15C. When only fruits from the first cycle were considered, this heat unit formula resulted in a CV of 5.7% which was similar to the alendar-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 fruits from both first and second cycle were considered (8.9% versus 14.0% 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.

The relationship between temperature from the meteorological station and from the datalogger are presented in Figure 5.1. Minimum temperatures recorded at the meteorological station were highly correlated with the minimum temperatures recorded in the experimental field with the datalogger ($r = 0.908$, $n = 91$). However, although significant, the simple linear correlation coefficient between maximum temperatures of the two recording sites was smaller ($r = 0.654$, $n = 91$). 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 and 12 September 1994, maximum temperatures were on average 6.0C higher and minimum temperatures 1.7C higher for the datalogger than those from the meteorological station.

5.42 A model for fruit growth

The average time of occurrence of eight phenological stages from Bud stage to Full-Slip stage in terms of days and degree days from the Bloom stage is presented in Table 5.3. Ovary dimensions (length, diameter and volume) are 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 fruits from five plants were expressed as the proportion from volume at Full-Slip versus two time scales (Fig. 5.2). When the X-axis is expressed in terms of days of the year (DY), two sets of curves were distinguished (Fig. 5.2A). A first set of 22 fruits starting blooming between DY 189 and DY 193 represented the first fruit cycle; a second set of 4 fruits blooming between DY 202 and DY 203 represented the second fruit cycle. When proportion from fruit volume at Full-Slip was expressed as a function of heat units (accumulated maximum temperature with a base temperature of 15C), fruits from the first cycle followed a common curve, but the curves representing fruits from the second cycle were still to the right of the curves of the first cycle fruits (data not shown). The shift for these fruits on the right side of the common growth curves suggested a delay in growth and development of the second cycle fruits compared with the fruits from the first cycle.

Richards growth functions were fitted to the fruit growth curves of the 22 fruits from the first cycle (Fig. 5.2B). The proportion from volume at Full-Slip Y, was expressed as a function of heat units X, in C.days, according to the following Richards function:

$$Y = Y_{max} R^{1/(1-m)}, \text{ with } R = 1-(Y_0^{(1-m)}-1)\, e^{-kX}$$

with Y_0=0.0004, being the proportion of ovary volume at the Bloom stage (Table 5.3) and Y_{max} the 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 (SAS Institute, 1988) 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.

For the second cycle fruits, lags in development of 30, 35, 40, 45, 50, 55, 60 and 65 degree days were tested with the data set of 55 fruits from various microclimates used earlier to develop a heat unit system for fruit development. This technique had the effect of shifting the curves of second cycle fruits 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 fruits, values from 50 to 65 degree days were subtracted from the accumulated degree days with a base of 15C. The lowest CV of 6.45% was found at 60 degree days. Including a lag time of 60 degree days in the heat unit formula decreased the CV by more than half, compared with the calendar-day-count CV of 14.0%.

5.43 Blooming and fruiting sequences in muskmelon

Based on 17 plants observed in five microclimates, 35% of the plants had only one fruit cycle and 65%, two fruit cycles. However, on a total of 156 fruits harvested from these plants, 72% came from the first cycle of fruiting and 28% from the second cycle. Then, modeling fruits from only the first cycle would account for more than 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 the weekly observations of ovary development in the four microclimates and from the dimensions and time of occurrence of the phenological stages from Bud to Unnetted described in Table 5.3. The blooming sequence of productive flowers covered a period of 42 days between DY 158 and DY 200. However, each of the two fruit cycles lasted an equal period of 29 days. Each of the four microclimates had plants which started anthesis at separate times. Start of anthesis within each microclimate was defined as the time when 90% of the plants were bearing at least one blooming perfect flower, and 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 days, each cycle covering an equal period of 19 days (Fig. 5.3A). One productive flower bloomed 4 days earlier than when 90% of the plants started to bloom. All the productive flowers of the first cycle occurred within 15 days 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 normally distributed during the following two-week period. Then, 71% of the productive flowers appeared during the first two weeks after the start of anthesis, 78% during the first 3 weeks, and all of them during a 30-day period after the start of anthesis. Based on a thermal-time scale (maximum temperature accumulation with a base temperature of 15C), blooming of productive flowers extended over 340 degree days, and first cycle flowers over 180 degree days (Fig. 5.3B).

5.5 Discussion

5.51 Contrasting between air and canopy temperatures for heat unit calculations

Using a base temperature of 11C and a maximum-reduced with an UT of 25C in an average temperature accumulation formula allowed more precise prediction of time from anthesis to Full-Slip for muskmelon fruits. The CV was reduced from 14.0% with the calendar-day-count method to 6.9% using canopy temperature data at 7.5 cm above the soil level.

Using air temperature data from the nearby meteorological station resulted in less precision (CV=8.9%) and required a different heat unit formula. As opposed to the temperature from near the canopy, temperature recorded from the nearby meteorological station did not precisely reflect the temperature experienced by the fruits, nor 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 15C. This is in accordance with Perry *et al.* (1986) who selected a base temperature of 15.5C with a maximum-reduced and an upper threshold of 32C 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 33.8C and temperatures above 32C for only 4 days (Fig. 5.1). 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 11C and a maximum-reduced with an UT of 25C. Base temperature is usually defined on a physiological basis, as the lowest temperature at which plant development will proceed. However, the appropriate base temperature in a heat unit system may not necessarily coincide with the physiological base temperature. Arnold (1959) defined the appropriate base temperature as that which gives the least variation in heat unit summations over the temperature range that is normally experienced in the phase of development of the crop. Although base temperatures calculated by the coefficient of variation technique proposed by Arnold usually seem too low to be physiologically realistic, his definition often results in more accuracy of prediction.

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 25C, the minimum temperatures sometimes tended to compensate and contribute heat units, especially with a relatively low base temperature value of 11C. 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 the fruit maturation process (Malézieux *et al.*, 1994). Schroeder (1965) reported that, during a sunny day with ambient air temperature at 36C, the upper pericarp of a muskmelon fruit was 15C warmer than for a shaded fruit and 7.5C warmer than ambient air.

In muskmelon, optimal air temperature range for growth was estimated to be 18 to 24C (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 30C but the developmental rate increased even more resulting in smaller fruits at maturity.

Using temperatures at 7.5 cm above soil level, developmental time from planting to anthesis was shown to have a linear response and could be predicted with a base temperature of 7C (Part 2). In contrast, fruit development was non-linear (data not shown) and time from anthesis to fruit maturity could be predicted with a base temperature of 11C and an upper threshold of 25C. The reproductive phase of development characteristically occurs during the warmer part of the 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).

Finally, temperatures at 7.5 cm in the experimental field were shown to be systematically higher than temperatures from the meteorological station, in the order of 6.0C for the maximum and 1.7C for the minimum temperatures (Fig. 5.1). The inclusion of an upper threshold in the case of the datalogger data set may have tended to compensate for the high maximum temperatures recorded, and 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 mid to upper portion of the canopy where there is a 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 it was 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. 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).

5.52 Growth and development of fruits from first and second cycles

Muskmelon as for many other fruits like apple, date, pineapple, banana, tomato, avocado, strawberry, orange and mango exhibits a single sigmoid cumulative growth curve (Bollard, 1970; Gustafson, 1926; McGlasson and Pratt, 1963). The volume of first cycle fruits with various final sizes fitted a common Richards growth curve when volume was expressed as the proportion from final fruit volume at maturity (Fig. 5.2). However, the fruits 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 fruits. This delay in growth and development of younger fruits from indeterminate plants has been reported by others (Bertin, 1995; De Koning, 1989). 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 fruits constitute strong sinks for assimilates, which draw heavily on plant supplies and inhibit the development of other fruits. Indeed, photosynthetic leaf area was found a limiting factor in cucurbits (Pharr *et al.*, 1985), reinforcing a concept of priority for assimilates to older fruits under limited source supply.

5.53 Predicting time to maturity and yield of muskmelon fruits

Results from this work have useful practical implications for crop management of muskmelon. Number of harvestable fruits and time to maturity can be predicted from simple measurements in the field.

Development of muskmelon fruit 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 15C. When muskmelon fruits reached 4 cm in length (Unnetted stage), there is a 99% chance that they will reach maturity (Part 4). The Unnetted stage is reached 45 degree days after the Bloom stage, which corresponded in 1994 to 4.3 days (Table 5.3). Mature fruits from the first cycle, representing 72% of total yield, originated from flowers blooming during the first 180 degree days (approximately two weeks) after the start of anthesis of perfect flowers. Therefore, a grower could go in his/her muskmelon field 225 degree days (approximately 20 days) after the start of anthesis (that is when 90% of the plants bear at least one blooming perfect flower), and count the number of fruits longer than 4 cm to obtain a rapid estimate of close to 75% of the total number of fruits 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 5.3) permit an evaluation of time to anthesis of individual growing ovaries. Time at Full-Slip of individual fruits can then be calculated from anthesis. Ovaries from the first cycle fruits, 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 was estimated to be more than 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. Varietal variability should be considered in relation to the accuracy of the model prediction. This model was developped using a fast ripening eastern variety of muskmelon and may not be precise for a typical western muskmelon.

Table 5.1. Coefficient of variability (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 muskmelon fruits. 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 14.0%.

	Base temperature (C)							
Upper Threshold (C)	Average Temperature Accumulation				Maximum Temperature Accumulation			
	6	10	14	18	6	10	14	18
	Air temperature 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	12.0	12.5	13.2	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	9.0	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	19.4	14.0	14.8	16.1	18.2
	Air temperature 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	9.3
None	9.0	9.0	9.8	12.1	9.2	9.1	9.0	9.1

Table 5.2. Coefficient of variability (CV) for heat unit accumulation with combinations of upper thresholds and base temperatures at intervals of 0.5C. Heat units were calculated from Bloom to Full-Slip stage of individual muskmelon fruits 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 14.0%.

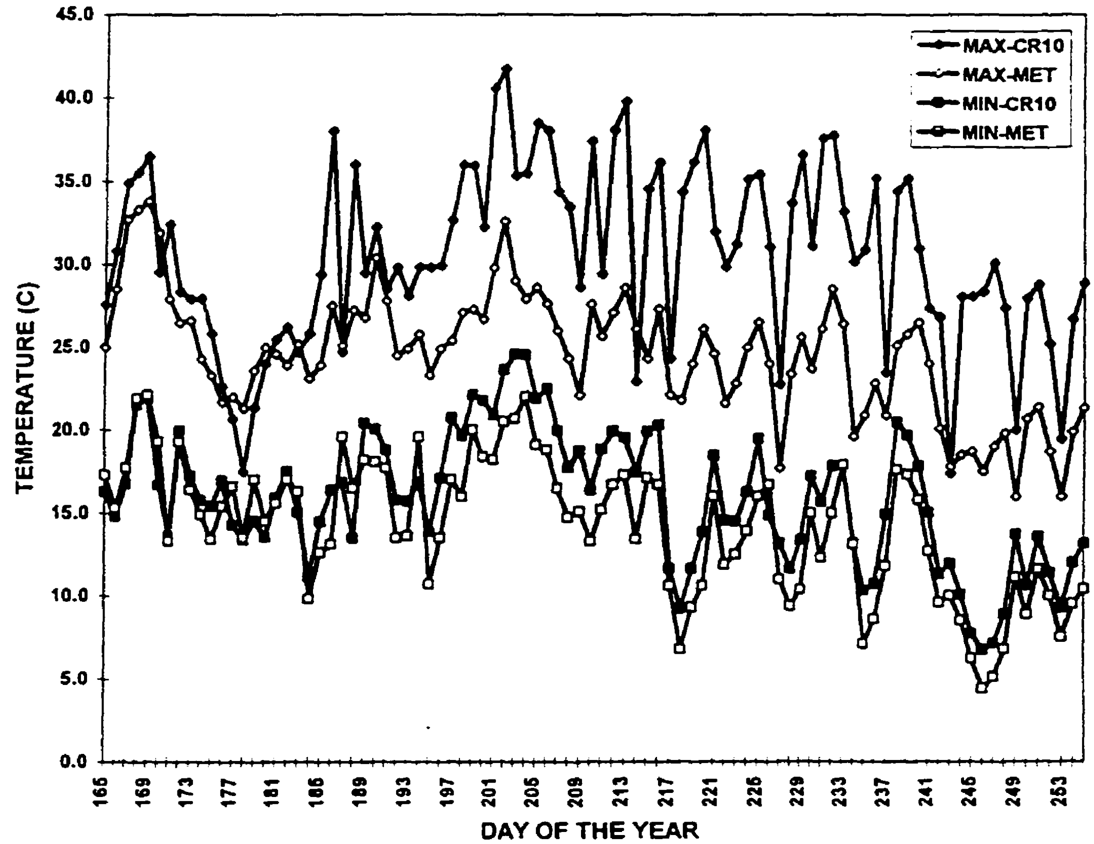
Upper Threshold (C)	Base temperature (C)												
	10	10.5	11	11.5	12	12.5	13	13.5	14	14.5	15	15.5	16
	Air temperature at 7.5 cm - Average temperature accumulation												
24.5	7.0	7.0	7.1	7.2	7.3	7.6	7.9	8.4	-	-	-	-	-
25	7.0	6.9	6.9	7.0	7.1	7.2	7.5	7.8	-	-	-	-	-
25.5	7.1	7.0	7.0	7.0	7.0	7.1	7.2	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	7.2	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	-	-	-	-	7.4	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	8.0	8.1	-
	Air temperature from meteorological station - Maximum temperature accumulation												
NONE	-	-	-	-	-	-	9.0	9.0	9.0	9.0	8.9	8.9	9.0

Table 5.3. 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 fruits from only the first cycle were considered. Heat units were calculated from the maximum temperature accumulation with a base temperature of 15C.

Phenological Stage[y]	Time From Bloom Stage (days)	Heat Units (degree-days)	Length (%)	Diameter (%)	Volume (%)
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

[y] each category represents the beginning of the phenological stage for fruits observed during their growth period.
[z] each datum represents the mean ± SE.

Figure 5.1. Minimum (MIN) and maximum (MAX) temperatures (C) from a meteorological station (MET) located 2 km from the experimental field, and at a height of 7.5 cm (CR10) located in the experimental field.



TEMPERATURE (C)
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
MAX-CR10
MAX-MET
MIN-CR10
MIN-MET
165
169
173
177
181
185
189
193
197
201
205
209
213
217
221
225
229
233
237
241
245
249
253
DAY OF THE YEAR

Figure 5.2. Fruit volume, expressed as the proportion of volume at Full-slip, as a function of (**A**) days of the year (fruits from both first and second cycles are shown) and (**B**) as a function of heat unit accumulation (daily accumulated maximum with a base temperature of 15 C; fruits from only the first cycle are shown). The solid line represents a Richards equation fitted to the 22 fruits (FR) of 5 plants (PL).

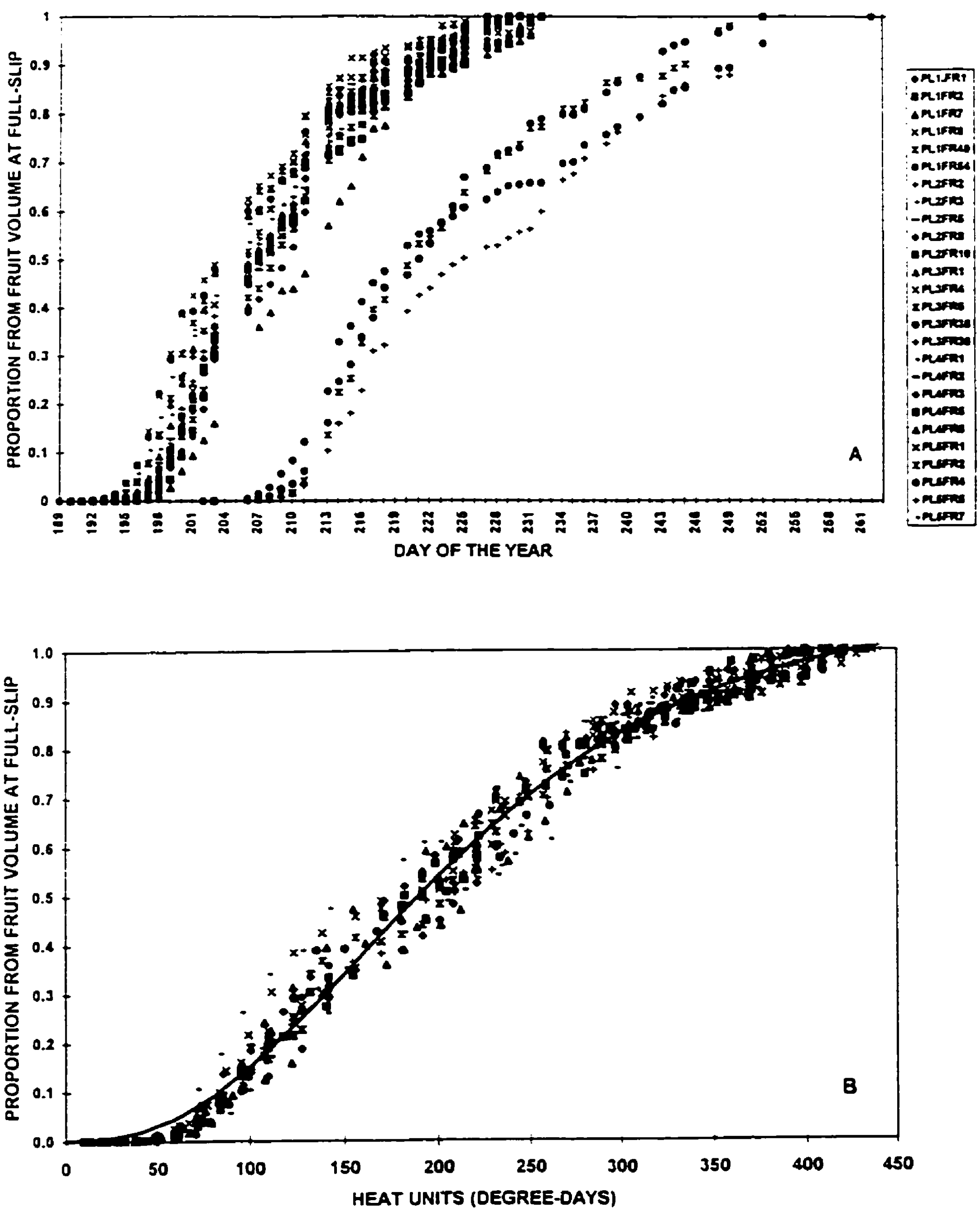
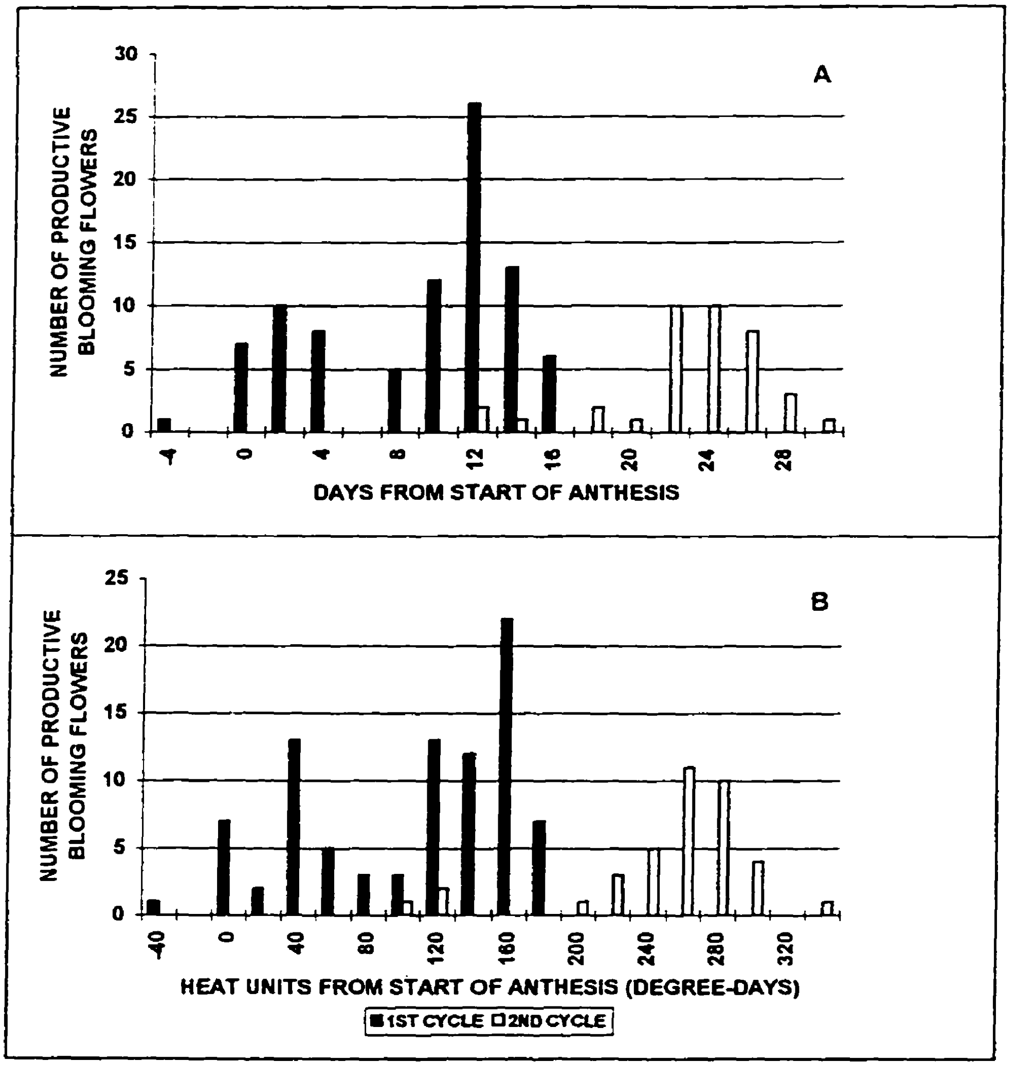

PROPORTION FROM FRUIT VOLUME AT FULL-SLIP
DAY OF THE YEAR
189 192 195 198 201 204 207 210 213 216 219 222 225 228 231 234 237 240 243 246 249 252 255 258 261
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
A
PROPORTION FROM FRUIT VOLUME AT FULL-SLIP
HEAT UNITS (DEGREE-DAYS)
0 50 100 150 200 250 300 350 400 450
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
B

Figure 5.3. 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 were 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/row cover combination was bearing at least one blooming perfect flower.


A
NUMBER OF PRODUCTIVE BLOOMING FLOWERS
30
25
20
15
10
5
0
-4
0
4
8
12
16
20
24
28
DAYS FROM START OF ANTHESIS
B
NUMBER OF PRODUCTIVE BLOOMING FLOWERS
25
20
15
10
5
0
-40
0
40
80
120
160
200
240
280
320
HEAT UNITS FROM START OF ANTHESIS (DEGREE-DAYS)
1ST CYCLE
2ND CYCLE

Introduction to Part 6

In previous work, mulches and rowcover systems were viewed as ways to create, under field conditions, various temperature regimes that would affect plant growth and development. From this range of temperatures, it was possible to define optimum heat unit formulas to predict growth and development of muskmelon at various stages during the growing season. In the next section, combinations of mulches and rowcovers are agronomically evaluated. The black and clear mulches are widely used in our region. The use of photoselective mulch is increasing. The perforated polyethylene mini-tunnel is the standard for early cucurbit production. However, unperforated mini-tunnels with a thermal tube is a new technique practically unknown commercially. Further, agrotextiles are usually used as unsupported floating rowcovers in cool-season crops, such as lettuce, chinese cabbage, radish or carrot, not in warm-season crops such as muskmelon. The effect of mulch and rowcover materials on temperature, plant development and yield of muskmelon is described in the next section.

Part 6. Chilling Injury, Early Development and Yield of Muskmelon Grown on Plastic Mulches in Combination with Rowcovers and Thermal Water Tubes

6.1 Summary

Combinations of mulch/rowcover systems were tested using 'Earligold' muskmelon transplanted between May 7 and May 9 during each of three years. The mulches used were either black (B), photoselective green (G) or clear (C). In 1993 and 1994, these 3 mulches were combined with 2 rowcover systems, either a clear perforated polyethylene (PO, 500 holes m^{-2}) or a clear unperforated polyethylene with a water-filled tube (UT, thermal tube). In 1995, only the green photoselective mulch was tested. A clear mulch combined with an infrared-treated polyethylene with a thermal tube (IT) and a spunbonded polypropylene agrotextile (AO) were also tested during the study. The highest air temperatures, sometimes above 40C, were recorded under the CIT and BUT treatments. Perforated tunnels were less efficient in increasing daytime air temperatures, particularly during windy conditions, than the unperforated tunnels. When combined with all tunnel types, the photoselective mulch produced effects intermediate between those of the clear and black mulches for air and soil temperatures, chilling injury and days to flowering of perfect flowers. In 1994, only those plants grown with a clear mulch combined with an infrared-treated or standard unperforated tunnel with a thermal tube (CIT and CUT) survived seven sequential night-temperatures between 1.6-5.8C. Plants in the unperforated tunnels flowered first, had the heaviest biomass at anthesis and gave the highest early yields, both in terms of fruit number and weight. However, total yields did not differ significantly between perforated and unperforated tunnels. Plants produced smaller fruits in treatments flowering earlier, i.e., unperforated tunnels, in part due to unfavorable conditions for bee pollination.

6.2 Introduction

Cucurbit are tropical or subtropical in origin make them particularly susceptible to chilling injury. Injury may be expressed as decreased vigor and yield, tissue dehydration, appearance of necrosis, increased susceptibility to pathogens, or even death of the plant (Rikin *et al.*, 1976; Sasson and Bramlage, 1981). The magnitude of injury is, for most plants, a function of both duration and severity of exposure to temperatures above the freezing point but below 12C and is related to other environmental factors such as light and relative humidity (Raison and Lyons, 1986). In muskmelon, severe tissue damage occurs when plants are exposed to constant temperature in the range of 5 to 15C (Mitchell and Madore, 1992). The critical period for exposure of cucumber to chilling at 2C was 5 days, after which irreversible damage occurred (Tanczos, 1977). Reyes and Jennings (1994) reported root growth of cucumber and squash seedlings continued, although at a reduced rate, at temperatures of 10 and 15C. Chilling affects photosynthesis, respiration, membrane integrity, water relations and hormonal balance (Graham and Patterson, 1982). Changes in sap composition following chilling may also contribute to stresses on sink tissues of cucurbit (Mitchell and Madore, 1992). In the field, chilling temperatures occur for shorter periods than those tested in growth chambers at constant temperatures, and are usually followed by higher day temperatures. The effect of diurnal temperature changes on chilling injury is poorly documented. Tanczos (1977) reported that short interruptions (up to 4 hours) of a 3-day chilling treatment diminished electrolyte leakage.

The effectiveness of polyethylene rowcovers to protect against chilling is doubtful. Frequent cases of radiation cooling, where night temperatures were lower under the polyethylene rowcover than those of ambient air have been reported, particularly during clear nights with little or no wind and low relative humidity (Tanner, 1974; Goldsworthy and Shulman, 1984). Further, excessively high air temperatures, above 30C, have been measured during warm sunny days under polyethylene rowcover. Although tolerance to these extreme conditions has been reported in muskmelon (Wells and Loy, 1985), temperature stress may offset some positive effect of rowcovers on plant growth (Hemphill and Mansour, 1986; Bonanno and Lamont, 1987; Motsenbocker and Bonanno, 1989). In previous work, we reported that 40C was a temperature threshold for this crop (Part 2). At temperatures above this value, biomass of pre-anthesis plants was reduced. Nethertheless, perforated polyethylene rowcovers have often permitted significant increases in early yield (Wiebe, 1973; Loy and Wells, 1982; Hemphill and Mansour, 1986; Motsenbocker and Bonanno, 1989), and they have become popular among muskmelon growers.

Other materials and techniques may be used to protect plants against cool spring temperatures. Agrotextiles generally provide lower air and soil temperatures than perforated polyethylene rowcovers, but similar yields have been reported (Loy and Wells, 1982). A relatively new technique, using unperforated polyethylene rowcover containing a water-filled tube, was originally developed to reduce heating costs in greenhouses (Grafiadellis, 1986; von Zabeltitz, 1989). This system is tested for its ability to moderate extreme temperatures inside mini-tunnels under our growing conditions. We report in this work the response of muskmelon transplanted in early spring to chilling protectant techniques and their subsequent effects on plant survival, early development and yield.

6.3 Materials and methods

6.31 Field layout

Three-week-old 'Earligold' muskmelon plants were transplanted on May 7, 6 and 8 in 1993, 1994 and 1995, respectively. Mulch treatments consisted of a black embossed, clear polyethylene (Plastitech, St-Rémi, Qué.) and photoselective polyethylene (IRT-76, AEP Industries, Moonachie, NJ). Rowcover treatments were a clear perforated polyethylene (500 holes m^{-2}; Plastitech Inc., St-Rémi, Qué.), a spunbonded polypropylene (Rotop, Plastitech, St-Rémi, Qué.) and two unperforated polyethylenes that included a standard clear polyethylene and an infrared-treated polyethylene (Polyon-Barkai, Polywest, Encinatas, CA). Each unperforated polyethylene tunnel contained an 8-m-long by 0.32-m-diameter clear polyethylene tube filled with 250 liters of water. The combinations of mulches and rowcovers in 1993 and 1994 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 non perforated tunnel/ thermal tube (CUT), 8) Photoselective green mulch/ clear non perforated tunnel/ thermal tube (GUT), 9) Black mulch/ clear non perforated tunnel/ thermal tube (BUT), 10) Clear mulch/ Infrared non perforated tunnel/ thermal tube (CIT), 11) Clear mulch/ Agrotextile tunnel/ no thermal tube (CAO). A supplemental experiment was set up in 1995 to test the following selected combinations: CIT, CAO, GUT, GPO and GOO.

The experimental field was located at the Horticulture Research Center at Macdonald Campus in Ste-Anne-de-Bellevue, Quebec, Canada (45° 24' 30" Lat., 73° 56' 10" Long.). The soil was a sandy loam fertilized with nitrogen at a rate of 100 kg/ha and rototilled prior to laying the mulch. Other fertilizer elements were applied according to soil tests (CPVQ, 1982). An herbicide, naptalam(2-[(1-naphthalenyl-amino)carbony]benzoic acid) was applied before clear mulch application according to the manufacturer's recommendations. One week before transplanting, drip irrigation was laid and mulches were installed mechanically over a 15-cm-high bed. Plots consisted of 11 plants with 70 cm between the plants and 2.0 meters between the rows. Immediately following transplanting, all tunnels were stretched over 80-cm-long wire hoops (# 10-gauge) and placed over the plants. Tunnels were left unventilated until anthesis. Anthesis was defined as the time when 90% of the plants had at least one fully opened perfect flower. Weekly sprays to control insects and diseases followed Quebec recommendations for growing muskmelon.

6.32 Experimental data

Replicated air and soil temperature data were collected from each plot using copper-constantan thermocouples connected to three AM-32 multiplexers and a CR-10 datalogger (Campbell Scientific Canada, Edmonton, AL) installed in Stevenson shelters. Temperatures were measured at 7.5 cm above and below ground level. Thermocouples used to measure air temperature were protected from direct solar radiation by placing them into white painted plastic tubes (15 cm in length and 3.3 cm in diameter). Temperatures were recorded every 10 minutes and averaged over each hour from transplanting until anthesis.

A destructive sample of two plants per treatment was taken at anthesis for measurement of fresh and dry weights. Due to severe frost damage during the spring of 1994, plants in all treatments except CIT and CUT were replaced on May 17 with 19-day-old transplants. Fruits were harvested and individually weighed three times a week at the Full-slip stage (McGlasson and Pratt, 1963). The last harvests of each season occurred Sept. 9, 12 and 6 in 1993, 1994 and 1995, respectively. Fruits were graded according to their weight. Categories of 8, 9, 12, 15, 18 and 23 fruits per boxes (30 cm X 35 cm X 43.5 cm) contained fruits in the range of more than 2100 g, 1800-2100 g, 1500-1800 g, 1200-1500g, 900-1200 g and 750-900 g, respectively. Fruit less than 750 g were deemed not marketable (culls). The seeds from 259 fruits in 1993 and 54 fruits in 1994 were removed, cleaned, dried, and separated into mature and immature seeds before being counted. Seed viability was judged by fullness, color and ease of detachment from the funiculus (Davis *et al.*, 1967).

6.33 Statistical analysis

The experiment was a randomized complete block design with three blocks. Data were analyzed using analysis of variance (ANOVA) and orthogonal contrasts (SAS Institute, Cary, N.C.). Percentage data were arc sine transformed before analysis.

6.4 Results and discussion

6.41 Effect on air and soil temperatures

6.411 Comparison among 1993, 1994 and 1995

Temperatures experienced by the muskmelon plants immediately post transplantation were crucial for establishment and survival in the field. In 1993, ambient air temperature at 7.5 cm above soil level decreased during the night following transplanting to 3.9C, and were followed by minimum temperatures ranging between 5.5 and 11.2C for a 5-day period. Transplants successfully established during this latter period and were then able to survive a frost on 14 May (Fig. 6.1B). In contrast, night temperatures during 1994 ranged between 1.6 to 5.8C for a period of seven consecutive days just after transplanting causing lethal chilling injury. In 1995, minimum temperatures decreased to 1.9C during the second night after transplanting. However, this event was immediately followed by a period of 6 days with minimum temperatures above 10C, during which the transplants could establish well.

In more general terms, the average temperature during the four-week period after transplanting (8 May- 4 June) was 13.4C, 13.4C and 16.0C in 1993, 1994 and 1995, respectively. Although 1993 and 1994 had the same average temperature during this period, 1994 had more extreme temperatures than 1993 (Fig. 6.1A). Consequently, 1994 had more potential to accumulate heat units above a base temperature, but at the same time, more risk of chilling injuries compared with 1993. Overall, 1995 had a much warmer spring than the two preceding years.

6.412 Comparison among microclimates

The mulch/rowcover/thermal tube combinations tested in this experiment followed typical patterns for air and soil temperatures (Fig. 6.2). For example, during warm and sunny days with ambient air maximum temperatures of 15.0C and 18.8C (Day of the year (DOY) 133 and 134 in 1993, respectively), CIT and BUT tended to have the highest air temperatures inside the tunnels, with maximum temperatures reaching 38.2C and 43.5C for CIT, and 40C and 43.5C for BUT during DOY 133 and DOY 134, respectively. For CIT, the high temperatures were probably an effect of the ability of the tunnel material to block the longwave radiation inside the tunnel, and the temperatures were greater than those under clear unperforated tunnels with a thermal tube (CUT). On the other hand, BUT had very high day-time temperatures most likely because of the effect of the black mulch radiating heat inside the nonventilated tunnel. Typically, GUT had 1 to 3C lower maximum temperatures than BUT, because the photoselective mulch lets more solar radiation be transmitted to the soil and less is absorbed by the material itself, as compared with the black mulch (Loy *et al.*, 1989). With CUT, most of the solar radiation was transmitted to the soil and little absorbed by the mulch, resulting in lower maximum air temperatures (32.2C for DOY 133 and 37.8C for DOY 134) than those with BUT and GUT.

Similar tendancies were found under perforated tunnels: higher air temperatures were found above black and photoselective mulches compared to those above clear mulches. However, the temperatures under perforated tunnels were more affected by windy conditions than those under the unperforated tunnels. The perforated tunnels had reduced air temperatures during windier days (DOY133, average wind speed 16.1 km/h) compared with days with low wind (DOY134, average wind speed 6.9 km/h). For example, maximum air temperature of CPO was 4.8C lower than that of CUT on a calm day, whereas this difference was of 6.6C on the windier day.

The agrotextile rowcover on clear mulch (CAO) consistently provided a microclimate with intermediate day-time air temperatures between the treatments with polyethylene rowcovers and the treatments with no rowcovers (BOO, GOO, COO) which had the lowest air temperatures. However, CAO provided little night frost protection, probably because of the high porosity of the rowcover material. Indeed, porosity of perforated tunnels usually ranges from 2 to 8 percent and for agrotextile, from 10 to 20 percent (CTIFL, 1987). During a cold night with a clear sky (night of DOY 133-134), minimum air temperature was 0.4C under CAO, compared with ambient minimum temperature of -0.1C (BOO, GOO and COO). As often occurs during these nights, minimum temperatures were even lower under perforated tunnels, because of radiation cooling (-0.7C under GPO and BPO). The clear mulch combination (CPO) had a slightly higher minimum temperature (0.0C) than the black or photoselective mulch combinations (BPO and GPO), probably because, during the night, some stored heat was released from the soil in the air under the tunnel (Table 6.1). The beneficial effect of the thermal tube was obvious during the night of DOY 134 (Fig. 6.2). During that night, minimum air temperatures under the tunnels with a thermal tube were 4.8 to 5.3C greater than ambient air minimum temperature. The infrared tunnel with a thermal tube provided the best cold temperature protection with minimum temperature 6.6C above ambiant. The inversion effect under the perforated tunnel was not experienced during the following night which was a cloudy night followed by a rainy morning (DOY 135). For all other treatments, the night-time temperatures followed the same tendencies as for the day-time temperatures.

Although greater average air temperatures were found under unperforated tunnels with a thermal tube, these tunnels produced a microclimate with the most frequent excessive day-time temperatures (Table 6.1). Indeed, over the three-week period after transplanting in 1993 and 1994, CIT, BUT and GUT treatments had seven to nine days with maximum temperatures above 40C compared with 5 days for GPO and BPO and none for the mulch alone. A clear mulch positioned under a perforated tunnel or an unperforated tunnel had the effect of reducing the number of days with excessively high air temperatures compared with the same tunnels coupled with black or photoselective mulches.

The green photoselective mulch had an intermediate effect on soil warming between those obtained under black and clear mulches with no tunnels or with a perforated tunnel. Similar results were reported by Loy and Wells (1990). However, soil temperatures were similar whether a black or photoselective mulch was used under the unperforated tunnel with a thermal tube (Table 6.1). Perhaps the thermal tube covered a large section of the mulch reducing the effectiveness of the latter compared with the perforated tunnel with no thermal tube and the mulch alone.

The water tube inside the unperforated tunnels clearly contributed to the release of heat during night-time (Pavlou, 1990). During the day-time, the lack of perforation and the presence of water droplets often found on the inside of unperforated tunnels may have contributed to the higher air temperature found under these types of tunnels compared with those of perforated tunnels. Nijskens *et al.* (1985) found that transmittance in the far infrared range of a dry polyethylene cover dropped from 77 % to 0 % after appearance of condensation which acts as a heat barrier.

6.42 Effect on chilling damage

The thermal tubes inside unperforated tunnels were efficient in reducing chilling temperatures in 1993 (Fig. 6.2, Table 6.1). Further, in 1994, only the unperforated tunnel with a thermal tube and clear mulch protected the muskmelon plants from lethal chilling injury (Table 6.2). As a result, 90.9 to 100% of the plants were damaged in the mulch alone treatments compared with 0.0% in CIT and 6.1% in CUT. These latter two combinations were the only ones not replanted. The reduction of chilling injury under the unperforated tunnels may not have been only a result of greater minimum temperatures compared with unperforated tunnel, agrotextile or no tunnel treatments, but also a result of a greater humidity, as indicated by water droplets or film in the inside of the tunnel. Indeed, chilling injury was reported to be less severe under conditions of high relative humidity, in which water loss from the cells is minimized (Wright and Simons, 1973; Rikin and Richmond, 1976).

The mulch type inside the tunnel had a significant effect ($P \leq 0.01$) on chilling injury. On treatments using the unperforated tunnel and the thermal tube, those with clear mulch had only 6.1% of plants killed compared with 39.4% for photoselective and 60.6% for black mulch. When the tunnels were perforated, 24.2% of the plants on clear mulch died of chilling injury, compared with 48.5% on photoselective and 93.9% on black mulch. The greater plant losses associated with the black mulch combinations might be a result not only of lower air temperatures under the tunnels, but also excessively high day-time temperatures (Fig. 6.2), which might have worsened the dehydration effect of chilling damage. The clear mulch alone allowed a small, but significantly greater ($P \leq 0.01$) proportion of plants to survive the cold temperatures compared with the photoselective mulch and the black mulch alone.

6.43 Effect on time to blooming of perfect flowers

Plants grown in unperforated tunnel treatments flowered first (Table 6.1). In 1993, plants grown in unperforated tunnels produced the first perfect flowers after 21-22 days compared with 27-28 days for perforated tunnels and 42-46 days for treatments with a mulch only. Indeed, anthesis of perfect flowers could be predicted from a simple heat unit formula based on average air temperature and a base temperature of 6.8C (Part 2). Similar tendencies were found in 1995. However, time to anthesis for CIT and CUT could not be compared in 1994 because plants in these treatments were not replaced as were those plants from other treatments killed by the spring frost.

6.44 Effect on plant biomass at blooming of perfect flowers

Even though they took less time to reach anthesis, plants grown in unperforated tunnels produced greater plant biomass than plants from perforated tunnels and mulch alone (Table 6.2). The effect of treatments on plant biomass at anthesis was greater during a cold spring. In 1993, significant differences were found between tunnel treatments and mulch alone treatments ($P \leq 0.10$), and between perforated tunnels and unperforated tunnels ($P \leq 0.05$), whereas in 1994 when muskmelon were replanted on 17 May, and in 1995, a warmer spring, no significant differences were found.

Clear mulch had a significant positive effect on plant biomass at anthesis, particularly when used in combination with perforated tunnels and treatments with no tunnels. Indeed, clear mulch was more effective in raising soil temperature in perforated tunnels and no tunnel treatments than in unperforated tunnel treatments (Table 6.1) and plant biomass from transplanting to anthesis was found to have a direct relationship with both soil and air temperatures (Part 2).

Photoselective mulch had an intermediate effect between black and clear mulch in increasing plant biomass at anthesis. However, the severe stunting accompanied by leaf marginal drying and necrosis of plants grown on mulch alone was typical of chilling injury (Rikin *et al.*, 1976). Further, leaves on plants with no tunnels looked smaller, and thicker than leaves of plants grown with perforated tunnels. Low temperatures, even unstressful, modify the morphology of the plants by affecting the dry matter distribution. In greenhouse tomato, reducing night temperature lead to a lower relative growth rate (RGR), due to a reduced leaf area ratio (LAR) and specific leaf area (SLA) (Franco, 1990). Then, low night temperature modified the growth pattern of the leaf by reducing the expansion and increasing the thickness (that is, decreasing SLA). Similarly, the SLA of cucumber grown in a temperature range of 12-24C increased sharply with increasing air temperatures and to a lesser extend with increasing soil temperatures, meaning that the leaves were getting thinner at higher temperatures (Kleinendorst and Veen, 1983). Under field conditions, the even larger and lusher leaves found under unperforated tunnels might be a result of higher air temperatures as well as higher relative humidity and absence of wind stress in this closed system. Special care should be taken when opening the unperforated tunnels. We observed that a drastic change in microclimate may result in severe wilting of the plants and even leaf burning.

6.45 Effect on yield and fruit size

A higher proportion of fruits < 750 g (27%) were harvested in 1993 compared with the following two years (Fig. 6.3). The average fruit weight was 1098, 1500 and 1637 g in 1993, 1994 and 1995, respectively. The distribution curve was flatter in 1995, reflecting the fact that there were more fruits of the various size categories, as compared with the relatively close to normal distributions in 1993 and 1994.

Unperforated tunnels, particularly CIT, produced the greatest early yields of all treatments, both in terms of number and weight of fruits (Table 6.3). Using CIT during cold springs in 1993 and 1994 resulted in a greater advantage in early yield than in 1995 which had a warm spring. Using tunnels resulted in significantly greater early yields over mulch alone during the 3 years of the experiment. Early yields were slightly greater, although not always significantly, for unperforated compared with perforated tunnels. Mulch type had no effect on early yields of plants grown under unperforated tunnels. Under perforated tunnels, the use of clear mulch produced plants with significantly ($P \leq 0.001$) more early fruits than plants grown with photoselective or black mulch. Plants covered with an agrotextile (CAO) gave early and total yields similar to those plants covered with a perforated tunnel.

Similar tendencies were noted for the total number of fruits. However, there were generally fewer differences among treatments. Fruit weight from plants grown in perforated and unperforated tunnels did not differ significantly. Average fruit weight tended to be smaller under unperforated tunnels, particularly for CIT (0.8, 1.3 and 1.3 kg for 1993, 1994 and 1995 respectively). In comparison, plants grown with mulch alone had the greatest average fruit weights, with 1.4 to 1.7 kg in 1993, 1.6 to 1.8 kg in 1994 and 1.7 kg for 1995. Perforated tunnels had intermediate average fruit weights of 1.3 to 1.4 kg in 1993, 1.4 to 1.6 kg in 1994 and 2.1 kg in 1995. Unperforated tunnels had values between CIT and perforated tunnels: 1.0 to 1.1 kg in 1993, 1.4 to 1.5 kg in 1994 and 1.6 kg in 1995. Treatments that resulted in early anthesis (unperforated tunnels) tended to yield smaller fruits than treatments with later anthesis, like perforated tunnels, CAO (1.1 kg in 1993, 1.7 kg in 1994 and 1.8 kg in 1995) and treatments with mulch alone.

After counting mature seeds of 313 fruits harvested in 1993 and 1994, a third degree polynomial relationship (r^2=0.648) between fruit weight and number of mature seeds was noted (Fig. 6.4). Although smaller fruit size can occur for reasons other than inadequate pollination, the relationship between fruit size and seed number suggests a pollination effect. The smaller fruit size for treatments with early anthesis may be partly a reflection of poor pollination due to unfavorable conditions for bee activity. McGregor and Todd (1952) reported that the production of a marketable fruit requires the successful fertilization of 400 to 600 ovules. Inadequately pollinated melon flowers abort or develop into malformed fruit which result in a reduced sink capacity (Bohn and Davis, 1964). Although beehives were located less than 10 meters from the muskmelon field, bees were not very active at the time of anthesis of earliest treatments. This may have been the case in 1993, a year when fruits were smaller than in 1994 and 1995 (Fig. 6.3). Indeed, average air temperature was less than 15C during a 2-week period after anthesis of plants grown in the unperforated tunnels (Fig. 6.1, Table 6.1). During the spring, temperature has been implicated as the most important factor influencing pollen collecting activity by bees, with collecting activity observed at temperatures below 10C (Stanley and Linskens, 1974). Langridge and Jenkins (1970) reported insignificant bee activity below 13C. The large proportion of small size fruits found in 1993 and in treatments with early anthesis was probably a result of unfavorable cool conditions for bee activity.

6.5 Conclusion

This 3-year experiment provided a range of conditions for testing plant survival to chilling temperatures in the field. When no period of plant establishment was allowed (with minimum temperatures above 10C), muskmelon transplants could survive in 1995 chilling temperatures down to 3.9C for one night, but not 7 nights in sequence between 1.6-5.8C, as in 1994. Only treatments having a clear mulch and an infrared-treated or standard unperforated tunnel with a thermal tube (CIT and CUT) survived the lethal frost in 1994. In 1993, transplants were allowed to establish for few nights above 5C and plants survived a night of frost (-0.1C) or 2 days below 4C. The chilling-induced dwarfing of the muskmelon plant was apparent until the termination of the plant's life cycle. Similar results were reported for cucumber (Rikin and Richmond, 1976). Most of the effect of protecting the plants from early chilling temperatures was reflected in early plant growth and development and early yields. Although the tendencies were significant in terms of total number of fruits produced, the differences in weight were small. This was a reflection of the smaller fruit size obtained under treatments which had anthesis under conditions too cool for adequate pollination.

It may be advantageous for growers to use a range of mulch/tunnel combinations in order to obtain a constant supply of fruits for their market. Early plantings which are risky from a production point of view should be made using protective tunnels. Unperforated tunnels with a thermal tube are more costly, but offer the best protection in case of chilling/freezing temperatures and the highest early yields, particularly during cool springs. Perforated tunnels should be used for a second early planting as they offer no chilling temperature protection, reasonably stable early yields and increase in total fruit number of 17-32% and in total weight of 12-43% over mulch alone treatments. Finally, although early and total yields are lower, larger fruits are obtained with the use of mulches alone, the photoselective mulch offering a compromise between the soil warming of the clear mulch and weed control of the black mulch.

Table 6.1. Air and soil temperatures at 7.5 cm from 8 to 28 May, dates of planting, blooming of perfect flowers and harvest of a muskmelon crop grown with mulch, rowcover and thermal tube.

Mulch/row cover/thermal tube[z]		CIT	CUT	GUT	BUT	CPO	GPO	BPO	CAO	COO	GOO	BOO
						Air temperature						
Average temperature	1993	21.9	19.5	20.3	20.7	16.7	17.4	17.3	15.0	13.3	13.2	13.3
(C)	1994	22.5	19.9	21.5	21.7	17.2	18.2	18.4	15.3	12.7	12.9	12.7
Number of days <5C	1993	0	0	1	1	6	6	6	6	5	5	5
	1994	3	6	7	7	13	13	13	12	6	7	8
Number of days >40C	1993	8	2	7	9	1	5	5	0	0	0	0
	1994	9	4	9	9	3	5	5	0	0	0	0
						Soil temperature						
Average temperature	1993	21.8	20.5	19.5	19.9	19.8	19.0	17.3	17.9	18.8	15.8	15.0
(C)	1994	23.2	22.4	20.9	21.7	21.6	18.7	16.7	19.1	18.4	15.0	13.7
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	6-May	17-May	17-May	17-May	17-May	17-May	17-May	17-May	17-May	17-May
	1995	8-May	8-May	-	8-May	-	-	8-May	-	-	8-May	-
Days to flowering	1993	21	22	22	22	27	28	28	32	42	46	46
	1994	26	29	23	23	25	27	29	29	36	38	45
	1995	25	-	27	-	-	29	-	31	-	42	-
Days to first harvest	1993	77	75	73	75	75	73	73	82	87	89	94
	1994	75	75	69	69	62	64	66	66	73	78	85
	1995	74	-	74	-	-	74	-	72	-	77	-

[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).

Table 6.2. Mulch, rowcover and thermal tube effects on plant chilling injury and plant dry matter (DM) at anthesis of muskmelon.

Mulch/row cover/thermal tube[z]	Chilling Injury[y] (%)	Plant Biomass at Anthesis (g DM/plant)		
	1994	1993	1994[x]	1995
CIT	0.0	25.5	(21.6)	31.7
CAO	69.7	17.2	20.1	24.0
Unperforated PE tunnels (Unperf.)				
CUT	6.1	20.2	(30.8)	-
GUT	39.4	22.0	35.3	34.6
BUT	60.6	17.0	24.7	-
Perforated PE tunnels (Perf.)				
CPO	24.2	16.5	22.7	-
GPO	48.5	12.6	22.2	12.9
BPO	93.9	9.9	23.1	-
Mulch alone (Mulch)				
COO	93.9	16.0	32.0	-
GOO	90.9	7.5	22.6	27.0
BOO	100.0	4.7	15.0	-
Significance[w]				
Treatment	***	***	**	*
Orthogonal contrasts				
CIT vs others	***	***	**	NS
CAO vs (Unperf.+Perf.+Mulch)	***	+	+	**
Mulch vs (Unperf.+Perf.)	NS	+	NS	NS
Unperf. vs. Perf.	***	*	NS	NS
CUT vs (GUT+BUT)	**	*	NS	-
GUT vs BUT	NS	NS	NS	-
CPO vs (GPO+BPO)	***	**	NS	-
GPO vs BPO	**	NS	*	-
COO vs (GOO+BOO)	**	**	NS	-
GOO vs BOO	NS	**	**	-

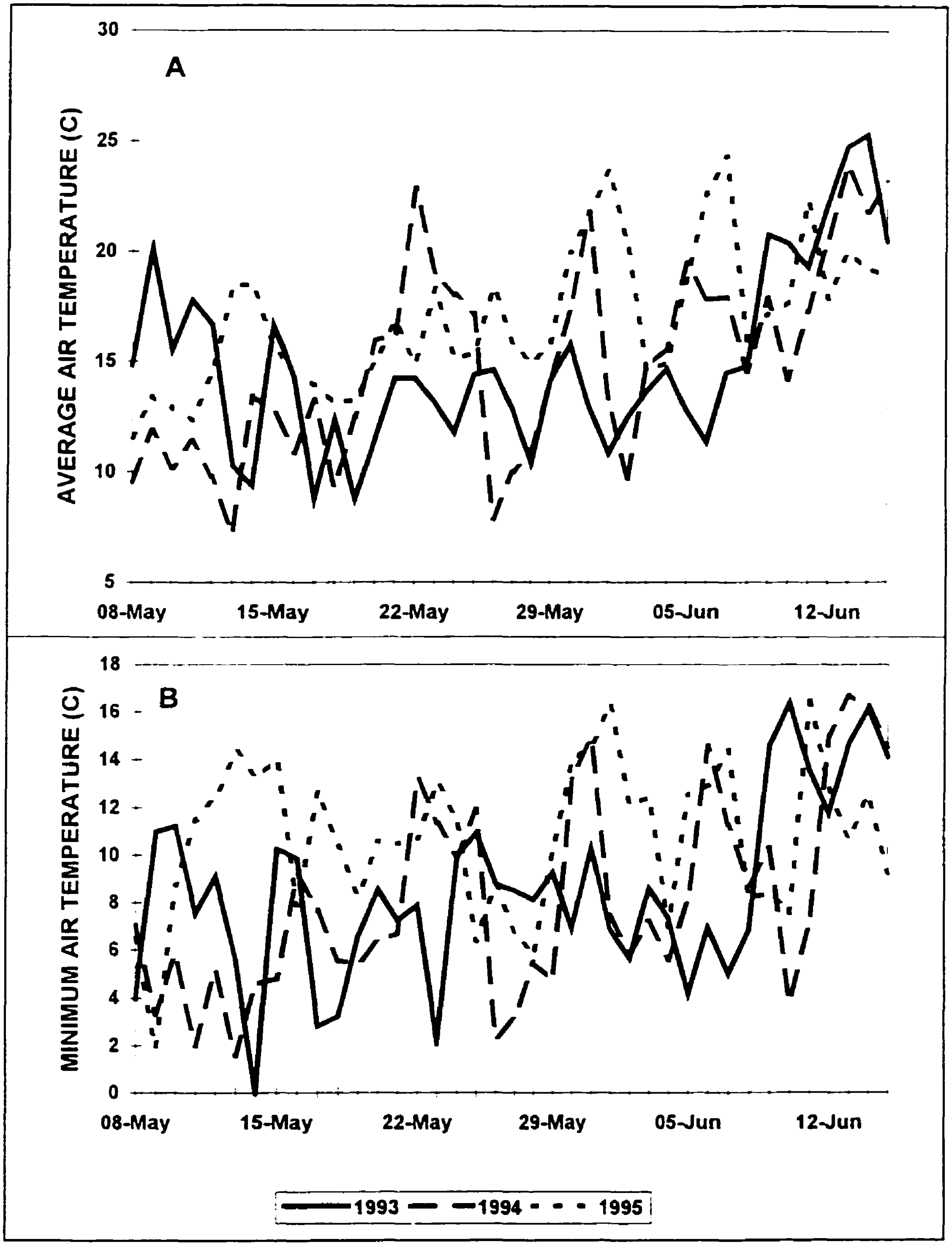
[z] First letter indicates mulch type, either clear (C), photoselective-green (G) or black (B); second letter indicates tunnel type, either perforated clear polyethylene (PE) tunnel (P), unperforated clear PE (U), infra-red treated unperforated PE (I) or polypropylene agrotextile (A); third letter indicates presence of a thermal tube (T) or absence of a thermal tube (O).
[y] Percentage data were Arc Sine transformed before analysis.
[x] Plants in all treatments except CIT and CUT were replanted 11 days after the original date of plantation. Then, CIT and CUT plant biomass, indicated in parenthesis, cannot be compared with other treatments.
[w] Probability of a significant F value. NS,+, *, **, ***, nonsignificant or significant at $P \leq 0.10, 0.05, 0.01$ or 0.001, respectively.

Table 6.3. Mulch, rowcover and thermal tube effects on yield of muskmelon. Early yield was harvested before 1 Aug. of each year

Mulch/row cover/thermal tube[z]	Early Yield (no./plant) 1993	Early Yield (no./plant) 1994	Early Yield (no./plant) 1995	Early Yield (kg/plant) 1993	Early Yield (kg/plant) 1994	Early Yield (kg/plant) 1995	Total Yield (no./plant) 1993	Total Yield (no./plant) 1994	Total Yield (no./plant) 1995	Total Yield (kg/plant) 1993	Total Yield (kg/plant) 1994	Total Yield (kg/plant) 1995
CIT	8.5	10.0	5.7	6.2	12.6	7.1	14.8	14.1	9.1	11.9	18.1	12.0
CAO	4.4	5.1	5.2	4.4	7.9	9.0	8.7	9.1	6.4	9.4	15.4	11.4
Unperforated PE tunnels (Unperf.)												
CUT	5.7	6.7	-	5.7	10.4	-	9.1	10.9	-	10.4	16.5	-
GUT	5.9	5.5	6.1	5.9	7.9	8.8	10.0	12.5	8.9	10.9	17.4	14.7
BUT	5.3	6.0	-	5.3	8.6	-	9.1	13.8	-	10.0	19.3	-
Perforated PE tunnels (Perf.)												
CPO	4.8	5.9	-	5.3	7.9	-	8.5	11.0	-	11.0	16.5	-
GPO	5.3	5.1	4.4	6.1	8.0	8.5	7.7	8.4	6.3	11.1	13.9	13.0
BPO	4.1	3.8	-	4.5	5.9	-	6.2	7.5	-	8.1	12.2	-
Mulch alone (Mulch)												
COO	0.7	1.1	-	0.7	1.4	-	6.4	8.5	-	9.1	14.0	-
GOO	0.3	0.3	3.7	0.3	0.3	5.6	5.2	7.5	5.4	8.6	12.8	9.1
BOO	0.1	0.0	-	0.1	0.0	-	5.4	6.3	-	9.0	11.2	-
Significance[y]												
Treatment	***	***	*	***	***	**	***	***	**	NS	***	+
Orthogonal contrasts												
CIT vs others	***	***	NS	***	***	*	***	***	NS	NS	***	NS
CAO vs (Unperf.+Perf.+Mulch)	**	*	NS	*	**	*	NS	NS	*	NS	NS	NS
Mulch vs (Unperf.+Perf.)	**	**	*	NS	*	**	*	**	*	NS	+	*
Unperf. vs. Perf.	NS	NS	*	+	NS	+	**	*	***	NS	NS	NS
CUT vs (GUT+BUT)	NS	+	-	NS	NS	-	**	***	-	NS	***	-
GUT vs BUT	NS	NS	-	NS	NS	-	NS	***	-	NS	**	-
CPO vs (GPO+BPO)	***	***	-	***	***	-	***	***	-	NS	*	-
GPO vs BPO	***	***	-	***	***	-	+	**	-	NS	+	-
COO vs (GOO+BOO)	***	***	-	***	***	-	***	***	-	NS	*	-
GOO vs BOO	NS	NS	-	NS	NS	-	*	***	-	NS	**	-

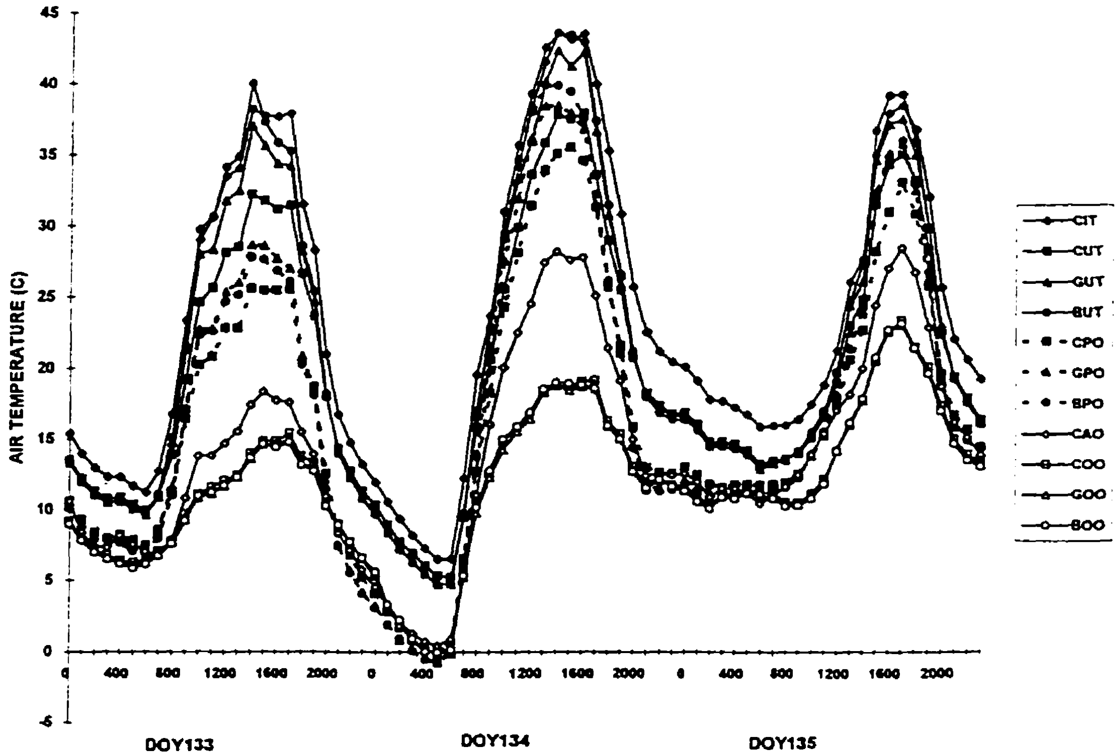
[z] First letter indicates mulch type, either clear (C), photoselective-green (G) or black (B); second letter indicates tunnel type, either perforated clear polyethylene (PE) tunnel (P), unperforated clear polyethylene (U), infra-red treated unperforated polyethylene (I) or polypropylene agrotextile (A); Third letter indicates presence of a thermal tube (T) or absence of a thermal tube (O).
[y] Probability of a significant F value. NS, +, *, **, ***, nonsignificant or significant at $P \leq 0.10, 0.05, 0.01$ or 0.001, respectively.

Figure 6.1. (**A**) Average and (**B**) minimum air temperatures (C) at 7.5 cm above soil level between May 8 and June 15 in 1993, 1994 and 1995.



A
AVERAGE AIR TEMPERATURE (C)
30
25
20
15
10
5
08-May
15-May
22-May
29-May
05-Jun
12-Jun
B
MINIMUM AIR TEMPERATURE (C)
18
16
14
12
10
8
6
4
2
0
08-May
15-May
22-May
29-May
05-Jun
12-Jun
1993
1994
1995

Figure 6.2. Typical air temperature at 7.5 cm above soil level recorded under 11 mulch/tunnel combinations during three days in the spring of 1993: 13 May (Day of Year (DOY) 133), 14 May (DOY 134) and 15 May (DOY 135). 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).



AIR TEMPERATURE (C)
45
40
35
30
25
20
15
10
5
0
-5
0
400
800
1200
1600
2000
0
400
800
1200
1600
2000
0
400
800
1200
1600
2000
DOY133
DOY134
DOY135
CIT
CUT
GUT
BUT
CPO
GPO
BPO
CAO
COO
GOO
BOO

Figure 6.3. Frequency distribution of fruits by 300 g increments and in each commercial grade for 1993, 1994 and 1995. The 'Box #' corresponded to the number of fruits per box of 30 cm X 35 cm X 43.5 cm and contained fruits of the weight range indicated. Only microclimates common to the three years were considered. Culls were fruits <750 g.

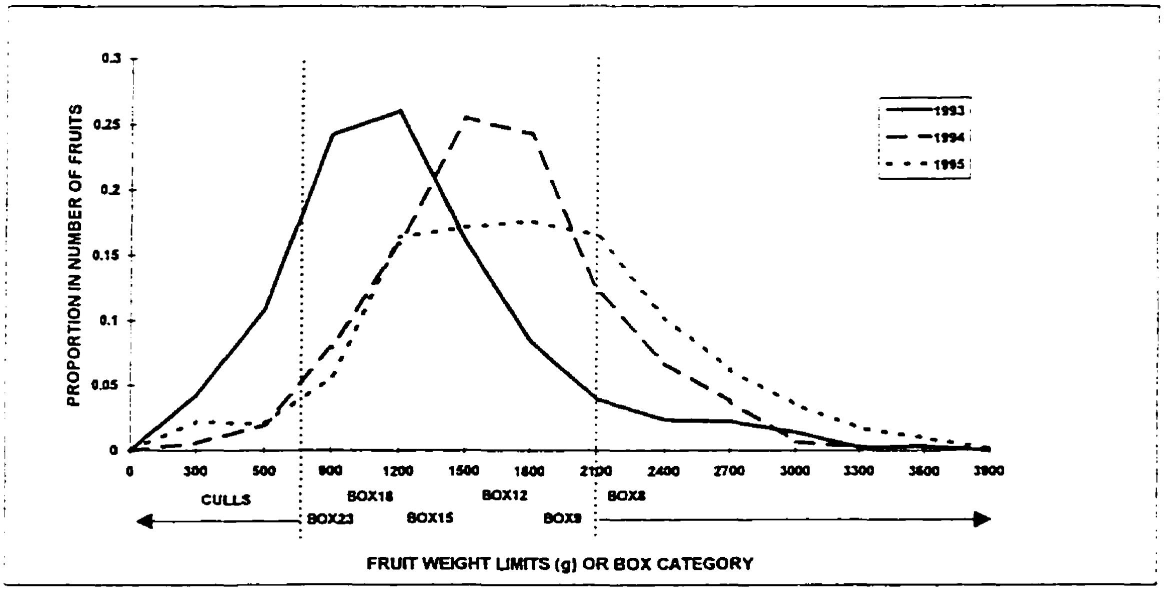
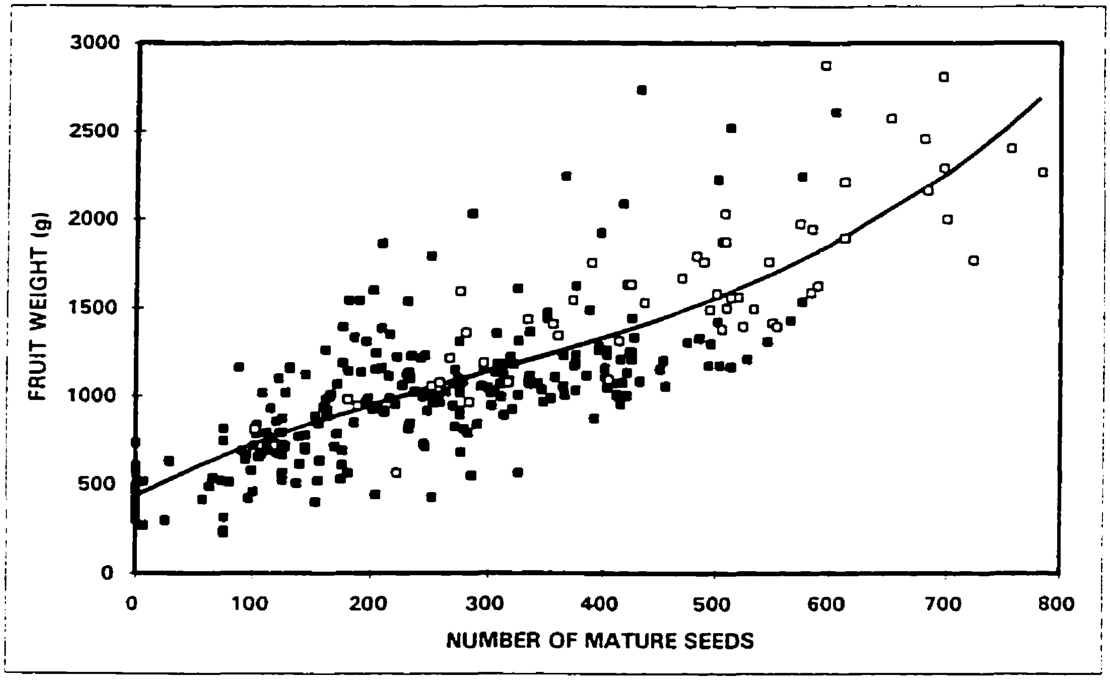

PROPORTION IN NUMBER OF FRUITS
0.3
0.25
0.2
0.15
0.1
0.05
0
1993
1994
1995
0
300
500
900
1200
1500
1800
2100
2400
2700
3000
3300
3600
3900
CULLS
BOX18
BOX12
BOX8
BOX23
BOX15
BOX9
FRUIT WEIGHT LIMITS (g) OR BOX CATEGORY

Figure 6.4. Effect of the number of mature seeds on fresh weight of muskmelon fruit (g). The relationship is described by $Y = 435.28 + 3.379\ X - 0.00523\ X^2 + 0.00000588\ X^3$; $r^2 = 0.648$, $n = 313$. All terms were significant at the 0.05 level. Black squares represent 1993 data and open squares 1994 data.


3000
2500
2000
1500
1000
500
0
FRUIT WEIGHT (g)
0
100
200
300
400
500
600
700
800
NUMBER OF MATURE SEEDS

Part 7. General conclusions

In all types of commercial vegetable production, a concept of timing is needed to secure a long season and an even distribution of supply. This is also important for scheduling labour, transport and deliveries of products to markets. One of the most common approaches to determine timing under field conditions is the heat-unit system, which is based on day-temperature sums over a fixed base-temperature. Earliest work in this area was done with processing vegetable crops which require a once-over mechanical harvest. However, this system also works for predicting key developmental phases for multiple harvested crops which mature at specific stages, such as muskmelon.

From the grower's point of view, this research can be summarized in few lines. The number of harvestable fruits and time to maturity can be predicted from simple measurements in the field. Time from transplanting to anthesis can be predicted from a standard heat unit formula with a base temperature of 6.8C. From anthesis, time to fruit maturity can be predicted from an accumulating daily maximum temperatures with a base temperature of 15C. A counting of the number of developing fruits longer than 4 cm after 225 degree days from the start of anthesis could give a rapid estimate of the number of fruits that will reach maturity.

Clearly, this model is more descriptive than explanatory and started with the highest abstraction level, neglecting all growth processes, like photosynthesis and carbon partitioning. This black box approach was chosen for several reasons. From a physiological point of view, it may be considered as an oversimplification. From a micrometeorological point of view, there is certainly room for more sophistication (Albright *et al.*, 1989). However, even such a rough approach may be extremely effective in improving precision for production planning. There are ways to refine this approach towards a less abstract level if necessary. Improvements of a model usually help to understand better the plant reactions but lead to more complicated models and not necessarily to a better prediction ability (Liebig, 1989)

Krug (1989) analyzed the advantages and limitations of planning models. These types of models are advantageous because the data are collected under conditions close to those in commercial practice; as such, collected values are more realistic and include factors such as fluctuations of climatic factors and seasonal effects. On the other hand, problems may arise through:

1) differing cultivar response. 'Earligold' is an eastern-type muskmelon which is fast-ripening. Western-type or more exotic types of melon may react differently.

2) environmental effects, which were not considered such as watering, fertilization, technical procedures or disturbing factors like pests and diseases. This study kept all of these factors constant.

In addition, the calculation of mean growth rates assuming linear relationships to mean climatic conditions may not always be realistic and there may be difficulties in finding good prediction of weather conditions. This is more important under field than under controlled environment such as greenhouses (Liebig and Lederle, 1989). Harvest dates could be predicted from historical weather data which could then be replaced by actual data as they become available. Then, accuracy in predicting harvest date increases as the actual harvest date approaches. Another potential application is the estimation of fruit harvest dates in new and marginal environments by using a weather data simulator such as the one incorporated in DSSAT (International Benchmark Sites Network for Agrotechnology Transfer, 1993).

In this perspective, the objectives of this thesis were met. The muskmelon development models could predict time from transplanting to anthesis and from anthesis to fruit harvest date with good accuracy under a wide range of microclimate where the crop was grown. Only minimum and maximum air temperatures were required. This simple model provides a valuable management tool for a grower who wants to predict harvest dates. In the process of modeling yield of muskmelon, basic informations on the crop were collected. A precise set of references for ovary phenology was developed, permitting an easy identification of age and stage in reference to the blooming stage. A rapid and non-destructive method to estimate ovary volume from length and diameter was established, allowing fruit growth studies from early stages of development. The fruiting dynamic of muskmelon was studied under northern climatic conditions.

This work may be most useful in helping design improved cultural systems in muskmelon. Furthermore, using mulches and row cover to modify the field microclimate within a year of production may have implications for other crops. Plasticulture techniques may create the extreme conditions necessary to determine the cardinal points for a heat unit system.

Part 8. Contribution to Knowledge

The following is considered original contribution to knowledge brought from the research described in this thesis:

1. A heat unit model was developed to predict growth and time from transplanting to anthesis of muskmelon perfect flowers.

2. Two heat unit models were developed to predict time from anthesis to maturity for individual muskmelon fruits depending on the temperature data set used.

3. A clear description of the phenology of the muskmelon fruit was established, from flower initiation to fruit maturity. Flower and fruit abortion was described, in relation to fruit phenology.

4. Fruit cycling of muskmelon in a northeastern climate was described.

5. Number of harvestable fruits and time to maturity of muskmelon was predicted from simple weather and crop observations.

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IMAGE EVALUATION TEST TARGET (QA-3)

150mm

6"

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