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Studies on procedures for calculating the base temperature and effects of temperature regimes on tomato transplant development and yield

Senshan Yang

To the Graduate Council:

I am submitting herewith a dissertation written by Senshan Yang entitled "Studies on procedures for calculating the base temperature and effects of temperature regimes on tomato transplant development and yield." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Plant, Soil and Environmental Sciences.

David Coffey, Major Professor

We have read this dissertation and recommend its acceptance:

John Foss, Fred Allen, Mary Leitnaker

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

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David L. Coffey

David Coffey, Major Professor

We have read this dissertation and recommend its acceptance:

Joanne Logan

Fred L. Allen

John E. Foss

Mary G. Leitnaker

Accepted for the Council:

Associate Vice Chancellor
and Dean of The Graduate School

STUDIES ON PROCEDURES FOR CALCULATING THE BASE TEMPERATURE AND EFFECTS OF TEMPERATURE REGIMES ON TOMATO TRANSPLANT DEVELOPMENT AND YIELD

A Dissertation

presented for the

Doctoral of Philosophy

Degree

The University of Tennessee, Knoxville

Senshan Yang

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DEDICATION

This dissertation is dedicated to my parents, Mr. Guoxiang Yang and Mrs. Zhangshi Yang, who are common people in the world but the greatest ones in my life. This dissertation is also dedicated to my wife, Mrs. Yuhuan Xin, who gives me love that encourages me to fulfill my commitments.

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ABSTRACT

In the prediction of crop development, the procedures to calculate the base temperature in heat unit systems are tedious and deficient in theoretical bases. Little information is available on effects of temperature regimes or temporal temperature distributions on crop development. The objectives of this dissertation were: 1) to develop new procedures for calculating the base temperature in heat unit systems for any crop, 2) to study the effects of temperature regimes for tomato seedlings in the preceding developmental stage on the succeeding developmental stage, 3) to study effects of temperature regimes for tomato transplants before transplanting on the subsequent yield in the field. Tomatoes were planted on different dates in the greenhouse under three temperature levels (average temperatures for each developmental phase were at 17-19 C, 21-23 C, 24-26 C in 1991 and 18-20 C, 20-22 C, and 22-24 C in 1992) and rotated among three temperature levels in such a way that all transplants received approximately the same temperature accumulation at the time of transplanting. Seedling emergence and the time of appearance of the first to sixth leaf were defined as developmental stages 1-6. Seedling emergence to the first and second, the first and second to the third, the third to the fourth, the fourth to the fifth, and fifth to the six leaf appearance were defined as developmental phases 1-6. Temperature and solar radiation were measured. Average temperatures and the number of days for each developmental stage and phase were recorded. Transplant height, stem diameter, leaf length, and weight were measured. When transplants reached the sixth developmental stage, they were transplanted to the field of the University of Tennessee Plant Field Science Laboratory at Knoxville. Tomato fruits were divided into six groups according to fruit size based on the Los Angeles system. Fruit yield and fruit number were measured in each of six groups. The results of this research showed that the four proposed formulas for calculating the base temperature in heat unit systems were superior to the previous procedures in terms of simplicity and mathematical bases. Temperature regimes experienced in the preceding developmental stage affected the succeeding developmental stages. The prediction of seedling development in the greenhouse considering effects of the preceding temperature regimes on the succeeding developmental stages was more accurate than that without considering such effects. Tomato seedling development was controlled by both temperature accumulations and the way temperature accumulations were achieved. Fruit yield and fruit number were significantly affected by temperature regimes experienced by seedlings in the greenhouse before transplanting. A sharp change in temperature regimes either from low to high or from high to low before the fourth leaf appearance appeared to have negative effects on fruit yield in the field. Temperature in the ranges of 18-21 C for seedling emergence and 19-22 C for the first and second leaf appearance resulted in the best quality of transplants.

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PART I

GENERAL INTRODUCTION AND OVERVIEW

1. INTRODUCTION AND OVERVIEW

"The state of a plant is determined by both growth and developmental processes. In modeling crop systems, separating the two processes is important because they are affected by different environmental variables. Development refers to the timing of critical events in the life cycle of a plant. Growth refers to the increase in weight, volume, length, or area of some part or all of the plant" (Ritchie and Nesmith, 1991). Crop growth and development are interrelated. Thus accurate prediction of plant development is important in crop management and in modeling crop growth. Many researchers have found that crop development is controlled by various environmental factors such as temperature, moisture, solar radiation, photoperiod. Among these environmental factors, temperature is dominant. Therefore, most research work done to date in prediction of crop development has focused on temperature effects.

The heat sum system, also termed growing degree days (GDD), degree days, cumulative degree days (CDD), heat summations, thermal units, or growth units, has been used extensively in the prediction of crop development, although it has several inaccuracies (Arnold, 1959; Cross and Zuber, 1972; Doyle, 1974; Coffey, 1978; Rinne, 1984; Bewick et al., 1988). Usually, heat sums are calculated as:

$$GDD = \sum_{s}^{h} (T - T_b) \qquad (1)$$

where GDD=growing degree days, T_b=the base temperature, s=sowing date, h=harvesting time, $T=(T_{max}+T_{min})/2$, daily average temperature, T_{max}=daily maximum temperature, and T_{min}=daily minimum temperature.

There are several assumptions in the heat sum system:

1) There is a linear relationship between the average air temperature above the base temperature and the plant developmental rate over the range of temperature experienced.
2) There is a constant temperature below which crop growth and development will cease.
3) The daily temperature does not fall below the base temperature for a significant part of the day.
4) The daily temperature does not exceed an upper threshold temperature for a significant part of the day (Ritchie and Nesmith,1991).
5) Other environmental factors only slightly affect crop development.

However, these assumptions are not always valid and therefore are questioned by many researchers. Coffey (1978) summarized the criticisms to the heat unit system:

"Probably the greatest weakness of any temperature summation system lies in the fact that growth and development are not directly proportional to temperature, especially to supraoptimal temperature. Although temperature as measured by accumulated heat units is one of the most important factors in determining development toward maturity, other factors must be considered:

(1) Soil fertility may affect maturity, high phosphorus hastening it and high nitrogen delaying it.

(2) Soil type is important, for heavy soils warm up slowly, whereas sandy soils warm up rapidly.

(3) Topography, slope, and drainage are important, since they affect temperature and moisture conditions.

(4) Altitude and latitude influence the number of heat units required to bring a crop to maturity.

(5) Frost and drought damage are not accounted for by the system.

(6) Wind, hail, storms, insects, and disease may influence heat values necessary to bring a crop to a given stage of maturity.

(7) Sunlight intensity measured in gram calories per square centimeter includes more than just temperature accumulation.

Temperatures above an optimal value or below a base value may decrease or stop crop growth and development. Selection of base temperatures and planting dates also affects cultivar constants, GDD required to bring a crop to a given developmental stage."

Most attention given to improving heat unit systems has focused on determining the base temperature below which development and growth stop and the ceiling temperature at which development ceases or begins to decline (Ritchie and NeSmith, 1991). Various statistical methods have been used to determine the heat summation and base temperature. Arnold (1959) summarized these methods and discussed advantages and disadvantages of these various methods in detail. From Arnold's analysis, it is known that procedures for calculating the base temperature are tedious and lack a mathematical basis.

Inaccuracies in prediction of crop development with temperature alone have been reported (Gilmore and Rogers, 1958; Arnold, 1959; Schaal and Dale, 1977; Bauer et al., 1983; Baker et al., 1986; Bewick et al., 1988; Perry and Wehner, 1990). In order to avoid shortcomings in prediction of crop development with temperature alone, several other methods, such as photothermal units (PTU) (Davison and Campbell, 1983), stress degree days (SDD) (Huda et al., 1987), effective degree days (EDD) (Scaife et al., 1978), have been developed to account for the effects of other environmental factors such as daylength, soil moisture, and solar radiation. All methods mentioned above were used to identify constants in a linear equation. However, when there is no linear relationship between temperature or photoperiod and crop development, such constants do not exist. A method to deal with this situation involves nonlinear regression models (Hodges, 1991).

In the crop development models discussed so far, there are some basic assumptions: 1) when the requirement of the accumulation of GDD, PTU, SDD, EDD, crop development has been met, the crop should be in a predicted developmental stage regardless of how these units are accumulated; 2) a crop has the same response to temperature in each developmental stage.

These assumptions are questionable. Many researchers (Cross and Zuber, 1972; Perry et al., 1986) have shown that there is considerable variation in accumulation of GDD or PTU between years or planting dates although total temperature accumulations between years or planting dates showed no significant differences.

Crop developmental rate is defined as the reciprocal of the number of days required to reach a given developmental stage (Anderson et al., 1978). In a greenhouse or growth chamber, plants can be grown at specific constant day and night temperature regimes and temperature response curves can be obtained, but under field conditions constant day and night temperature regimes seldom occur. Therefore, the application of temperature response curves to predict crop development obtained from data in growth chamber studies to field conditions may not be appropriate. Under field conditions, temperature accumulations vary among years not only in quantity but also in distribution.

For example, temperature accumulations (base temperature is not considered) at Knoxville in 1974 in May, June and July, were 574 C, 614 C, and 746 C, and 590 C, 687 C, and 768 C in 1984, respectively. Although there are large differences between monthly accumulations from year to year, the overall temperature accumulation is approximately the same in these two years. Crop responses to these GDD may be different, although other environmental conditions may be similar. The change in temperature accumulation patterns, defined as the manner in which a certain temperature accumulation is reached, in a growing season may influence crop growth and development. There is little information about how temperature change patterns influence crop growth and development, and affect the prediction of crop development with various models. Variation in temperature accumulation patterns among years may contribute to the variation in GDD or days for crop development. There is also little information about how temperature change patterns within year affect crop growth and the relationship between crop growth and development.

The quality of tomato transplants is very important to the subsequent yield and quality in the field (McCollum, 1980; Adelana, 1983). Weston and Zandstra (1986) reported that yields varied considerably with transplant quality. Research in this area has been well documented. It is known that transplant quality is determined by transplant age, size, and morphology (Cooper and Morelock, 1983; Weston and Zandstra, 1986). In turn, transplant size and morphology are influenced by environmental conditions such as temperature, light density, nutrition and cultural practices such as sowing date, flat spacing, and container volume (Anderson, 1985; Gorski and Wertz, 1985).

Transplant age and size are two key factors affecting transplant performance in the field. However, the manner in which a transplant reaches its size and age on the subsequent yield also is important. Effects of container size, nutrition level, flat spacing, temperature on tomato transplant quality have been studied (Knavel, 1965; Anderson, 1985; Rutledge, 1989), but there is little information about how temperature regimes experienced by transplant in the greenhouse before transplanting affect their subsequent yield in the field. Temperature distribution during transplant growth is important to both transplant development and quality and is useful to transplant producers and tomato growers. Understanding effects of temperature regimes on transplant quality and performance in the field may assist producers to grow better transplants.

2. OBJECTIVES

The objectives in this study were to:

1) develop new and improved procedures for calculating the base temperature in heat unit systems for any crop.
2) study the effects of temperature regimes for tomato seedlings in the preceding developmental stage on the succeeding developmental stage.
3) study the effects of temperature regimes experienced by tomato transplants in the greenhouse before transplanting on the subsequent yield in the field.

3. OVERVIEW

This dissertation is divided into three different manuscripts, each addressing one of the objectives stated above. The first manuscript, "New Procedures for Calculating the Base Temperature in Heat Unit Systems" compares previous procedures for determining base temperature for GDD with the proposed formulas. It is found that proposed formulas are better than previous procedures for calculating the base temperature in terms of accuracy and simplicity.

The second manuscript, "Effects of Temperature Regimes on Tomato Transplant Growth and Development", studies and models the effects of temperature regimes experienced in the previous developmental stage by tomato seedlings on the subsequent development. Environmental factors affecting crop development and methods to predict crop development are reviewed and discussed. Developmental rates are modeled with two approaches. One approach takes the effects of temperature regimes experienced in the preceding developmental stages on tomato seedling development on the following developmental stage into consideration. The other approach does not take such effects into the consideration.

The third manuscript, "Effects of Temperature Regimes Experienced in the Greenhouse by Tomato Transplants on the Subsequent Yield in the Field" describes how temperature regimes during the growth of tomato transplants affect the subsequent performance of these transplants in the field. In this manuscript, variance analysis is used to compare tomato fruit yield and number of different treatments. Tomato fruit yield and number are regressed to tomato transplant height, stem diameter, weight, and leaf length. More attention is given to efforts of finding temperature regimes under which transplants with high quality will be produced.

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PART II

NEW PROCEDURES FOR CALCULATING THE BASE TEMPERATURE IN HEAT UNIT SYSTEMS

ABSTRACT

Much research has been done on finding methods to determine the base temperature, a very important variable in computation of growing degree days (GDD). Four common methods have been reported: 1) the least standard deviation in growing degree days, 2) the least standard deviation in days, 3) coefficient of variation, and 4) regression coefficient. These methods are tedious and lack a theoretical basis in mathematics. The objective of this research was to find simple and mathematically sound formulas to calculate the base temperature for GDD. Mathematical formulas are proposed, proved and tested using temperature data during tomato transplant development in the greenhouse. Compared with previous procedures, these proposed mathematical formulas can calculate the base temperature easily and accurately. These formulas are applicable to calculating the base temperature for GDD of any developmental stage for any crop.

1. INTRODUCTION AND LITERATURE REVIEW

In modeling crop growth, accurate prediction of crop development is necessary. Much research has been done in this area (Anderson et al., 1978; Angus et al., 1981; Bewick et al., 1988). Researchers have found that air temperature is a dominant factor controlling crop development. To predict crop development with air temperature, growing degree days (GDD) or a similar linear unit system is a basic and widely used method in practice (Madariaga and Knott, 1951; Hoover, 1955; Gilmore and Rogers, 1958; Hortic and Arnold, 1965). The selection of an appropriate base temperature is critical to the GDD or any heat unit model.

The concept of base temperature can be described either physiologically or statistically. Physiologically, it is assumed that below a certain temperature level, crop growth and development will cease. However, usually it is difficult to determine the physiological base temperature, and each developmental phase may have a different base temperature. In physiology, the base temperature should be the same or at least similar for a crop in a given developmental stage in any growing season. But in practice, the base temperature selected may vary among years or growing seasons. For example, Arnold (1959) reported that the base value for corn was 6 C in 1954 and 4.3 C in 1955. Statistically, the base temperature is that which results in the lowest standard deviation in GDD accumulations. In most cases, the base temperature is determined statistically rather than physiologically due to criteria of selecting the base temperature. Even if the base temperature is said to be determined biologically, the final criterion to accept or reject it is to see if that base temperature results in the lowest standard deviation in GDD accumulations. In research, the base temperature is selected in a such way that the variation in GDD is minimized (Arnold, 1959; Goyne et al., 1977; Fernandez and Chen, 1989). However, the base temperature may sometimes be calculated to be below zero, which is difficult to explain in biology.

Several methods to determine the base temperature have been reported. They are:

1) the least standard deviation in GDD (Magoon and Culpepper, 1932; Stier, 1939).
2) the least standard deviation in days (Arnold, 1959).
3) the coefficient of variation in days (Nuttonson, 1958).
4) the regression coefficient (Hoover, 1955).

1). <u>The Least Standard Deviation in GDD Method</u>

In this method the base temperature is selected in such a way that the resultant variation in GDD using a series of plantings is minimized. The least standard deviation in GDD is defined as

$$SD_{gdd} = \left(\frac{\Sigma(GDD_i - MGDD)^2}{n-1}\right)^{\frac{1}{2}} \qquad (1)$$

where SD_{gdd} is the least standard deviation in GDD, GDD_i is growing degree days of the ith planting, MGDD is the overall mean of GDD of entire plantings, and n is the number of plantings.

In this method, GDD is calculated using a series of candidate base temperatures. each one resulting in a set of GDDs and a standard deviations. The temperature value that generates GDDs with the smallest standard deviation will be selected as the base temperature. Goyne et al. (1977) used temperatures from -6 C to 9 C to calculate the base temperature for sunflowers (*Helianthus annuus L.*). Perry et al. (1986) selected the base temperature from 5 temperatures (0 C, 10 C, 13 C, 18 C and 25.5 C) in the prediction of cucumber (*Cucumis sativus L.*) harvest date.

2). <u>The Least Standard Deviation in Days Method</u>

Arnold (1959) suggested that "those who use heat units as a tool are not interested in the error in heat units as such but rather the error in days which the heat unit error represents". He defined the least standard deviation in days as

$$SD_{day} = \frac{SD_{gdd}}{x_t - t_b} \qquad (2)$$

where SD_{day} is the standard deviation in days, SD_{gdd} is the standard deviation in GDDs, X_t is the mean temperature for the entire series of plantings, and t_b is the base temperature.

As in method 1, this procedure also requires the selection of a base temperature from a series of candidate temperatures. There is no difference between two methods in terms of calculations.

3). Coefficient of Variation in Days Method

Methods 1 and 2 both give absolute magnitudes of the variation in GDD and in days, but fail to mention relative magnitudes of the variation. Nuttonson (1958) defined coefficient of variation with the equation

$$CV_{day} = \frac{SD_{day}}{x_d} \times 100\% \qquad (3)$$

where CV_{day} is coefficient of variation in days, SD_{day} is the standard deviation in days, and X_d is the mean of number of days required to reach a given developmental stage. Because X_d is a constant for all plantings, independent of the base temperature selected, there is no difference between this method and methods 1 and 2 in terms of the base temperature selected and calculation procedures.

It is obvious that three methods discussed above to calculate the base temperature are tedious and empirical. To obtain a base temperature which generates the least standard deviation in GDD or days, a range of candidate temperatures must be selected to calculate GDD or days and their associated standard deviations in GDD or days. If the base temperature that generates GDD with the least standard deviation is well below zero, it is very possible to miss it in the process of selecting candidate base temperatures. Because the calculation procedure is empirical in all three methods, it is difficult to select the correct temperature that generates GDD or days with the least standard deviation.

4). Regression Coefficient Method

In order to overcome shortcomings of the three methods discussed above, Hoover (1955) developed a regression coefficient method to estimate the base temperature with the equation

$$Y_i = a+bT_i, \qquad Y_i = (T_i-x)d_i \tag{4}$$

where a and b are constants, T_i is the mean of temperature for the ith planting, and d_i is the number of days required for a developmental stage for the ith planting.

He studied the relationship between the mean temperature and GDD with a linear regression model. In this linear regression model, the mean temperature was the independent variable and GDD was the dependent variable. Theoretically, if the selected temperature was too high, the regression coefficient in the model was positive; otherwise it was negative. When the regression coefficient was zero, the selected temperature was considered to be the base temperature. This method is based on the assumption that GDD is constant and independent of mean temperature. Hoover located points in the positive and negative range and found the zero point by graphic interpolation.

In statistics, the regression method is not much different from the least standard deviation method and shows no improvement in GDD calculation procedures (Arnold, 1959). As with methods 1,2 and 3 it also requires the calculation of GDD using a series of values to find the base temperature. In addition, this graphic interpolation method cannot give an accurate base temperature because it is difficult to determine exactly a number from a graph.

2. PROPOSED FORMULAS FOR CALCULATING THE BASE TEMPERATURE IN HEAT UNIT SYSTEMS

The procedures associated with the four methods for selecting the base temperature for GDD discussed above have some shortcomings. Theoretical and simple procedures are needed for calculating the base temperature. Four mathematical formulas for calculating the base temperature are derived to each of the four methods:

1) the least standard deviation in GDD.

2) the least standard deviation in days.

3) the coefficient of variation in GDD.

4) the regression coefficient.

Mathematical proofs appear in Appendix.

1). <u>The Least Standard Deviation in GDD Method</u>

For a certain set of plantings, GDD is a function of the base temperature selected. Let $f_i(x)$ be GDD of the ith planting, the function of the base temperature selected. Then $f_i(x)$ is expressed as

$$f_i(x) = (T_i - x) * d_i \tag{5}$$

where $f_i(x)$ is GDD accumulation of the ith planting, T_i is the overall mean temperature of the ith planting, d_i is the number of days of the ith planting to reach a given developmental stage under study, and x is the base temperature selected.

Let

$$f(x)=\frac{\Sigma f_i(x)}{n} \qquad (6)$$

be the mean of GDD accumulations for the all plantings. Where n is the number of plantings. Then the standard deviation in GDD accumulations for the entire plantings is defined as

$$SD_{gdd}=\left[\frac{\Sigma[f_i(x)-f(x)]^2}{n-1}\right]^{\frac{1}{2}} \qquad (7)$$

where SD_{gdd} is the abbreviation of the standard deviation of GDD accumulations.

By taking derivative to SD_{gdd}, the equation

$$\frac{dSD_{gdd}}{dx}=\left[\left(\frac{\Sigma(f_i(x)-f(x))^2}{n-1}\right)^{\frac{1}{2}}\right]' \qquad (8)$$

will be obtained.

Let equation (8) equal zero, then the base temperature can be calculated with equation

$$x=\frac{\Sigma T_i d_i \Sigma d_i - n\Sigma d_i^2 T_i}{(\Sigma d_i)^2 - n\Sigma d_i^2} \qquad (9)$$

where x is the base temperature, T_i is the mean temperature of the ith planting, d_i is the number of days for the *ith* planting to reach a developmental stage under study, and n is the number of plantings.

2). <u>The Least Standard Deviation in Days Method</u>

Standard deviation in days is defined as

$$SD_{day} = \frac{SD_{gdd}}{T-x}$$

where SD_{day}, SD_{gdd}, T, and x are standard deviation in days, standard deviation in GDD, the mean temperature of entire plantings, and the base temperature, respectively.

By taking derivative to SD_{day}, the equation

$$\frac{dSD_{day}}{dx} = \left[\left(\frac{\Sigma[f_i(x)-f(x)]^2}{(n-1)(T-x)^2}\right)^{\frac{1}{2}}\right]' \tag{11}$$

will be obtained. Where T is the overall mean of average temperature in the entire plantings, x is the base temperatures, and n is the number of days required to reach a developmental stage under study.

Let equation 11 be zero, then the base temperature can be calculated with the equation

$$x = T - \frac{(\Sigma t_i d_i)^2 - n\Sigma t_i^2 d_i^2}{n\Sigma d_i^2 t_i - \Sigma t_i d_i \Sigma d_i} \tag{12}$$

where d_i is the number of days required to reach a developmental stage for the ith planting, t_i is the difference of the overall mean of average temperature in the entire plantings and the mean temperature of the ith plantings, and n is the number of plantings.

3). Coefficient of Variation in GDD Method

Coefficient of variation in GDD is defined as:

$$CV_{gdd} = \frac{SD_{gdd}}{f(x)} \times \frac{100}{100} \tag{13}$$

where CV_{gdd} is coefficient of variation in GDD, SD_{gdd} is standard deviation of GDD accumulations in n plantings, and f(x) is the mean of GDD accumulations with n plantings.

By taking derivative to CV_{gdd}, the equation

$$\frac{dCVGDD}{dx} = \left[\left[\frac{\Sigma[f_i(x) - f(x)]^2}{(n-1)f(x)} \right]^{\frac{1}{2}} \right]' \tag{14}$$

will be obtained.

Let equation (36) be zero, then the base temperature, x, can be expressed as:

$$x = \frac{\Sigma T_i d_i^2 \Sigma T_i d_i - \Sigma d_i \Sigma T_i^2 d_i^2}{\Sigma d_i^2 \Sigma T_i d_i - \Sigma d_i \Sigma T_i d_i^2} \tag{15}$$

where T_i, d_i, and x have the same meanings as above.

4). <u>Regression Coefficient Method</u>

The equation $Y_i=a+Bt_i$ was discussed in the literature review. Hoover (1955) selected several temperature values to get negative and positive regression coefficients and then used a graphical method to find the base temperature. By studying this simple linear regression model, it was found that there was an analytical way to calculate the base temperature with the regression coefficient method. The basic idea was that if the true base temperature is used in the calculation of GDD_i of the ith planting, GDD_i should be independent of T_i, the average temperature of the ith planting, that is, the regression coefficient of T_i, b, should be equal to zero. In this regression model, the regression coefficient of T_i can be expressed as

$$b = \frac{n\Sigma GDD_i T_i - \Sigma T_i \Sigma GDD_i}{n\Sigma T_i GDD_i - \Sigma T_i^2} \tag{16}$$

and then the base temperature can be calculated by the equation

$$x = \frac{\Sigma T_i \Sigma d_i T_i - n\Sigma d_i T_i^2}{\Sigma d_i \Sigma T_i - n\Sigma d_i T_i} \tag{17}$$

where x, T_i, and d_i are same as above.

3. RESULTS AND DISCUSSION

The base temperatures for six developmental stages were calculated for tomato seedlings grown in the greenhouse in 1991 with the four proposed mathematical formulas (Table 1). In Table 1, the base temperatures of the first two developmental stages calculated from four methods were similar. After the second developmental stage, however, base temperatures calculated from methods of coefficients of the least standard deviation in days (SD), variation (CV), and regression coefficient (RE) departed considerably from those calculated from the least standard deviation in GDD method (ST). There was some variation in base temperatures calculated from the ST, CV, and RE methods, but the standard deviations and coefficients of variation in GDD and days were comparable. Therefore, when the base temperature is to be calculated, any of three methods can be used. CV, RE, and SD methods are better than ST in terms of coefficients of variation in GDD and days.

When previous procedures associated with methods of the least standard deviation (Magoon and Culpepper, 1932) and coefficient of variation (Nuttonson, 1958) were used to calculate the base temperature, a range of temperatures had to be examined and the tedious calculation work was required. When the regression coefficient method (Hoover, 1955) was used, a series of temperatures had to be evaluated and graphic work had to be done to select the base temperature. With the four proposed formulas, only one attempt is needed to calculate the base temperature and the results are more accurate than those from the previous procedures.

Table 1. The base temperatures (T), standard deviation in growing degree day accumulation (SD_{gdd}), standard deviation in days (SD_{day}), coefficients of variation in growing degree day accumulations (CV_{gdd}), and coefficients of variation in days (CV_{day}) calculated from planting to the first, second, third, fourth, fifth, and sixth developmental stages with the standard deviation in GDD (ST), the standard deviation in days (SD), coefficient of variation method (CV), and regression coefficient method (RE) for 1991 tomato seedlings grown in the greenhouse.

Developmental stages	Methods	T (C^0)	SD_{gdd}	SD_{day}	CV_{gdd}	CV_{day}
Emergence	ST	12.1	9.3	1.00	10.89	10.41
	SD	10.0	10.4	0.91	9.76	9.41
	CV	9.9	10.4	0.91	9.76	9.41
	RE	9.9	10.4	0.91	9.75	9.41
1*st* & 2*nd* leaf appearance	ST	10.5	10.8	0.97	7.34	7.15
	SD	8.5	11.7	0.89	6.74	6.59
	CV	8.4	11.8	0.89	6.47	6.59
	RE	8.2	12.0	0.89	6.76	6.59
3*rd* leaf appearance	ST	11.0	22.4	2.09	10.31	10.14
	SD	4.5	28.1	1.65	8.13	8.04
	CV	4.6	28.3	1.65	8.13	8.04
	RE	4.5	28.5	1.66	8.13	8.04
4*th* leaf appearance	ST	9.2	25.9	2.07	8.65	8.55
	SD	2.0	32.5	1.64	6.86	6.80
	CV	1.9	32.6	1.64	6.86	6.80
	RE	1.8	32.8	1.64	6.86	6.80
5*th* leaf appearance	ST	10.8	35.9	3.27	11.11	10.98
	SD	0.3	50.9	2.31	7.78	7.74
	CV	-0.4	51.2	2.31	7.78	7.74
	RE	0.2	50.6	2.31	7.82	7.76
6*th* leaf appearance	ST	8.9	39.8	2.99	8.73	8.66
	SD	-2.9	54.1	2.20	6.40	6.37
	CV	-3.0	54.3	2.20	6.40	6.37
	RE	-3.2	54.7	2.20	6.40	6.37

4. CONCLUSIONS

Four proposed mathematical formulas for calculating the base temperature in heat unit systems using the least standard deviation in GDD, the least standard deviation in days, coefficients of variation in GDD, and regression coefficient methods can compute the base temperature more easily and accurately than the previous procedures.

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APPENDIX

MATHEMATICAL PROOFS OF FOUR PROPOSED FORMULAS IN CALCULATION OF THE BASE TEMPERATURE

1). <u>The Least Standard Deviation in GDD Method</u>

Let SD_{gdd} represent the standard deviation in GDD, then

$$SD_{gdd} = \left[\frac{\Sigma[f_i(x) - f(x)]^2}{n-1}\right]^{\frac{1}{2}}$$

the derivative of SD_{gdd} is

$$\frac{dSD_{gdd}}{dx} = \frac{1}{2}\left[\frac{\Sigma[f_i(x) - f(x)]^2}{n-1}\right]^{-\frac{1}{2}} \times \frac{2\Sigma[f_i(x) - f(x)][f_i'(x) - f'(x)]}{n-1}$$

Let

$$\frac{dSD_{gdd}}{dx} = 0$$

then

$$\Sigma[f_i(x) - f(x)]\,[f_i'(x) - f'(x)] = 0$$

$$\therefore \quad \Sigma[f_i(x) - f(x)]\,[f_i'(x) - f'(x)]$$

$$= \sum \left[(T_i - x)d_i - \frac{\Sigma(T_i - x)d_i}{n} \right] \left[-d_i + \frac{\Sigma d_i}{n} \right]$$

$$= \sum \left[\frac{n(T_i - x)d_i - \Sigma(T_i - x)d_i}{n} \right] \left[\frac{\Sigma d_i - nd_i}{n} \right]$$

$$= \frac{1}{n} \Sigma[nT_i d_i - nxd_i - \Sigma T_i d_i + x\Sigma d_i]\,[\Sigma d_i - nd_i]$$

$$\Sigma d_i = D \quad and \quad \Sigma T_i d_i = A$$

then

$$\Sigma[f_i(x) - f(x)]\,[f_i'(x) - f'(x)]$$

$$= \frac{1}{n} \Sigma[nT_i d_i - nxd_i - A + xD]\,[D - nd_i]$$

$$= \frac{1}{n}[\Sigma nDT_i d_i - nxd_i D - AD + XD^2 - n^2 T_i D_i^2 + n^2 x d_i^2 + nAd_i - xDnd_i]$$

$$= \frac{1}{n}[\Sigma nAD - nxD^2 - nAD + nxD^2 - n^2 \Sigma T_i d_i^2 + n^2 x \Sigma d_i^2 + nAD - nxD^2]$$

$$= -n\Sigma T_i d_i^2 + nx\Sigma d_i^2 + AD - xD^2$$

$$\therefore \quad x = \frac{AD - n\Sigma T_i d_i^2}{D^2 - n\Sigma d_i^2} = \frac{\Sigma T_i d_i \Sigma d_i - n\Sigma T_i d_i^2}{(\Sigma d_i)^2 - n\Sigma d_i^2}$$

2). <u>The Least Standard Deviation in Days Method</u>

Let SD_{day} represent the standard deviation in days, then

$$SD_{day} = \frac{SD_{gdd}}{T-x} = \left[\frac{\Sigma[f_i(x)-f(x)]^2}{(n-1)(T-x)^2}\right]^{\frac{1}{2}} = \frac{1}{\sqrt{n-1}}\left[\frac{\Sigma[f_i(x)-f(x)]^2}{(T-x)^2}\right]^{\frac{1}{2}}$$

Let y=T-x, then x=T-y. Therefore $f_i(x)=f_i(T-y)=(T_i-T+y)d_i=(t_i+y)=f_i(y)$.

$$\therefore\ SD_{day} = \frac{1}{\sqrt{n-1}}\left[\frac{\Sigma[f_i(y)-f(y)]^2}{y^2}\right]^{\frac{1}{2}}$$

The derivative of SD_{day} is

$$\frac{dSD_{day}}{dy} = \frac{2}{\sqrt{n-1}}\left[\frac{\Sigma[f_i(y)-f(y)]}{y^2}\right]^{-\frac{1}{2}}\left[\frac{2\Sigma[f_i(y)-f(y)][f_i'(y)-f'(y)]y^2-2y\Sigma[f_i(y)-f(y)]^2}{y^4}\right]$$

Let

$$\frac{dSD_{day}}{dy} = 0$$

then

$$\frac{2\Sigma[f_i(y)-f(y)][f_i'(y)-f'(y)]y^2-2y\Sigma[f_i(y)-f(y)]^2}{y^4} = 0$$

$$\therefore \quad \Sigma[f_i(y)-f(y)][f_i'(y)-f'(y)]y-\Sigma[f_i(y)-f(y)]^2 = 0$$

$$\because \quad f_i'(y) = d_i \,, \qquad f'(y) = \frac{\Sigma d_i}{n}$$

$$\therefore \quad \Sigma[f_i(y)-f(y)][f_i'(y)-f'(y)]-\Sigma[f_i(y)-f(y)]^2$$

$$= \Sigma[f_i(y)-f(y)][d_i-\frac{\Sigma d_i}{n}]y-\Sigma[f_i(y)-f(y)]^2$$

$$= \Sigma\left[[f_i(y)-f(y)][(t_i+y)d_i-t_id_i-\frac{\Sigma(t_i+y)d_i}{n}+\frac{\Sigma t_id_i}{n}]\right]-\Sigma[f_i(y)-f(y)]^2$$

$$= \Sigma[f_i(y)-f(y)][(f_i(y)-f(y))-(t_id_i-\frac{\Sigma t_id_i}{n})]-\Sigma[f_i(y)-f(y)]^2$$

$$= -\Sigma[f_i(y)-f(y)][t_id_i-\frac{\Sigma t_id_i}{n}] = \Sigma[f_i(y)-f(y)][t_id_i-\frac{\Sigma t_id_i}{n}] = 0$$

$$\therefore \quad \Sigma[f_i(y)-f(y)][t_id_i-\frac{\Sigma t_id_i}{n}] = \Sigma[t_id_i+d_iy-\frac{\Sigma t_id_i+y\Sigma d_i}{n}][t_id_i-\frac{\Sigma t_id_i}{n}]$$

$$=\Sigma[t_id_i-\frac{t_id_i\Sigma t_id_i}{n}+t_id_i^2y-d_iy\Sigma t_id_i-\frac{t_id_i\Sigma t_id_i}{n}-\frac{t_id_iy\Sigma t_id_i}{n}+\frac{(\Sigma t_id_i)^2}{n^2}+\frac{y\Sigma t_id_i\Sigma d_i}{n^2}$$

$$=\Sigma t_i^2d_i^2-\frac{(\Sigma t_id_i)^2}{n}+y\Sigma t_id_i^2-\frac{y\Sigma t_id_i\Sigma d_i}{n} = 0$$

$$\therefore \quad y = \frac{(\Sigma t_id_i)^2-n\Sigma t_i^2d_i^2}{n\Sigma t_id_i^2-\Sigma t_id_i\Sigma d_i}$$

$$\therefore \quad x = \frac{\Sigma T_i}{n} - \frac{(\Sigma t_i d_i)^2 - n\Sigma t_i^2 d_i^2}{n\Sigma t_i d_i^2 - \Sigma t_i d_i \Sigma d_i}$$

$$= \frac{\Sigma T_i}{n} - \frac{[\Sigma(T-T_i)d_i]^2 - n\Sigma(T-T_i)^2 d_i^2}{n\Sigma(T-T_i)d_i^2 - \Sigma(T-T_i)d_i\Sigma d_i}$$

3). Coefficient of Variation in GDD Method

Let CV_{gdd} represent the coefficient of variation in GDD, then

$$CV_{gdd} = \frac{SD_{gdd}}{f(x)} = \left[\frac{\Sigma[f_i(x)-f(x)]^2}{(n-1)f^2(x)}\right]^{\frac{1}{2}}$$

The derivative of CV_{gdd} is

$$\frac{dCV_{gdd}}{dx} = \frac{1}{2}\left[\frac{\Sigma[f_i(x)-f(x)]^2}{(n-1)f^2(x)}\right]^{-\frac{1}{2}}\left[\frac{\Sigma[f_i(x)-f(x)]^2}{(n-1)f^2(x)}\right]'$$

$$\because \quad \Sigma[f_i(x)-f(x)]^2 = \Sigma f_i^2(x) + nf^2(x) - 2f(x)\Sigma f_i(x)$$

$$nf^2(x) - 2f(x)\Sigma f_i(x) = f(x)\left[\frac{n\Sigma f_i(x)}{n} - 2\Sigma f_i(x)\right] = -f(x)\Sigma f_i(x)$$

$$\therefore \quad \Sigma[f_i(x)-f(x)]^2 = \Sigma f_i^2(x) - f(x)\Sigma f_i(x)$$

$$\therefore \quad \left[\frac{\Sigma[f_i(x)-f(x)]^2}{(n-1)f^2(X)}\right] = \frac{1}{(n-1)}\left[\frac{\Sigma f_i^2(x)}{f^2(x)} - \frac{\Sigma f_i(x)}{f(x)}\right]$$

$$= \frac{1}{n-1}\left[\frac{\Sigma f_i^2(x)}{f^2(x)} - \frac{n\Sigma f_i(x)}{\Sigma f_i(x)}\right] = \frac{1}{n-1}\left[\frac{\Sigma f_i^2(x)}{f^2(x)} - n\right]$$

Let

$$\frac{dCV_{gdd}}{dx} = 0$$

Then

$$\left[\frac{\Sigma[f_i(x) - f(x)]^2}{(n-1)f^2(x)}\right]' = \frac{1}{(n-1)}\left[\frac{\Sigma f_i^2(x)}{f^2(x)} - n\right]' = 0$$

$$= \left[\frac{1}{n-1}\right] \frac{2\Sigma f_i(x) f_i'(x) f^2(x) - 2f(x) f'(x) \Sigma f_i^2(x)}{f^4(x)}$$

$$= \left[\frac{1}{n-1}\right] \frac{2\Sigma f_i(x) f_i'(x) f(x) - 2f'(x) \Sigma f_i^2(x)}{f_3(x)} = 0$$

$$\therefore \quad \Sigma f_i(x) f_i'(x) f(x) = f'(x) \Sigma f_i^2(x)$$

$$\therefore \quad \Sigma(T_i - x)d_i(-d_i)\frac{\Sigma(T_i - x)d_i}{n} = -\frac{\Sigma d_i}{n}\Sigma[T_i d_i - x d_i]^2$$

Let $\Sigma d_i = D$ and $\Sigma T_i d_i = A$, then

$$\Sigma(T_i - x)d_i(-d_i)\frac{\Sigma(T_i - x)d_i}{n} = \frac{[\Sigma(-T_i d_i^2 + x d_i^2)][A - xD]}{n}$$

$$-\frac{\Sigma d_i}{n}\Sigma[T_i d_i - x d_i]^2 = -\frac{D}{n}\Sigma[T_i^2 d_i^2 + x^2 d_i^2 - 2xT_i d_i^2]$$

$$\therefore \quad -A\Sigma T_i d_i^2 + Ax\Sigma d_i^2 + Dx\Sigma T_i d_i^2 - Dx^2\Sigma d_i^2 = D(-\Sigma T_i^2 d_i^2 - x^2\Sigma d_i^2 + 2x\Sigma T_i d_i^2)$$

$$-A\Sigma T_i d_i^2 + Ax\Sigma d_i^2 = -D\Sigma T_i^2 d_i^2 + x\Sigma T_i d_i^2$$

$$\therefore \quad x = \frac{A\Sigma T_i d_i^2 - D\Sigma T_i^2 d_i^2}{A\Sigma d_i^2 - D\Sigma T_i d_i^2} = \frac{\Sigma T_i d_i \Sigma T_i d_i^2 - \Sigma d_i \Sigma T_i^2 d_i^2}{\Sigma T_i d_i \Sigma d_i^2 - \Sigma d_i \Sigma T_i d_I^2}$$

4). Regression Coefficient Method

Growing degree days can be expressed as:

$$f_i(x) = a + Bt_i$$

where x is the base temperature selected and T_i is the mean of average daily temperature of the ith planting. Because GDD is a constant for crop development, $f_i(x)$ does not depend on T_i. Therefore, the regression coefficient of T_i will be zero.

$$\because \quad b = \frac{n\Sigma T_i f_i(x) - \Sigma T_i \Sigma f_i(x)}{n\Sigma T_i - (\Sigma T_i)^2} = 0$$

$$\therefore \quad n\Sigma T_i f(i(x) - \Sigma T_i \Sigma f_i(x) = 0, \quad n\Sigma T_i f_i(x) = \Sigma T_i \Sigma f_i(x)$$

$$\therefore \quad n\Sigma T_i (T_i - x) d_i = \Sigma T_i \Sigma (T_i - x) d_i$$

$$\therefore \quad n\Sigma T_i^2 d_i - nx\Sigma T_i d_i = \Sigma T_i \Sigma T_i d_i - x\Sigma T_i \Sigma d_i$$

$$\therefore \quad x = \frac{\Sigma T_i \Sigma T_i d_i - n\Sigma T_i^2 d_i}{\Sigma T_i \Sigma d_i - n\Sigma T_i d_i}$$

PART III

EFFECTS OF TEMPERATURE AND SOLAR RADIATION REGIMES ON TOMATO SEEDLING DEVELOPMENT

ABSTRACT

The accurate prediction of crop development is very important in crop modeling. The effects of environmental factors such as temperature, moisture, daylength, and solar radiation on crop development have been extensively studied. However, these studies exclusively focused on the magnitude of the environmental factors and little attention was devoted to the effects of the environmental factor's temporal distribution on crop development. Because temperature and solar radiation are dominant factors controlling crop development, the effects of their temporal distribution on crop development also are important. The objectives of this research were to investigate the effects of temperature and solar radiation's temporal distributions on tomato (Lycopersicon esculentum L.) seedling development in the greenhouse and to model tomato seedling development taking into account for such effects. Tomatoes were planted on different dates in the greenhouse under three temperature levels (average temperature for level was 17-19 C, 21-23 C, and 24-26 C in 1991 and 18-20 C, 20-22 C, and 22-24 C in 1992) and rotated among the different temperature levels. The date of seedling emergence and leaf appearance were recorded. Temperature and solar radiation were measured. Seedling emergence, the first & second, third, fourth, fifth, and sixth leaf appearance were defined as 1-6 developmental stages. Growing degree days (GDD) and coefficient variation in GDD and days were calculated and compared with considering effects of temperature regimes experienced in the preceding developmental stage on the following developmental stage and without considering such effects. Results showed that

temperature regimes experienced in the preceding developmental stage did affect tomato seedling development in the following developmental stage. Linear regression models that took into account the effects of temperature regimes in the preceding developmental stage on the following developmental stage fitted better than those which did not consider such effects. Therefore, the effects of temperature regimes experienced during crop growth on crop development should be accounted for in the prediction of crop development.

1. INTRODUCTION AND LITERATURE REVIEW

The relationship of plant growth and development to air temperature has been a major field of study in the plant sciences (Coffey, 1978). Studies in this area can be traced back to Renè Rèaumur in 1735. Rèaumur summed up the mean daily air temperature for growing seasons and found that the sum was nearly a constant value for the development of a particular species from year to year (Wang, 1960). This discovery has been widely used and revised in the 20th century and has become the basis of the heat sum system of today.

The heat sum system, also termed growing degree days (GDD), degree days, cumulative degree days (CDD), heat summations, thermal units, or growth units, has been used extensively in the prediction of crop development. Several methods have been used to calculate GDD depending on different assumptions. The most widely used formula for GDD calculation is

$$GDD = \Sigma(\frac{T_{max}+T_{min}}{2}-T_{base}) \qquad (1)$$

where T_{max}, T_{min}, and T_{base} are daily maximum temperature, daily minimum temperature, and the base temperature, respectively.

This formula is applicable to the study of crop development when there is a linear relationship between crop development and air temperature. However, in many cases, crop development will decline or stop when temperature is above a critical level or ceiling temperature (Madariaga and Knott, 1951). Methods which consider the ceiling temperature for crop development provide better predictions (Gilmore and Rogers, 1958; Cross and Zuber, 1972; Dufault et al., 1989), but in general they do not show significant improvement over heat unit systems and are not used as commonly as GDD.

Logan and Boyland (1983) indicated that temperature fluctuated greatly within a day and that heat units should not be determined simply by the mean of maximum temperature and minimum temperature. They used a sine function to incorporate into the heat unit model the fluctuations in temperature during the day rather than relying on a mean temperature. In the early developmental stages, crop development is influenced by soil temperature instead of air temperature because the growing point is under the soil. Law and Cooper (1976) found that corn plant development was more related to soil temperature than to air temperature until the 12th leaf tip was visible.

Although temperature is a dominant factor controlling crop development, other environmental factors also have effects on crop development. The prediction of crop development with a heat sum system alone, regardless of effects of other environmental factors, is not satisfactory for some crops (Davidson and Campbell, 1983; Wright Hughes, 1987). Therefore, concepts of photothermal units dealing with daylength effects on crop development (Doyle, 1974; Goyne et al., 1977; Wallace and Enriquez, 1980; Goyne and Hammer, 1982; Davidson and Campbell, 1983; Undersander and Christansen, 1986; Kristansen et al., 1988; Fernandez and Chen, 1989; Major and Kiniry, 1991; Ritchie and NeSmith, 1991), water stress dealing with moisture effects on crop development (Brown and Chapman, 1960; Anderson et al., 1978; Idso et al., 1978; Stout et al., 1978; Hodges and French, 1985; Huda et al., 1987; Throssel et al., 1987), and effective day-degrees (EDD) dealing with solar radiation effects on crop development (Scaife et al., 1978; Wurr and Fellows, 1988) have been developed.

There have been some studies in which the effects of environmental factors and management practices on crop development were investigated. The temperature index, as presented by Coligado and Brown (1975), was used to predict the occurrence of the maturity of sweet corn (*Zea mays L.*) by Rinne (1984). The effect of plant spacing on corn phasic development was studied by Greenwood et al. (1974) and Alessi and Power (1975). They concluded that row spacing generally had little or no effect upon the development of corn plants. Heuvelink (1989) studied the effect of day and night temperature on tomato growth and development and found that different day and night regimes had different effects on tomato development. The effect of sowing dates on GDD accumulations and the number of days to a given developmental stage was studied by Doyle (1974) on sunflowers. The results showed that sowing dates affected heat unit accumulation. When crisp lettuce varieties were planted from April 9 through July 19, the number of days from sowing to maturity increased exponentially, but GDD from sowing to maturity increased linearly with later sowing (Wurr and Fellows, 1988). No constant GDD accumulation was found in this study. Cao and Moss (1989a and 1989b) reported similar results in wheat and barley. The reason that GDD accumulation for a developmental stage varies with planting dates may be that when planting dates are changed, temperature regimes experienced by crops throughout season are also changed.

In general, researchers have considered many possible factors (daylength, solar radiation, moisture, planting date, row space, and soil conditions) which may affect crop development and have formulated various heat unit models in order to predict crop development. However, the capability of these models to predict crop development has not been satisfactory. Therefore, it is proposed that there might be other factors which affect crop development that have been overlooked. From the literature review, it is found that only the magnitudes of temperature have been used in the prediction of crop development. However, the effect of planting dates on crop development is evidence of the effect of average daily temperature's distribution on crop development. No research has been found about the effect on crop development of distribution of temperature or solar radiation in a year or a growing season. The objective of this research is to investigate whether the distribution of temperature and solar radiation during transplant growth affects crop development and to determine how to take this effect, if it exists, into the consideration in the prediction of crop development.

2. MATERIALS AND METHODS

A developmental stage is defined as an easily recognized morphological state, such as having a certain number of leaves. Six developmental stages were defined for tomato seedlings in the greenhouse as seedling emergence (1), the first and second leaf (first and second leaf occurred at the same time) (2), the third leaf (3), the fourth leaf (4), the fifth leaf (5), and the sixth leaf appearance (6). When a leaf was about 0.5 cm long, it was considered present.

'Sunny' tomato transplants were grown in the greenhouse at three temperature levels during different developmental stages in 1991 and 1992. The range of the day/night average temperature difference in the greenhouse from the lowest to the highest was 5-7 C in 1991 and 3-5 C in 1992. The difference in daily average temperature among three temperature levels was monitored at about 3-4 C in 1991 and 1-2 C in 1992. In 1991, the day/night average temperature was monitored at about 17-19 C in greenhouse 1 (G1), 21-23 C in greenhouse 2 (G2), and 24-26 C in greenhouse 3 (G3), respectively. In 1992, the day/night average temperature was monitored at about 18-20 C in G1, 20-22 C in G2, and 22-25 C in G3.

Tomato seeds were planted in Speedling® styrofoam flats containing twenty four cells (3.8 cm wide and 5.0 cm long) per flat. Flats were watered and fertilized (soluble fertilizer 20-20-20) as needed for optimal transplant production.

From the experience in tomato growing in East Tennessee (Rutledge et al., 1989), it is known that at an average temperature of about 20 C, tomato needs 40-45 days to reach optimal transplanting size (6 leaves and 15.2 cm tall), approximately 800-900 heat units (the base temperature C is set to zero). Therefore, temperature accumulations for tomato transplants in the greenhouse before transplanting were around 800 heat units with the base temperature 0 C.

Flats were seeded on March 19, 22, 24, 26, 28, and 29, in 1991 and March 12, 16, 19, 21, and 23, in 1992. In 1991, flats were rotated twice among the three temperature levels in the greenhouses. The rotations were scheduled in such a way that all transplants experienced approximately the same temperature accumulations (no base values were considered) at the time of transplanting. Seeding dates and codes for 1991 are shown in Table 1. Rotation schedules appear in Appendix Tables A-1 and A-2. In 1992, in order to focus more on the differences between temperature regimes for developmental stages, the rotations were made at two specific times (developmental stages 2 and 4). Seeding dates and codes for 1992 are shown in Table 2.

Data for tomato seedling development were taken from 5 plants in each replication of each treatment. The measurements made and recorded were:

1) the number of days required to reach each stage of development,

2) the number of leaves of each seedling (observed twice daily),

3) temperature accumulation from planting to the *ith* stage,

4) temperature accumulation at the time of measurement,

5) temperature accumulation from the (i-1)*th* to the *ith* stage,

6) solar radiation accumulation at the time of measurement,

7) solar radiation accumulation from planting to the *ith* leaf appearance,

Table 1. Seeding dates of tomato and the number of flats seeded and placed at each temperature level in the greenhouse in 1991.

Seeding date	seeding code	Temperature Levels		
		T1 (17C-19C)	T2 (21C-23C)	T3 (24C-26C)
		-------------------------	No.	-------------------------
3/19	(A)	3	0	0
3/22	(B)	6	3	0
3/24	(C)	9	6	3
3/26	(D)	6	9	9
3/28	(E)	3	6	9
3/29	(F)	0	3	9

Notes: The letters, A, B, C, D, E, and F used hereafter refer to respective planting date in 1991; T1, T2, and T3 refer to temperature levels in 1991.

Table 2. Seeding dates of tomato and the number of flats seeded and placed at each temperature level in the greenhouse in 1992.

Seeding date	seeding code	Temperature Levels		
		T1 (18C-20C)	T2 (20C-22C)	T3 (22C-24C)
		-------------------------	No.	-------------------------
3/12	(G)	3	0	0
3/16	(H)	6	3	0
3/19	(I)	9	6	3
3/21	(J)	6	9	6
3/23	(K)	0	6	3

Notes: The letters, G, H, I, J, and K refer to respective planting date in 1992; T1, T2, and T3 refer to temperature levels in 1992.

9)solar radiation accumulation from the (i-1)*th* to the i*th* leaf appearance.

The maximum, minimum, and average air temperature in the greenhouse 30 cm above the flat was measured at 5-second intervals with copper-constantan thermocouple sensors and recorded every hour. Photosynthetically active radiation (PAR) also was measured with quantum sensors at 5-second intervals and recorded every hour. (μmol/s cm^2). Sensors were connected to a Campbell 21X datalogger.

Temperature accumulations (GDD base 0 C) were calculated from seeding to each developmental stage in 1991 and 1992. The coefficient of variation method developed in Part II was used to calculate the correct base temperature for GDD for each stage of development and for the period between two successive stages. The least standard deviation and coefficients of variation resulting from the calculation of the correct base temperature for GDD were used to detect qualitatively the effects of temperature regimes during previous stages on the next stage.

Since GDD are not effective in the prediction of crop development when there is no linear relationship between temperature and crop development, some other procedures, such as regressing developmental rates to environmental factors, have been used in the prediction of crop development. In this study, the dependent variable was developmental rate which was defined as the reciprocal of the number of days required to reach a given developmental stage (Ferguson, 1958; Brown and Chapman, 1960; Hortik and Arnold, 1965).

Two approaches were used. First, developmental rates were modeled as reported by Hortik and Arnold (1965) without the consideration of the effect of temperature and solar radiation regimes experienced in the preceding developmental stages on the following developmental stages. Their equation

$$R_i = b_0 + b_1 AT_i + b_2 AT_i^2 + b_3 AS_i + b_4 AT_i AS_i \tag{2}$$

was used to predict the developmental rate, where R_i was the developmental rate in the ith developmental stage, AT_i was the mean of daily average temperature, AS_i was daily average solar radiation accumulation (mol/day), and AT_iAR_i was the product of solar radiation accumulation and the mean of daily average temperature, of the period from the planting to the ith developmental stage. Second, the effect of temperature and solar radiation regimes experienced in the preceding developmental stage on the following developmental stage was considered. This effect was represented by the developmental rate in the preceding developmental stage. For example, if the developmental rate in the *ith* developmental stage was the dependent variable, the developmental rate in the (i-1)*th* developmental stage was used as an independent variable because the developmental rate in the (i-1)*th* developmental stage was controlled by temperature regimes and solar radiation experienced in the (i-1)*th* developmental stage. It was assumed that the current developmental rate, R_i, was the function of the preceding developmental rate, R_{i-1}, the overall mean of daily temperature, and average daily solar radiation accumulation of the period from the (i-1)*th* developmental stage to the *ith* developmental stage.

In modeling the developmental rate, the following variables were selected as potential independent variables:

1) the overall mean of daily average temperature calculated from the (i-1)*th* to the *ith* developmental stage.

2) the overall mean of daily average solar radiation calculated from the (i-1)*th* to the i*th* developmental stage.

3) the developmental rate in the preceding developmental stage.

4) the overall mean of daily average temperature calculated from seedling emergence to the (i-1)*th* developmental stage.

5) daily average solar radiation calculated from seedling emergence to the (i-1)*th* developmental stage.

Stepwise regression STEPWISE/MAXR (Myers, 1990) was used to select significant independent variables. Data for 1991 and 1992 were modeled separately first. When there were no significant differences in regression coefficients, the data for both years were pooled. The coefficients of variation resulting from linear regression analyses were used to detect quantitatively the effects of temperature and solar radiation regimes during previous stages on the next stage.

3. RESULTS AND DISCUSSION

The mean of daily average temperature and the number of days for 1-6 developmental phases appear in Tables A-3 and A-4 for 1991 and A-5 and A-6 for 1992.

Base temperatures and their associated least standard deviation and coefficient of variation based on days in 1991 and 1992 are reported in Table 3. Coefficients of variation in days for the GDD accumulation for *ith* developmental stage, which considers the effects of temperature regimes during previous stages, were much smaller than those calculated from the (i-1)*th* to the *ith* development stage, which does not take into account the effect temperature regimes during previous stages, for both years. This decrease in CV indicates that GDD accumulation during the preceding developmental stages has an effect on GDD required to reach the next developmental stage. The smaller CVs in 1992 compared to 1991 are due to the smaller differences between the three temperature levels.

Regression models, adjusted R^2's, and coefficients of variation for tomato seedlings in the greenhouse in 1991 and 1992 with developmental rate as the dependent variable and the overall mean of average daily temperature from the 1*st* to the *ith* developmental stage as the independent variable appear in Table 4. Only the regression coefficient for the mean of daily average temperature (AT_i) experienced for that developmental stage was significant at the P=0.05 probability level. In the first two developmental stages, the intercept and regression coefficients for development rate were significantly different between years. Therefore, the first two developmental stages were

Table 3. The base temperatures (T), standard deviation in days (SD_{day}), coefficients of variation based on days (CV_{day}) calculated from the first, second, third, fourth, fifth, and sixth developmental stages, and for the periods between successive stages, with the coefficient of variation method for tomato seedlings grown in the greenhouse in 1991 and 1992.

Developmental stage	Year	*i*th developmental stage: T (^{0}C)	SD_{day}	CV_{day}	from the (i-1)*th* to *i*th developmental stage: T (^{0}C)	SD_{day}	CV_{day}
Emergence	1991	9.9	0.9	9.4	9.9	0.9	9.4
	1992	-6.7	0.3	3.1	-6.7	0.3	3.1
1*st* & 2*nd* leaf appearance	1991	8.4	0.9	6.6	9.0	1.2	30.0
	1992	0.5	0.3	1.9	7.1	0.4	5.8
3*rd* leaf appearance	1991	4.6	1.7	8.0	-5.7	1.4	20.4
	1992	6.9	0.7	3.3	10.6	0.6	9.1
4*th* leaf appearance	1991	1.9	1.6	6.8	-19.4	0.8	22.4
	1992	7.9	1.0	3.9	13.3	0.6	12.5
5*th* leaf appearance	1991	-0.4	2.3	7.7	-6.5	1.7	29.4
	1992	0.4	1.5	5.1	-6.1	0.6	22.9
6*th* leaf appearance	1991	-3.0	2.2	6.4	3.1	1.6	33.1
	1992	4.5	1.2	3.3	13.4	0.7	15.6

Table 4. Regression models, adjusted R^2's, and coefficients of variation for tomato seedlings in the greenhouse in 1991 and 1992 with developmental rate (R_i) as the dependent variables and the overall mean of average daily temperature (AT_i) from the 1*st* to the *ith* developmental stage as the independent variable.

Developmental stage		Regression model*	Adjusted R^2	CV
Emergence	(1-1)†	R_1=-0.0911+0.0094AT_1	0.73	10.36
1&2nd leaf app.	(1-2)†	R_2=-0.4554+0.0437AT_2-0.0009AT_2^2	0.86	6.08
Emergence	(1-3)‡	R_1=0.0283+0.0046AT_1	0.70	3.25
1&2nd leaf app.	(1-4)‡	R_2=-0.6984+0.0766AT_2-0.0019AT_2^2	0.95	1.24
3th leaf app.	(1-5)¶	R_3=0.0023AT_3	0.99	7.42
4th leaf app.	(1-6)¶	R_4=0.0019AT_4	0.99	5.95
5th leaf app.	(1-7)¶	R_5=0.0016AT_5	0.99	7.16
6th leaf app.	(1-8)¶	R_6=0.0014AT_6	0.99	6.37

* *significant at P=0.05 probability level for all regression coefficients and intercepts.*
† *regression models for 1991 data.*
‡ *regression models for 1992 data.*
¶ *regression models for 1991 and 1992 data combination.*
Notes: *AT_1, AT_2, AT_3, AT_4, AT_5, and AT_6 were the mean of average daily temperature from the first to the second, third, fourth, fifth, and sixth developmental stages, respectively.*

modeled separately for each year. From the third through the sixth developmental stages, the intercept and regression coefficients were not significantly different, thus data from both years were pooled. Linear models 1-2 and 1-4 (stage 2) in Table 4 were quadratic models and their intercepts were significant. In stages 3 - 6, developmental rates responded linearly to the mean of daily average temperature and the intercepts were not significant.

In order to better predict seedling development with regression models, the effect of temperature regimes and solar radiation experienced in the preceding developmental stage on the following developmental stage was considered. Regression models, adjusted R^2, and coefficients of variation for tomato seedlings in the greenhouse in 1991 and 1992 with developmental rate as the dependent variable and the overall mean of average daily temperature, product of temperature and solar radiation from the (i-1)*th* to the i*th* developmental stage and the preceding developmental rates as independent variables are reported in Table 5.

From the first to the second developmental stage, developmental rate was affected by the same independent variables in both years and regression coefficients were not significantly different. However, the intercepts were significantly different. Therefore, models for second developmental stage share the same independent variables and regression coefficients with different intercepts. In the third developmental stage, independent variables and regression coefficients were the same both years and there were no significant differences between regression coefficients and intercepts. Thus, data from both years were combined into one equation. As developmental stages progressed,

Table 5. Regression models, adjusted R^2, and coefficients of variation for tomato seedlings in the greenhouse in 1991 and 1992 with developmental rate (R_i) as the dependent variable and the overall mean of average daily temperature from the (i-1)*th* to the i*th* developmental stage (PAT_i), the product of temperature and solar radiation (RT_i) and the preceding developmental rate (R_{i-1}) as independent variables.

Developmental stage		Regression model*	Adjusted R^2	CV
1&2nd leaf app.	(2-1)†	$R_2=-0.0848+0.00239PAT_2+1.682R_1-6.221R_1^2$	0.86	5.19
1&2nd leaf app.	(2-2)‡	$R_2=-0.0892+0.00239PAT_2+1.682R_1-6.221R_1^2$	0.86	5.19
3rd leaf app.	(2-3)¶	$R_3=-0.0728+0.0091PAT_3-0.00031PAT_3^2-8.589R_2^2+0.0745RT_3$	0.82	4.90
4th leaf app.	(2-4)†	$R_4=0.0082+0.000007PAT_4^2+0.609R_3$	0.93	2.82
4th leaf app.	(2-5)‡	$R_4=0.0082-0.00073PAT_4+0.00001PAT_4^2+0.609R_3$	0.93	2.82
5th leaf app.	(2-6)†	$R_5=0.0178+0.000005PAT_5^2+7.778R_4^2$	0.75	4.75
5th leaf app.	(2-7)‡	$R_5=0.0178+0.00006PAT_5+0.000005PAT_5^2+7.778R_4^2$	0.78	4.75
6th leaf app.	(2-8)¶	$R_6=0.0055+0.000005PAT_6^2+0.635R_5$	0.75	4.44

* *significant at P=0.05 probability level for all regression coefficients and intercepts.*
† *regression models for 1991 data.*
‡ *regression models for 1992 data.*
¶ *regression models for 1991 and 1992 data combination.*
Notes: *R_i was the developmental rate of the ith developmental stage and PAT_i was the overall mean of daily temperatures.*

temperature regimes experienced by tomato seedlings became diverse and the response of seedling development in both years to average daily temperature and the preceding developmental rates also differed. In the fourth developmental stage, the intercepts and regression coefficients of R_3 were not significantly different between years. However, coefficient of square of average daily temperature, PAT_4 was significantly different between years; the regression coefficient of PAT_4 was significant for 1991 data, but not for 1992 data. Thus two distinct models were used to predict 1991 and 1992 data. In the fifth developmental stage, seedling development had the same response to PAT_5^2 and R_4^2 for both years, but seedlings in 1992 also responded to PAT_5. In the sixth developmental stage, tomato seedlings had the same responses to average daily temperature and the preceding developmental rates with same intercepts.

Models 2-1 through 2-8 (Table 5) showed that developmental rate R_i in the *ith* developmental stage was controlled by average daily temperature (PAT_i) from the (i-1)*th* to the *ith* stage and by developmental rate, R_{i-1}, in the (i-1)*th* developmental stage. From the third to the sixth developmental stages, average daily temperature positively affected seedling developmental rates. Developmental rates were nonlinearly affected by the preceding developmental rates in second, third, and fifth developmental stages, but linearly in the fourth and sixth developmental stages. Results showed that developmental rates in the preceding developmental stages promoted developmental rates in the following developmental stages. It was interesting to notice that when a majority of seedlings were rotated among different temperature levels at the second and fourth developmental stages, R_2 and R_4 had a nonlinear effect on R_3 and R_5, the developmental rates in the third and fifth developmental stages. When seedlings were exposed to the same temperature regimes for a longer time, the effect of developmental rates in the third and fifth developmental stages on the developmental rates in the fourth and sixth developmental stages became linear. Looking at the coefficients of variation in Table 4, it was interesting to see that the coefficients of variation changed with seedling rotation. CV values in Table 4 from the second to sixth developmental stages were 1.24, 7.42, 5.95, 7.16, and 6.37, respectively, with a pattern of increase, decrease, increase, and decrease. After the second developmental stage, most of seedlings were rotated and moved to new temperature regimes. Therefore, the adaptation of seedlings to temperature regimes was disturbed and the development of seedlings did not respond to daily average temperature as the same as they did before the rotation. This led to the increase of coefficients of variation in the third developmental stage. After the rotation, the adaptation of seedlings to new temperature regimes started to be established as they were grown in new temperature regimes for a period of time and the development of seedlings better responded to daily average temperature than they did in the preceding developmental stage. This led to the decrease of coefficients of variation in the fourth developmental stage. After the fourth developmental stage, most of seedlings were rotated and moved to new temperature regimes again. Thus, coefficients of variation increased in the fifth developmental stage. In Table 5, because the models considered the effect of temperature regimes experienced in the preceding developmental stages on the following developmental stages, coefficients of variation did not show a pattern in change with rotation.

The coefficients of variation in the first approach (Table 4) were greater than those obtained in the second approach (Table 5). In general, tomato seedling development in the greenhouse was a time dependent event and responded to environmental conditions experienced in the preceding developmental stages.

Figures A-1 through A-4 show observed values and predicted values from regression equations without considering the effects of temperature regimes experienced in the preceding developmental stages (Table 4) and with the consideration of this effect (Table 5). Observed developmental rates were greatly dispersed. The dispersion of observed values indicated that as seedlings were rotated among different temperature levels, seedling development not only responded to the magnitude of temperature, but also to temperature's temporal distribution. Predicted values from models with the consideration of the effects of temperature regimes experienced in the preceding developmental stage on the following developmental stage better matched observed values better than the models without the consideration of such effects.

4. CONCLUSIONS

In this research, the effects of temperature regimes and solar radiation experienced in the preceding developmental stage on the following developmental stage of tomato seedlings were investigated. Significant effects of temperature regimes experienced in the previous developmental stage on seedling development in the following developmental stage were found. Tomato seedling development was affected not only by average temperature and but also by the sequence of average temperatures experienced in each developmental stage. Coefficients of variation calculated from planting to seedling emergence (stage 1) and the appearance of the 1*st* & 2*nd*, 3*rd*, 4*th*, 5*th*, and 6*th* leaf (stages 2-6) were significantly smaller than those calculated from the periods between successive stages.

Discoveries in this research provide a new approach to improve the prediction of crop development and indicate that effects of temperature's temporal distribution on crop development should be considered. Because this research was done only on tomato transplants in the greenhouse, more work should be done on other crops for entire growing season.

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APPENDIX A

Table A-1. Schedule of the first rotation of tomato seedlings among temperature levels in the greenhouse in 1991.

T1	TL	RD	ND	T12
A1	1			A11
B1	1			B11
C1	1			C11
B2	1	4/7	17	B21
C2	1	4/7	15	C21
D2	1	4/9	13	D21
C3	1	4/7	15	C31
D3	1	4/8	14	D31
E3	1	4/9	13	E31
B1	2	4/6	15	B12
C1	2	4/8	15	C12
D1	2	4/8	13	D12
C2	2			C22
D2	2			D22
E2	2			E22
D3	2	4/8	13	D32
E3	2	4/10	13	E32
F3	2	4/12	14	F32
C1	3	4/8	15	C13
D1	3	4/8	13	D13
E1	3	4/11	14	E13
D2	3	4/9	14	D23
E2	3	4/8	11	E23
F2	3	4/8	10	F23
E3	3			E33
F3	3			F33
F3	3			F33

Notes: In Column T1, letters represent planting dates and numbers represent temperature levels under which tomatoes were seeded. Numbers in column TL represent temperature levels where flats were moved to. Numbers in column RD were the date of rotation. Numbers in column ND were the number of days for which flats remained in the temperature level until rotated. T12 represent the history of temperature exposure of flats after the first rotation.

Table A-2. Schedule of the second rotation of tomato seedlings among temperature levels in the greenhouse in 1991.

T12	TL	RD	ND	T123
A11	1			A111
B12	1	4/23	17	B121
C13	1	4/21	13	C131
B21	1			B211
C22	1	4/20	29	C221
D23	1	4/20	15	D231
C31	1			C311
D32	1	4/19	17	D321
E33	1	4/20	25	E331
B11	2	4/19	26	B112
C12	2			C122
D13	2	4/21	13	D132
C21	2	4/22	15	C212
D22	2			D222
E23	2	4/23	15	E232
D31	2	4/21	13	D312
E32	2			E322
F33	2	4/23	25	F332
C11	3	4/20	31	C113
D12	3	4/21	15	D123
E13	3			E133
D21	3	4/20	15	D213
E22	3	4/19	22	E223
F23	3			F233
E31	3	4/23	14	E313
F32	3	4/28	18	F323
F33	3			F333

Notes: In Column T12, letters represent planting dates, numbers right after letters represent temperature levels before the first rotation, and numbers in the last represent temperature levels after the first and before the second rotation. Numbers in column TL represent temperature levels where flats were moved to. Numbers in column RD were the date of rotation. Numbers in column ND were the number of days for which flats remained in the temperature level until rotated. T123 represent the history of temperature exposure of seedlings in the greenhouse.

Table A-3. Daily average temperature from planting to seedling emergence (TE), from seedling emergence to the first & second (T12), from the first & second to the third (T3), from the third to the fourth (T4), from the fourth to the fifth (T5), and from the fifth to the sixth (T6) leaf appearance in 1991.

Treatment	TE	T12	T3	T4	T5	T6
	----------	----------	----------^{0}C	----------	----------	
A111	19.6	18.2	19.3	19.4	17.4	19.2
A222	23.1	19.9	21.5	22.5	21.4	21.2
A333	26.6	22.8	25.0	25.7	24.1	24.9
B112	19.6	18.7	17.9	19.8	18.9	19.1
B121	19.6	19.6	20.7	21.6	21.3	19.1
C113	18.5	19.3	18.5	20.5	25.3	24.2
C122	18.5	21.3	21.4	22.0	20.5	19.3
C131	18.1	22.6	25.7	26.7	20.1	20.5
D123	18.8	21.6	21.8	20.7	25.8	No
D132	18.4	25.6	26.1	22.3	19.9	No
E133	18.8	23.0	25.9	24.1	25.9	No
B211	22.8	19.5	20.0	18.0	17.9	19.0
C212	21.2	21.1	19.0	19.2	18.9	18.9
C221	21.2	21.1	21.9	21.5	20.8	17.6
D213	20.8	22.8	18.5	19.7	16.2	25.8
D222	20.8	22.8	21.2	22.4	20.0	20.0
D231	20.8	22.8	25.2	25.5	26.7	19.3
E223	20.5	21.8	21.8	23.2	26.3	25.1
E232	20.6	24.9	25.9	26.4	24.1	25.5
F233	20.6	24.9	25.9	26.4	24.1	25.5
C311	24.0	25.2	20.0	18.1	17.8	19.7
D312	23.4	24.9	19.6	19.6	19.5	19.6
D321	23.3	25.4	22.9	21.4	19.5	18.3
E313	22.4	25.8	19.0	17.5	23.8	26.0
E322	22.4	25.8	21.4	22.1	19.8	19.9
E331	22.4	25.8	25.6	26.1	22.4	18.6
F323	23.7	26.0	22.3	21.1	22.0	25.9
F333	23.7	26.0	25.6	26.5	24.7	25.7
F332	23.7	26.0	25.6	26.5	23.6	25.0

Notes: TE, T12, T3, T4, T5, and T6 were average daily temperature accumulations from planting to emergence, first and second, third, fourth, fifth, and sixth leaf appearance, respectively. No means the sixth leaf had not show up at the time of transplanting.

Table A-4. The number of days from planting to seedling emergence (DE), from seedling emergence to the first & second (D12), from the first & second to the third (D3), from the third to the fourth (D4), from the fourth to the fifth (D5), and from the fifth to the sixth (D6) leaf appearance in 1991.

Treatment	DE	D12	D3	D4	D5	D6
A111	12.0	6.0	7.9	4.0	5.9	6.1
A222	7.7	6.2	4.9	3.3	6.8	6.9
A333	6.7	5.2	6.8	3.1	7.9	3.1
B112	11.0	6.2	7.2	4.0	4.0	6.1
B121	11.0	6.0	4.8	3.0	7.0	6.1
C113	13.0	4.0	7.9	2.9	7.0	2.1
C122	13.0	4.0	6.9	2.9	4.8	6.0
C131	13.0	3.0	6.8	1.9	9.1	2.0
D123	12.9	3.9	7.9	3.1	6.0	No
D132	12.9	2.9	8.0	4.0	6.0	No
E133	11.8	3.0	7.9	4.1	4.0	No
B211	6.7	5.1	9.8	3.9	7.0	6.2
C212	7.7	5.3	6.9	3.8	7.1	7.1
C221	7.7	5.3	4.8	3.9	7.0	2.2
D213	10.0	3.0	9.7	2.0	4.7	5.2
D222	10.0	3.0	6.7	4.0	4.0	4.0
D231	10.0	3.0	3.8	4.0	3.0	2.9
E223	9.8	5.0	6.9	5.0	3.1	2.1
E232	9.8	2.0	7.0	1.9	6.7	5.1
F233	9.0	3.8	5.9	3.0	4.1	6.1
C311	6.9	4.9	8.2	4.7	9.1	4.0
D312	6.8	4.2	9.9	3.9	9.8	4.0
D321	6.8	4.2	6.0	4.8	4.5	6.5
E313	8.8	2.3	9.7	4.2	3.8	4.0
E322	8.8	2.3	8.7	3.9	5.2	4.8
E331	8.8	2.3	5.9	2.8	5.0	6.1
F323	8.5	2.5	7.7	5.0	4.4	3.0
F333	8.5	2.5	5.9	3.9	5.2	4.1
F332	8.5	2.5	5.9	3.9	5.2	4.5

No means the sixth leaf had not show up at the time of transplanting.

Table A-5. Daily average temperature from planting to seedling emergence (TE), from seedling emergence to the first & second (T12), from the first & second to the third (T3), from the third to the fourth (T4), from the fourth to the fifth (T5), and from the fifth to the sixth (T6) leaf appearance in 1992.

Treatment	TE	T12	T3	T4	T5	T6
	----------	----------	----- ^0C -----	----------	----------	
A111	17.7	17.8	18.6	21.5	21.5	22.1
B121	17.5	19.9	19.9	23.1	21.5	22.8
C131	17.6	18.5	23.1	24.1	21.9	22.0
B211	19.0	21.8	18.2	21.5	22.3	21.2
C221	19.3	20.4	21.6	23.4	22.5	21.4
D231	20.2	19.8	23.1	24.3	22.1	21.2
C311	19.7	20.6	19.6	21.2	22.5	No
D321	19.7	20.4	21.4	23.1	22.4	No
B112	17.5	19.9	18.5	21.6	23.2	23.2
C122	17.6	18.5	21.7	23.2	23.1	23.6
D132	18.5	17.9	23.7	24.8	23.7	22.3
C212	19.3	20.2	20.0	21.4	23.7	22.4
D222	20.2	19.8	21.7	23.1	23.3	23.4
E232	21.2	19.6	24.1	23.7	23.6	No
D312	19.7	20.4	20.2	21.5	23.4	22.4
C113	17.6	18.5	20.3	21.5	25.4	23.7
D123	18.5	17.9	22.4	22.4	25.7	23.2
D213	20.2	19.8	20.1	21.5	26.6	No
E223	21.2	19.6	22.7	23.0	25.9	No
E333	20.6	20.4	24.2	23.9	25.4	No

Notes: TE, T12, T3, T4, T5, and T6 were average daily temperature accumulations from planting to emergence, first and second, third, fourth, fifth, and sixth leaf appearance, respectively. No has the same meaning as in Table A-4.

Table A-6. The number of days from planting to seedling emergence (DE), from seedling emergence to the first & second (D12), from the first & second to the third (D3), from the third to the fourth (D4), from the fourth to the fifth (D5), and from the fifth to the sixth (D6) leaf appearance in 1992.

Treatment	DE	D12	D3	D4	D5	D6
A111	9.0	9.8	7.1	4.8	4.1	8.5
B121	9.1	5.8	7.0	4.0	4.9	8.9
C131	9.1	6.9	5.8	3.1	3.9	7.5
B211	8.9	5.0	8.9	6.2	4.0	6.3
C221	8.8	5.2	7.0	4.8	4.2	6.3
D231	8.1	5.9	5.8	3.1	5.1	6.3
C311	9.1	4.9	7.7	5.3	4.8	No
D321	7.9	6.2	4.9	4.7	5.1	No
B112	9.1	5.7	9.2	5.0	4.0	6.7
C122	9.1	6.9	5.8	4.1	2.9	8.0
D132	8.9	6.0	5.9	4.1	3.1	6.8
C212	8.8	5.2	7.8	5.1	3.1	6.8
D222	8.1	6.0	5.7	4.3	2.1	8.0
E232	8.1	5.7	5.0	4.9	5.2	No
D312	7.9	6.2	5.8	5.3	2.8	6.8
C113	9.1	7.0	6.6	4.4	2.9	6.3
D123	8.9	6.0	5.9	4.2	2.1	7.7
D213	8.1	5.9	6.8	4.9	4.1	No
E223	7.9	5.9	6.0	4.0	3.5	No
E333	8.1	5.7	6.0	3.2	4.7	No

No has the same meaning as Table A-4.

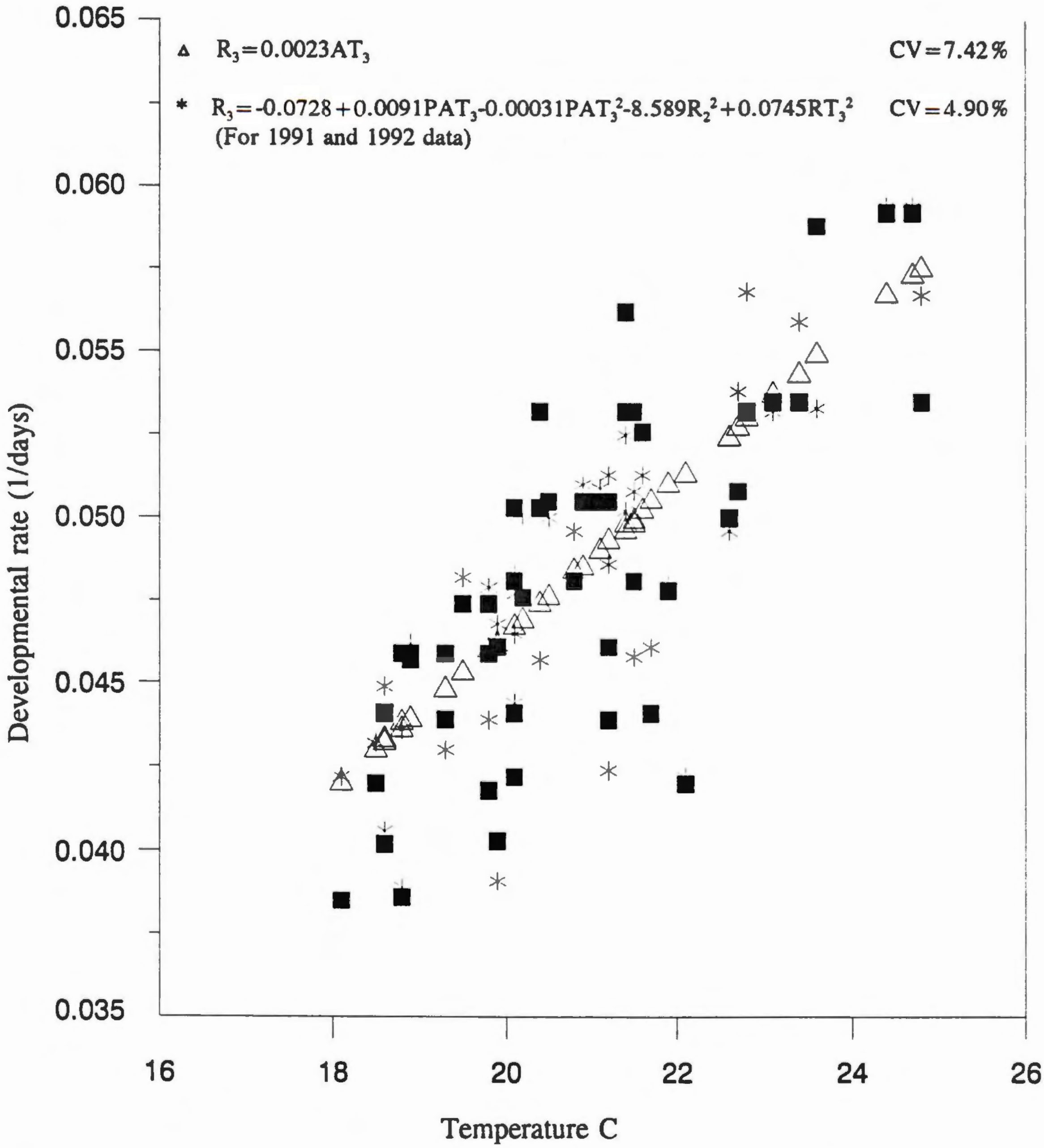

Figure 1. Developmental rates of the third developmental stage of tomato seedlings grown in the greenhouse in 1991 and 1992.

- ■ Observed values.
- △ Predicted values with models without the consideration of the effects of temperature regimes experienced in the preceding developmental stage on the following developmental stages.
- * Predicted values with models with the consideration of such effects.

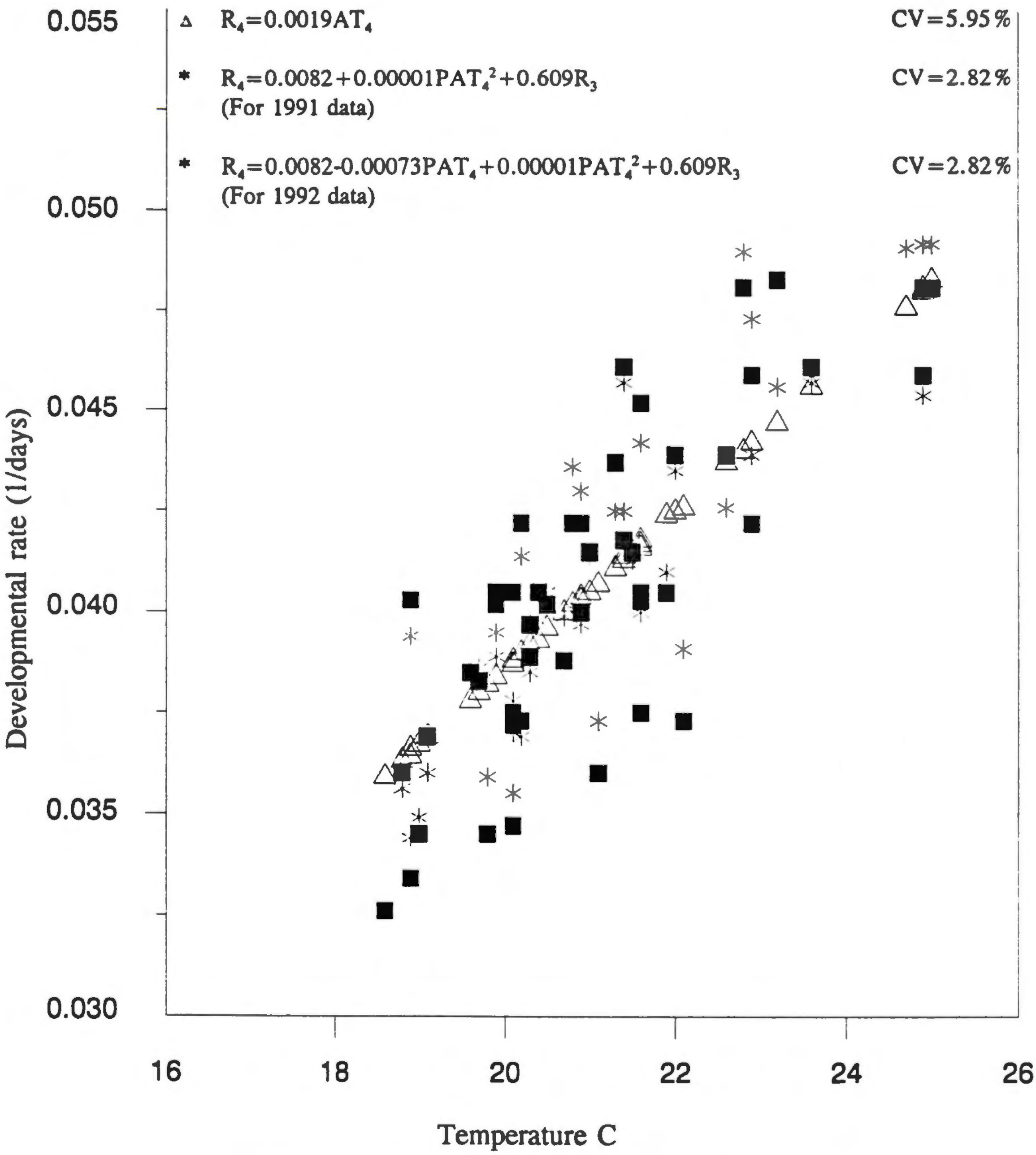

Figure 2. Developmental rates of the fourth developmental stage of tomato seedlings grown in the greenhouse in 1991 and 1992.

- ■ Observed values.
- △ Predicted values with models without the consideration of the effects of temperature regimes experienced in the preceding developmental stage on the following developmental stages.
- * Predicted values with models with the consideration of such effects.

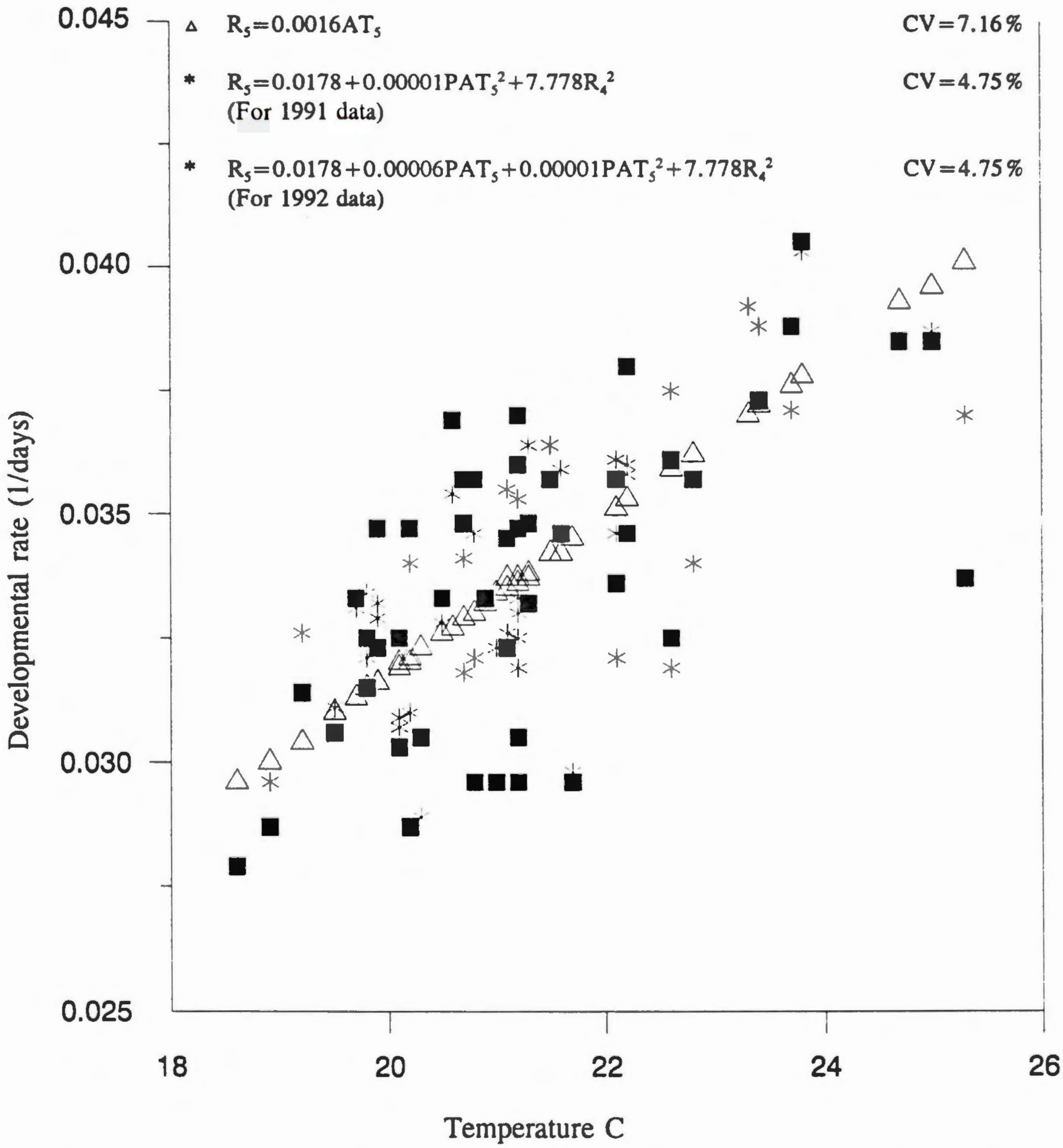

Figure 3. Developmental rates of the fifth developmental stage of tomato seedlings grown in the greenhouse in 1991 and 1992

- ■ Observed values.
- ▵ Predicted values with models without the consideration of the effects of temperature regimes experienced in the preceding developmental stage on the following developmental stages.
- * Predicted values with models with the consideration of such effects.

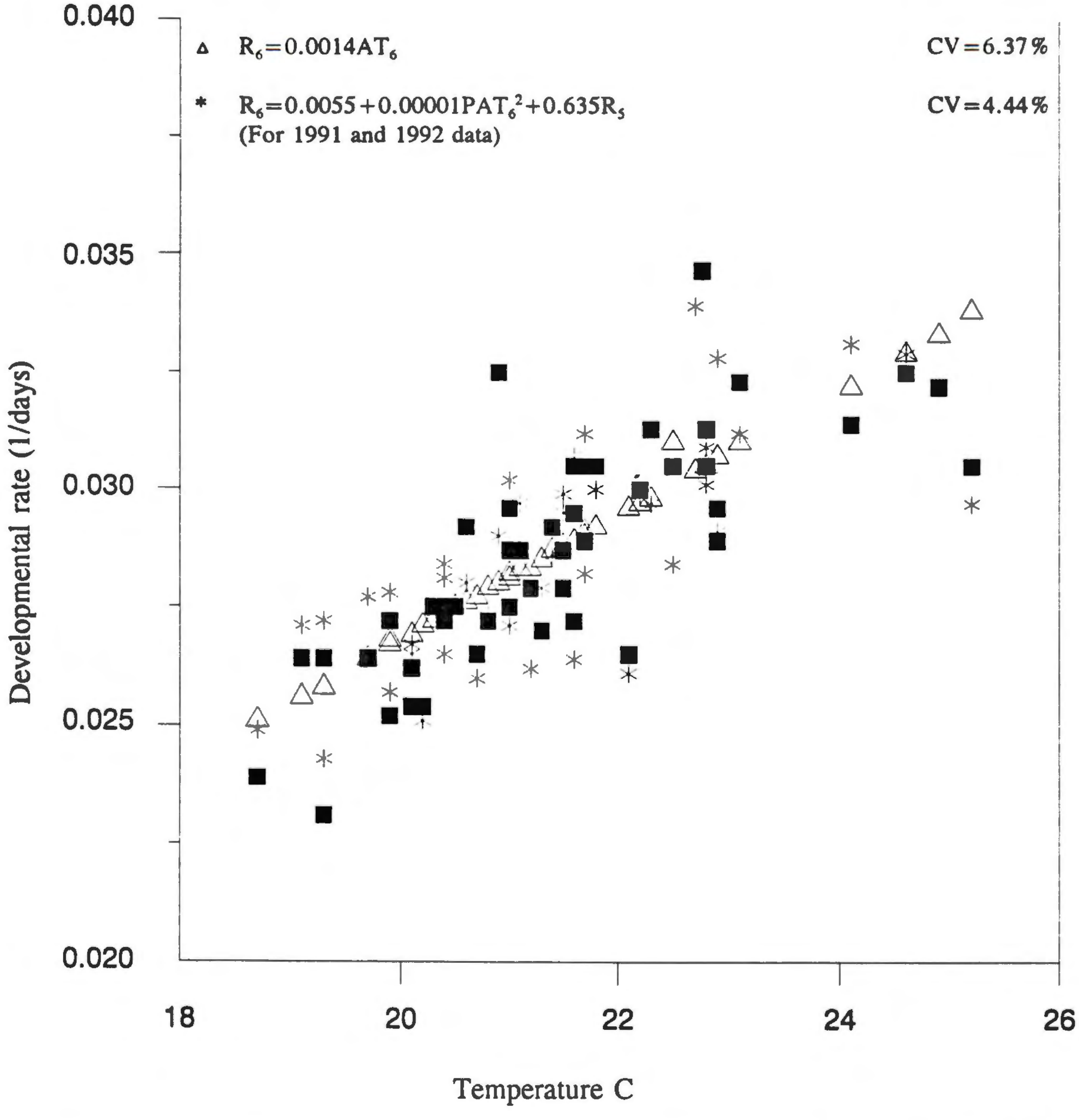

Figure 4. Developmental rates of the sixth developmental stage of tomato seedlings grown in the greenhouse in 1991 and 1992.

- ■ Observed values.
- △ Predicted values with models without the consideration of the effects of temperature regimes experienced in the preceding developmental stage on the following developmental stages.
- * Predicted values with models with the consideration of such effects.

PART IV

EFFECTS OF TEMPERATURE REGIMES EXPERIENCED BY TOMATO TRANSPLANTS IN THE GREENHOUSE ON THE SUBSEQUENT FRUIT YIELD IN THE FIELD

ABSTRACT

The quality of tomato (*Lycopersicon esculentum L.*) transplants is important to the subsequent yield in the field. Effects of size and age, temperature, light density, sowing date, container size, and flat spacing on transplant quality have been extensively studied. However, little information is available on effects of temperature regimes or temporal temperature distribution experienced by tomato transplants in the greenhouse on transplant quality and the subsequent performance in the field. Therefore, this study was conducted in 1991 and 1992 to investigate these effects. Tomato seeds were sowed in Speedling® styrofoam flats containing twenty four cells (3.8 cm wide and 5.0 cm deep) per flat in the greenhouse under three temperature levels at different times. Transplants were rotated among three temperature levels in such a way that at the time of transplanting all transplants had experienced approximately the same temperature accumulations. Average temperatures were 17-19 C, 21-23 C, and 24-26 C in 1991 and 18-20 C, 20-22 C, and 22-24 C in 1992. The air temperature in the greenhouse 30 cm above the flat was measured and average temperatures were calculated from sowing to seedling emergence, from seedling emergence to the first and second, from the first and second to the third, from the third to the fourth, from the fourth to the fifth, and from the fifth to the sixth leaf appearance for all transplants. Transplant height, stem diameter, leaf length, and weight were measured at the time of transplanting. When transplants reached the sixth leaf developmental stage, they were transplanted to the field at the University of Tennessee Plant Science Field Laboratory at Knoxville. Results in

this study showed that temperature regimes before transplanting significantly affected the subsequent fruit yield and number in the field. The quality of tomato transplants was very sensitive to temperature regimes before the first and second leaf appearance. A sharp change in temperature regimes either from high to low or from low to high before the fourth leaf appearance and especially before the second leaf appearance had negative effects on the subsequent performance of transplants in the field. Temperature in the ranges of 18-21 C for seedling emergence and 19-22 C for the first and second leaf appearance produced optimum quality transplants. The difference between temperatures for seedling emergence and for the first and second leaf appearance should not be greater than 4 C. Regression models revealed that transplants were oversized in 1991. The age of transplants in 1992 was older than that of transplants in 1991, but the size of transplants in 1992 was smaller than that of transplants in 1991. This meant rapid growth rate of transplants had negative effects on fruit yield in the field in 1991.

1. INTRODUCTION AND LITERATURE REVIEW

The quality of tomato transplant is important to the subsequent fruit yield and quality in the field. Much research has been conducted on tomato transplant production. It is known that the quality of tomato transplants is determined by their size, age, and morphology (Weston and Zandstra, 1986). Research devoted to effects of tomato transplant quality on the subsequent yield and quality in the field has been well documented (Adelana, 1983; Cooper and Morelock, 1983; Petrikova, 1984; Weston and Zandstra, 1986).

Adelana (1983) studied effects of transplant age on the subsequent yield of tomatoes in the field. In his study, seedlings were transplanted after 3, 4, 5, or 6 weeks after sowing in the nursery. His results showed that the younger transplants grew faster and produced more dry matter than older ones. Also, flowering and fruiting were earlier in the younger transplants. Fruit yield was highest in the 3-week-old transplants, but was not significantly higher in 3- than in 4-week-old transplants. He suggested that seedlings should be transplanted when they were between 3 and 4 weeks old. However, in Cooper and Morelock's research (1983), the early yield was highest with 7-week-old transplants, total fruit yield was highest with 5-week-old transplants, and fruit weight was also greatest raised from 5-week-old transplants. In literature, there are some variations in transplant age for higher yield. This is not surprising because temperatures under which transplants are grown vary. Woodrow and Liptay (1987) reported that compact and sturdy transplants have higher survival rate and early yield in the field.

The size and morphology of transplants influence plant quality and performance in the field. Size and morphology are influenced by environmental conditions such as temperature, light density, and nutrition and a number of cultural practices such as sowing date, flat spacing, chemical application, and container volume (Nicklow and Minges, 1963; Knavel, 1965; Anderson, 1985; Gorski and Wertz, 1985; Lipari and Paratore, 1986; Adler and Wilcox, 1987).

Weston and Zandstra (1986) compared tomato transplants (cv. Pik-Red) produced in 6 root cell sizes (cell volumes were 4.6, 5.5, 15.4, 18.8, 30.7, and 39.5 cm^3, respectively) for fruit productivity in the field. They concluded that large root cell size had a greater effect on transplant size than did wide spacing in the flat. Transplants grown in large cells (39.5 cm^3) produced more early yields than those grown in small cells, but, generally, did not produce more total yield. Gorski and Wertz (1985) also conducted trials with 6 seedling containers which consisted of Speedlings and 5 sizes of cell pak, with 18 to 96 cells to compare the subsequent yield of tomatoes in the field. Their results showed that early fruit yield increased significantly and total fruit yield increased slightly as individual container sizes increased.

Effects of N and P nutrition available to tomato transplants (cv. Pik-Red) grown in the greenhouse on the subsequent growth and yield of tomatoes were investigated and reported (Weston and Zanstra, 1989). Transplants fertilized with moderate and high N levels (200 and 400 mg/liter) in the greenhouse and later transplanted (5-week-old transplants) produced large early yields in the field and there was no effect of N and P level applied in the greenhouse on the total yield.

As discussed above, there is considerable information available concerning effects of age, size, and morphology of transplants, root cell size, and nutrition level available to transplants on the subsequent yield in the field. However there is little information reported concerning the effects of temperature accumulations and temperature regimes or temperature's temporal distribution experienced by transplants in the greenhouse before transplanting on the subsequent yield of fruit in the yield. It is assumed that when transplants are exposed to different temperature accumulations and temperature regimes before transplanting they will respond differently to environmental conditions in the field. Temperature accumulations and temperature regimes experienced by transplants before transplanting may be more important than transplant age in explaining variations in the subsequent yield of tomatoes in the field. The objective of this research was to investigate if temperature regimes experienced by transplants in the greenhouse before transplanting affect the subsequent yield of tomatoes.

2. MATERIALS AND METHODS

'Sunny' tomato transplants were grown in the greenhouse at three temperature levels at different times of development in 1991 and 1992. The range of the day/night average temperature difference in the greenhouse from the lowest to the highest was 5-7 C in 1991 and 3-5 C in 1992. The difference in daily average temperature among three temperature levels was monitored at about 3-4 C in 1991 and 1-2 C in 1992. In 1991, the day/night average temperature was monitored at about 17-19 C in greenhouse 1 (G1), 21-23 C in greenhouse 2 (G2), and 24-26 C in greenhouse 3 (G3). In 1992, the day/night average temperature was monitored at about 18-20 C in G1, 20-22 C in G2, and 22-24 C in G3.

Tomato seeds were planted in Speedling® styrofoam flats containing twenty four cells (3.8 cm wide and 5.0 cm deep) per flat. Flats were watered and fertilized (soluble fertilizer 20-20-20) as needed for optimal transplant production.

Flats were seeded on March 19, 22, 24, 26, 28, and 29, in 1991 and March 12, 16, 19, 21, and 23, in 1992. In 1991, flats were rotated twice among the three temperature levels in the greenhouses. The rotations were made in such a way that all transplants had experienced approximately the same temperature accumulations (no base temperature were considered) at the time of transplanting to the field. Twenty seven temperature regimes or treatments were obtained (Table A-1). In 1992, flats were rotated at the developmental stages of the first and second leaf appearance and the fourth leaf appearance. Not all temperature regimes or treatments were kept. Twenty temperature regimes that well represented twenty seven temperature regimes of 1991 remained (Table A-2). Five seedlings were sampled from each flat at the time of transplanting to measure seedling height, stem diameter, leaf length, above ground fresh weight, dry root weight, and dry shoot weight.

The average air temperature in the greenhouse 30 cm above the flat was measured and temperature accumulations were calculated from sowing to seedling emergence, from seedling emergence to the first and second, from the first and second to third, from the third to fourth, from the fourth to fifth, and from the fifth to sixth leaf appearance.

When tomato seedlings reached the sixth leaf developmental stage, they were transplanted to the field of the University of Tennessee Plant Science Field Laboratory at Knoxville on May 1, 1991 and April 30, 1992. Plants were arranged in plots in a randomized incomplete block design with three replications in nine blocks in 1991 and six blocks in 1992 in Etowah silt loam (Fine-loam siliceous, thermic Typic paleudult). Each plot was comprised of six plants. Plants were spaced 45 cm apart in rows and rows were spaced 135 cm apart. Complete fertilizer (6-12-12) was broadcasted at the rate of 895 kg ha^{-1} at transplanting and two sidedressings of 34 kg N ha^{-1} were applied at early and mid fruit set. Plants were irrigated as needed and weeds were control with Metribuzin (4-amino-6-tert-butyl-3-(methylthio)-as-triazin-5(4H)-one) at a rate of 0.84 kg ha^{-1} when necessary. Diseases such as early blight were controlled with Maneb (Manganese ethylenebisdithiocarbamate) and Chlorothaniol (Tetrachloroisophthalonitrile) and insects were controlled with Carboryl (Naphthyl-N-methyl-carbamate) weekly. Plants were staked and trained, according to The "Florida Weave System" (Rutledge, 1989) (1 stake every two tomato plants) was used to support tomato plants. Fruits were harvested at the pink to light red stage. Tomato fruits were grouped into six groups according to fruit size (diameters) by Los Angeles system. These groups were 4 x 5, 5 x 5, 6 x 6, 6 x 7, 7 x 7, and culls (unmarketable) with respective diameters of 6.4, 5.2, 4.5, 4.3, 3.8, and smaller than 3.8 cm, respectively. Fruit weights and numbers in each group were recorded at each harvest. Date of flowering and first harvesting and the number of fruits and clusters per plant were recorded.

Analysis of variance and regression were applied to data. In the regression analysis, the STEPWISE/MAXR (Myers, 1990) method was used. All possible independent variables were put into regression models for variable selection. With the STEPWISE/MAXR method, all best models with all possible number of independent variables in regression models were found. For instance, if there are five possible independent variables which will be retained in a regression model, the best models with one independent variable, two independent variables, three independent variables, four independent variables, and five independent variables were found. Data for 1991 and 1992 were modeled separately first with two models. If independent variables remained in two models are same, regression coefficients in two models will be compared to see if regression coefficients in the models are significantly different. When regression coefficients of two models are significantly different, data in two years will be modeled with two models, otherwise data will be pooled and modeled with one model.

Adjusted R^2, which was defined as 1- ME/total MS, coefficients of variation, and variance inflation were used as criteria to select the best regression equations. SAS (SAS

Institute Inc., 1985) and QUATTRO were used in the analyses of data.

3. RESULTS AND DISCUSSION

Transplanting height, stem diameter, leaf length, fresh weight, dry weight, dry root weight, dry shoot weight measured at the time of transplanting appear in Tables A-3 and A-4 for 1991 and A-5 and A-6 for 1992. Temperature accumulations for transplants in each developmental phase in the greenhouse appear in Tables A-7 for 1991 A-8 for 1992. Total marketable fruit yield (Mg ha^{-1}) MY, fruit yield (Mg ha^{-1}) in the first grade, second grade, third grade and fourth grade (Y1, Y2, Y3, and Y4, respectively), total marketable fruit number (1000 ha^{-1}) (MN), fruit number (1000 ha^{-1}) in the first grade, second grade, third grade, and fourth grade (N1, N2, N3, and N4, respectively), and marketable fruit size (MS) (kg/fruit) appear in Tables A-9 and A-10 for 1991 and A-11 and A-12 for 1992. Daily average temperatures from sowing to seedling emergence, from seedling emergence to the first and second leaf appearance, from the first and second to the third leaf appearance, from the third to the fourth leaf appearance, from the fourth to the fifth leaf appearance, and from the fifth to the sixth leaf appearance appear in Tables A-13 in 1991 and A-14 in 1992.

1). Variance Analysis of the Fruit Yield, Fruit Number and Fruit Size

Analysis of results for the effect of treatments (TRT), planting dates (DAT), temperature levels before the first rotation (T1), temperature levels after the first and before the second rotations (T2), temperature levels after the second rotation (T3), and temperature levels before the second rotation (T12) on tomato yield and yield components is reported in Table 1 for 1991 and 1992. Effects of treatments, temperature levels before the first rotation, temperature levels between the first and second rotations, and before the second rotation on tomato yield and some yield components were significant in 1991, but only treatments and temperature levels before the second rotation significantly affected fruit yield and fruit number.

Treatments had significant effects on the total yield, total marketable tomato yield, and the yield and fruit numbers in the first grade, but had no significant effect on other variables in both 1991 and 1992. In 1991, the yield in the first and second grades accounted for about 50.2 and 32.1 % of the total marketable yield and, basically, was determined by the number of fruits in these two grades. In 1992, the yield in the first and second grades accounted for about 34.8 and 42.0 % of the total marketable yield. Thus, treatments affected the total marketable tomato yield by affecting fruit number and yield in the first two grades. Planting dates had no significant effects on any yield component since seedling sizes and temperature accumulations were independent of planting dates. Temperature before the first rotation had significant effects on the total and total marketable tomato yields, the yield in the first grade, and the fruit size of the total yield in 1991. This meant that temperature from planting to the second leaf appearance was important. In 1992, however, temperature before the first rotation had no significant effects on fruit number and fruit yield. This result might be as explained by the range of temperatures before the first rotation in two years. Before the first rotation, the difference of temperature level 1 and level 3 was 5.1 C in 1991 but only 2.8

Table 1. Effects of treatments (TRT), temperature levels before the first rotation (T1), between the first and second rotations (T2), and before the second rotation (T12) on fruit yield, fruit number, and fruit size of tomatoes in 1991 and 1992.

Variables	TRT†	TRT‡	T1†	T2†	T12†	T12‡
TY	*	*	*	NS	*	NS
MY	*	*	*	NS	NS	NS
Y1	*	*	*	NS	NS	NS
Y2	NS	NS	NS	NS	*	*
Y3	NS	NS	NS	NS	NS	NS
Y4	NS	NS	NS	NS	NS	NS
TN	NS	NS	NS	NS	NS	NS
MN	NS	NS	NS	NS	NS	NS
N1	*	*	NS	NS	NS	NS
N2	NS	NS	NS	NS	*	*
N3	NS	NS	NS	NS	NS	NS
N4	NS	NS	NS	NS	NS	NS
TS	NS	NS	*	NS	NS	NS
MS	NS	NS	NS	*	*	*

* *significant at P=0.05 probability level.*
NS *not significant at P=0.05 probability level.*
† *for 1991 data.*
‡ *for 1992 data.*
Notes: TY and TN were total fruit yield and fruit number, MY and MN were total marketable fruit yield and fruit number, Y1, Y2, Y3, Y4 were yields of the first, second, third, and fourth grade, respectively, TY, MY, N1, N2, N3, and N4 were fruit numbers of the total, the marketable total, the first, second, third, and fourth grade, respectively, TS and MS were the fruit sizes of the total and marketable tomatoes.

C in 1992.

Temperature between the first and the second rotations did not significantly affect any variable in 1992 but the size of the total marketable fruit was affected in 1991. Temperature after the second rotation had no effect on any variable in two years. The order of importance of temperature during the three periods was: temperature before the first rotation (T1), temperature between the first and second rotations (T2), and temperature after the third rotation (T3). In the first period, seedlings were very small and were more sensitive to temperature regimes. From the second to third period, seedlings grew larger and thus became more resistant to unfavorable environmental conditions. Temperature regimes before the second rotation significantly affected the total marketable yield, the yield and fruit number in the first grade, and the overall size of total marketable fruit in 1991. In 1992, temperature regimes significantly affected fruit yield and number in the second grade and marketable fruit size. Fruit yield in the first grade was larger than that in the second grade in 1991, but smaller than that in the second grade in 1992.

a). <u>Duncan's Multiple Range Test of Fruit Yield, Fruit Number and Fruit Size</u>

<u>The Effect of Treatment on the Total Fruit Yield, Total Marketable Fruit Yield, and Fruit Yield in the First Grade.</u>

Duncan's multiple range test for the total yield (TY), total marketable yield (MY), and the yield (Y1) and fruit number (N1) in the first grade was conducted for all treatment (Tables 2 for 1991 and 3 for 1992). From Tables 2 and 3, it was seen that

Table 2. Effects of treatment on means of the total fruit yield (TY), total marketable fruit yield (MT), fruit yield in the first grade (Y1), and fruit number in the first grade (N1) of tomatoes from the field at Knoxville, TN in 1991.

Treatment	TY	MY	Y1	N1
	(Mg ha^{-1})	(Mg ha^{-1})	(Mg ha^{-1})	(1000 ha^{-1})
A§1†1‡1¶	74.1*abc	69.2*abcde	38.6*ab	168*abc
B121	62.0c	59.1de	26.2c	116c
C131	76.9abc	71.9abcd	36.3abc	164abc
B211	73.9abc	68.9abcde	33.9abc	148abc
C221	70.2abc	65.0abcde	34.1abc	152abc
D231	85.0a	83.0a	44.2a	190a
C311	75.9abc	72.7abcd	36.6abc	168abc
D321	69.7abc	65.9abcde	27.9c	128bc
E331	65.5bc	60.1bcde	27.7c	127bc
B112	68.9bc	64.3abcde	36.3abc	167abc
C122	76.1abc	72.4abcd	35.3abc	160abc
D132	62.8c	57.6de	25.7c	116c
C212	75.1abc	68.9abcde	30.4abc	133abc
D222	72.7abc	69.5abcde	34.4abc	152abc
E232	71.1abc	75.9ab	39.0ab	167abc
D312	63.8c	54.4e	24.5c	110c
E322	73.6abc	70.9abcde	37.6abc	168abc
F332	63.8c	58.6de	29.9bc	122bc
C113	75.9abc	71.2abcd	34.8abc	156abc
D123	71.4abc	68.2abcde	26.7c	120bc
E133	67.0bc	62.8bcde	32.4abc	134abc
D213	77.6abc	69.9abcde	37.1abc	158abc
E223	77.6abc	71.2abcd	39.5ab	175ab
F233	76.4abc	70.2abcde	39.3ab	176ab
E313	71.5abc	75.1abc	36.1abc	158abc
F323	65.5c	59.6cde	28.7c	128bc
F333	76.4abc	69.7abcde	39.5ab	168abc

* *Means in columns followed by the same letter are not significantly different at P=0.05 level using Duncan's Multiple Range Test.*

† *Numbers=temperature levels under which transplants were grown before the first rotation.*

‡ *Numbers=temperature levels under which transplants were grown after the first and before the second rotation.*

¶ *Numbers=temperature levels under which transplants were grown after the second rotation and before transplanting.* § *Letters=planting date code.*

Table 3 . Effects of treatment on means of the total fruit yield (TY), total marketable fruit yield (MT), fruit yield in the first grade (Y1), and fruit number in the first grade (N1) of tomatoes in the field at Knoxville, TN in 1992.

Treatment	TY	MY	Y1	N1
	(Mg ha^{-1})	(Mg ha^{-1})	(Mg ha^{-1})	(1000 ha^{-1})
A§1†1‡1¶	95.9*abcde	86.2*abcde	28.4*bcde	101*abcde
B121	83.5bcdef	75.9bcdef	27.9bcde	101abcde
C131	88.7abcdef	76.4bcdef	25.9cde	86cde
B211	96.1abcde	90.2abc	26.2cde	93bcde
C221	77.1cdef	68.4cdef	21.0de	67de
D231	84.3bcdef	75.1bcdef	26.2cde	92bcde
C311	70.7f	62.0ef	19.8de	68dec
D321	79.8cdef	70.4cdef	26.9cde	91bcde
B112	95.4abcde	86.7abcd	27.9bcde	94bcde
C122	90.7abcdef	81.3abcdef	29.4bcde	99abcde
D132	76.4def	67.7cdef	25.2cde	103abcd
C212	72.2ef	63.3def	15.8e	55e
D222	106.0ab	96.1ab	41.0ab	137ab
E232	101.1abc	90.9abc	32.4abcd	109abcd
D312	87.7abcdef	67.7cdef	28.7bcde	100abcde
C113	109.2a	100.08a	42.0a	144a
D123	84.8bcdef	79.8abcdef	25.2cde	89cde
D213	99.1abcd	85.5abcde	35.8abc	121abc
E223	67.7f	60.3f	18.0e	653de
F333	89.5abcdef	78.6abcde	26.2cde	89cde

* *Means in columns followed by the same letter are not significantly different at P=0.05 level using Duncan's Multiple Range Test.*

† *Numbers=temperature levels under which transplants were grown before the first rotation.*

‡ *Numbers=temperature levels under which transplants were grown after the first and before the second rotation.*

¶ *Numbers=temperature levels under which transplants were grown after the second rotation and before transplanting.*

§ *Letters=planting date code.*

total fruit yield, total marketable fruit yield, and fruit yield and number in the first grade were significantly affected by temperature regimes in two years. In 1991, total marketable fruit yield among treatments differed more than total fruit yield. In 1992, both MY and TY varied more than they did in 1991.

The top five treatments that produced higher total fruit yield (TY), total marketable fruit yield (MY), fruit yield in the first grade (Y1), and fruit number in the first grade (N1) were D231, E232, C311, C122, and C131 in 1991 (Table 2). Characters of temperature regimes of the top five treatments except C311 were: 1) temperature level before seedling emergence were 1 or 2; 2) temperatures after seedling emergence and before the fourth leaf appearance smoothly increased, and 3) temperatures after the fourth leaf appearance decreased (Table A-13). The bottom five treatments that produced lower fruit yield and fruit number were D312, D132, F332, B121, and F323. Temperatures increased very little as seedling development progressed for treatment B121 (Table A-13). Temperatures were high before the first and second leaf appearance for treatments D312, F332, and F323, and sharply changed as seedling development progressed for treatment D132.

Top five treatments with higher TY, MY, Y1, and N1 were C113, D222, E232, B211, and B112 and bottom five treatments were E223, C311, C212, D132, and C221 in 1992 (Table 3). Differences in temperature regimes of five top treatments and five bottom were difficult to determine (Table A-14).

The effect of temperature regime on total yield, total marketable yield, yield in the first grade, and the fruit size of the total yield before the first rotation.

Duncan's multiple range test for the total yield (TY), the total marketable yield (MY), the yield in the first grade (Y1), and the fruit number of the total yield (TN) was conducted for temperature regime before the first rotation (Table 4). In Table 4, TY, MY, and Y1 from transplants grown in temperature level 2 before the first rotation were significant higher than those from transplants grown in temperature levels 3 and 1. There was no significant difference in MY produced in transplants grown in temperature levels 3 and 1, but there was significant different in MY produced in transplants grown in temperature levels 2 and 3. Transplants grown in temperature 2 produced the highest fruit yield in the first grade, in total marketable fruit yield, in total fruit yield, and the highest number in total fruit. In general, transplants from temperature level 2 (20-21 C)

4. Effects of temperature level on means of total fruit yield (TY), total marketable fruit yield (MY), fruit yield in the first grade (Y1), and the number of total fruit (TN) of tomatoes in the field at Knoxville, TN in 1991.

Temperature level	Fruit yield			Fruit number
	TY	MY	Y1	TN
	---------	(Mg ha^{-1})------------		(1000 ha^{-1})
1†	70.6*b	66.4*ab	32.5*b	451*b
2	76.7a	70.9a	36.9a	484a
3	70.7b	65.3b	32.0b	467ab

* *Means in columns followed by the same letter are not significantly different at P=0.05 level using Duncan's Multiple Range Test.*

† *1, 2, and 3=temperature levels under which transplants were grown before the first rotation.*

performed best and transplants from temperature level 3 (22-26 C) produced more unmarketable cull fruits than transplants from temperature level 1 (18.1-19.6 C).Table

In 1992, fruit yield and fruit number were not significantly affected by temperature levels before the first rotation because there were no considerable differences in three temperature levels (Table A-14). Compared the temperature range of 18.1-26 C before the first rotation in 1991, the temperature range in three levels was only 17.5-21.2 C in 1992.

<u>The Effect of Temperature Regime before the Second Rotation.</u>

Duncan's multiple range test for the total fruit yield (TY), fruit yield (Y1) and fruit number (N1) in the first grade, and the fruit size (MS) of marketable tomatoes (Table 5) indicated that transplants grown in temperature regime 23 (tomatoes were seeded in temperature level 2, and then moved to temperature level 3) produced the highest TY, Y1, N1, and the largest fruit and transplants grown in temperature regimes 12, 13, 32, and 33 produced lower TY, Y1, and N1 in 1991.

In 1992, Duncan's multiple range test for fruit yield (Y2) and fruit number (N2) in the second grade, and the fruit size (MS) of marketable tomatoes (Table 6) indicated that fruit yield (Y2) and fruit number (N2) in the second grade and the largest fruit size (MS) were significantly affected by temperature regimes before the second rotation. However, both temperature regimes before the first rotation and temperature regimes after the first and before the second rotation did not significantly affect fruit yield and fruit number. This phenomena showed that temporal temperature distribution for

Table 5. Effects of temperature regimes on means of the total fruit yield (TY), fruit yield in the first grade (Y1), fruit number in the first grade (N1), and the total marketable fruit size (MS) of tomatoes in the field at Knoxville, TN in 1991.

Temperature regimes	TY	Y1	N1	MS
	($Mg\ ha^{-1}$)	($Mg\ ha^{-1}$)	($1000\ ha^{-1}$)	(kg)
1†1‡	72.4*ab	36.3*ab	162*ab	0.170*ab
1 2	69.9b	29.2b	132b	0.162b
1 3	68.9b	31.6b	138b	0.167ab
2 1	75.9ab	33.9b	146ab	0.167ab
2 2	73.6ab	36.1ab	159ab	0.173ab
2 3	80.8a	41.0a	177a	0.162a
3 1	73.4ab	32.1b	144ab	0.162b
3 2	69.7b	31.4b	141b	0.162b
3 3	68.9b	32.4b	139b	0.170ab

* *Means in columns followed by the same letter are not significantly different at P=0.05 level using Duncan's Multiple Range Test.*

† *Numbers=temperature levels under which transplants were grown before the first rotation.*

‡ *Numbers=temperature levels under which transplants were grown after the first and before the second rotation.*

Table 6. Effects of temperature regimes on means of fruit yield in the second grade (Y2), fruit number in the second grade (N2), and the total marketable fruit size (MS) of tomatoes in the field at Knoxville, TN in 1992.

Temperature regimes	Y2	N2	MS
	($Mg\ ha^{-1}$)	($1000\ ha^{-1}$)	(kg)
1†1‡	39.0*a	203*a	0.193*ab
1 2	35.6ab	177ab	0.197a
1 3	27.2b	140b	0.175b
2 1	34.4ab	179ab	0.185ab
2 2	35.8ab	153ab	0.188ab
2 3	35.8ab	177ab	0.202a
3 1	29.4ab	153ab	0.188ab
3 2	27.7ab	151ab	0.190ab
3 3	34.4ab	173ab	0.195ab

* *Means in columns followed by the same letter are not significantly different at P=0.05 level using Duncan's Multiple Range Test.*

† *Numbers=temperature levels under which transplants were grown before the first rotation.*

‡ *Numbers=temperature levels under which transplants were grown after the first and before the second rotation.*

transplants was important to their performance in the field. Temperature regime 11 produced the highest Y2 and Y2 and temperature regimes 13 produced the lowest Y2,and N2.

Fruit yield in the first grade accounted for 50% of total marketable fruit yield in 1991, while fruit yield in the second grade accounted for 42% of total marketable fruit yield in 1992. Therefore, it was not surprising to see that temperature regimes before the second rotation significantly affected Y1 and N1 in 1991, but Y2 and N2 in 1992.

Total marketable fruit yields between two years were significantly different. Transplants in 1992 performed better in the field than did those in 1991. Two factors might make contributions to differences in transplant performance between two years. One factor was environmental conditions in the field. The other was temperature regimes in the greenhouse. Cultural practices were similar in two years and should not have resulted in remarkable differences in fruit yields. Environmental conditions in the field were different in two years in terms of climatic factors. For example, daily average temperature was higher after transplanting in 1991 than in 1992. Differences in precipitation were largely balanced by irrigation. However, it was no clear what effects of such differences were on fruit yields in two years.

Differences of temperature regimes in the greenhouse were obvious in two years (Tables A-13 and A-14). Greenhouse temperatures before the first and second leaf appearance in 1992 were obviously lower than those in 1991. In 1991, greenhouse temperatures did not change sharply from seedling emergence to the fourth leaf appearance as they did in 1991. It appeared that the quality of tomato transplants was negatively affected by an abrupt temperature change and benefitted from temperature regimes of 18-21 C for seedling emergence and 19-22 C for the first and second leaf appearance.

2). Regression Models of Fruit Yield, Fruit Number, and Fruit Size

Variables MY, Y1, Y2, MN, N1, N2, and MS in 1991 were regressed to transplant conditions to see how transplant conditions affected tomato fruit yield and yield components (Table A-15).

For model 1, transplant height, transplant diameter, and transplant weight did not affect marketable yield significantly, but leaf length and leaf number did affect yield significantly. The fifth and sixth leaf length made positive contributions to the yield, the third leaf length affected the yield nonlinearly, while the fourth leaf length had negative effects on the yield. This result can not be explained by the fourth leaf morphology, but might be related to temperature regimes experienced as the fourth leaf grew. The number of leaves per transplant negatively affected fruit yield. The reason for negative effect of leaf number on fruit yield was that transplants experienced too large proportion of the chronological time of their life cycle in the greenhouse at the time of transplanting. Since water and fertilizer were not limiting for transplant growth in the greenhouse but the space for root system was very limited, transplant shoots grew very well, but transplant roots were stressed. The longer the transplants grew in the greenhouse, the more the root systems were stressed. There were six to eight leaves per transplant in all treatments. When transplants were transplanted in the field, they experienced a shock. Older leaves which had appeared earlier on the transplant usually experienced more shock and senesced earlier when the transplants were transplanted in the field. Top leaves of transplants experienced less shock and had a higher survival rate. Therefore, transplants largely depended on top leaves to recover from transplanting. If top leaves were longer, photosynthetic effective leaf area index was larger, then the recovery of transplants from shock was faster and the yield was higher. It is possible that not only leaf length but also how leaves achieve their length affects tomato fruit yield. Likely other physiological factors that were not reflected by morphological measurements affected fruit yield. The first and second leaf length had no direct effect because these two leaves were fully expanded before the time of transplanting.

For model (2), the sixth leaf length had positive effects on total marketable fruit number and the third leaf length affected it nonlinearly. The fourth leaf length and the total leaf number per transplant negatively affected fruit number. The growth rate of transplant height, R_2, had a negative effect on fruit number because when transplant grew in length too quickly the stems were weak and transplants were "leggy". The growth rate of transplant diameter, R_3, had a positive effect on fruit number. When transplant grew fast in diameter, they were more stocky.

For model (3) of fruit size, regression coefficients of the fourth leaf length (L_4), transplant fresh weight (FRE), and the product of transplant height and diameter (HD) were negative, while regression coefficients of the fifth leaf length (L_5), the growth rate of transplant height (R_2), and transplant dry weight (DWT) were positive. Negative regression coefficients of transplant fresh weight and the product of transplant height and transplant diameter indicated that larger transplants produced lighter fruits. However, the positive regression coefficient of dry transplant weight seemed contradictory to the effect of transplant fresh weight on fruit size. Water content of transplant was different among treatments. The correlation coefficient was 0.82 between fresh weight and dry weight , 0.50 between transplant size and fresh weight, but only 0.27 between transplant size and dry weight.

For model (4) of fruit yield in the first grade and model (6) of fruit number in the first grade, regression coefficients were positive for the fifth leaf length and were negative for the fourth leaf length and leaf number . Fruit number in the first grade (N1) was affected only by the length of the fourth and fifth leaves. Fruit yield in the first grade (Y1) was affected by NL and the length of the fourth and fifth leaves. Adjusted R^2 for model (4) was very high, 0.98, but very low for model (6), being only 0.38, meaning that fruit yield largely depended on fruit size in the first grade.

For models (5) and (7), fruit yield (Y2) and fruit number (N2) in the second grade responded similarly to the same factors. The length of the fifth leaf positively affected Y1 and N1, but negatively affected Y2 and N2. Other factors that affected Y2 and N2 did not affect Y1 and N1.

Comparing regression coefficient signs of the leaf length in models (1), (4), and (5), it can be seen that the sign of the regression coefficients of L_4 and L_5 were the same as in models 1 and 4. The fifth leaf length promoted fruit yield in the first grade, but inhibited fruit yield in the second grade. The opposite sign of the regression coefficients for the fifth leaf length in models 4 and 5 can be explained by the difference in percentages of fruit yield of the first grade and second grade in the total marketable fruit yield. Fruit yield in the first and second grade accounted for about 80% of total marketable yield and, therefore, greatly influenced the total marketable yield. Correlation coefficients among total marketable yield, percentages of the fruit yield in the first grade, the second grade, the third grade, and the addition of the first grade and second grade appear in Table 7. As would be expected, the total marketable yield was positively correlated with the percentage of the first grade fruit yield in the total marketable fruit yield. Percentage of fruit yield in the first grade was negatively correlated with percentages of fruit yield in the second grade and the third grade.

Table 7. Correlation coefficients of the total marketable yield and percentages of fruit yields of the first, second, and third grade second grade in the total marketable fruit yield of tomato in the field at Knoxville TN, 1991.

	MY§	PY1†	PY2‡	PY3¶
MY	1.000	0.330	-0.262	-0.146
PY1	0.330	1.000	-0.836	-0.509
PY2	-0.262	-0.836	1.000	0.095
PY3	-0.146	-0.509	0.095	1.000

§ *MY=the total marketable fruit yield.*
† *PY1=the percentage of the first grade yield in the total marketable fruit yield.*
‡ *PY2=the percentage of the second grade yield in the total marketable fruit yield.*
¶ *PY3=the percentage of the third grade yield in the total marketable fruit yield.*

Tomato fruit yield was influenced by the leaf length and the leaf number, but was not significantly affected by transplant height, stem diameter, or transplant weight. Fruit yield responded positively to the fifth and sixth leaf length, negatively to the fourth leaf length and the leaf number, and nonlinearly to the third leaf length. Besides the leaf length and leaf number, the fruit number was also affected by the growth rate of transplant height and transplant stem diameter. Fruit sizes were correlated to the transplant size, transplant dry weight, transplant fresh weight and the leaf length. With the exception of model 6, adjusted R^2s were high in all other regression models in Table A-15.

For 1992 fruit data, total marketable fruit yield (MY), total marketable fruit number (MN), and total marketable fruit size (MS), were regressed to transplant conditions to see how transplant conditions affected yield components (Table A-16). Independent variables that significantly affected MY, MN, and MS in 1992 were different from those in 1991. In 1991, the number of leaves per transplant had negative effect on all dependent variables, but in 1992, no significant effect of the number of leaves on dependent variables was detected. These results suggested that 1991 transplants were oversized in terms of the number of leaves per seedling in the greenhouse at the time of transplanting. Transplant measurement data showed that there were 6-8 leaves per transplant in 1991, but only 5-6 leaves per transplant in 1992. The second and sixth leaf length had positive effect on total marketable yield and marketable fruit number. The reason was that at the time of the second leaf appearance for transplants in some treatments, transplants experienced cold shock due to very low temperature which resulted from poor temperature control in the greenhouse (temperature was below 10 C) at that time. When transplants experienced shock at that time, the second leaf did not grow normally and leaf length was shortened. Dry root weight had a positive effect on MY, MN, and MS. Considering small transplant size in 1992, transplants with greater dry root weights were less stressed than those with smaller dry root weights and recovered quickly when transplanted to the field. Dry shoot weight had negative effect on MY and MN. This was difficult to interpret.

Comparing transplant conditions that significantly affected tomato fruit yield and fruit number, it was seen that several more transplant condition variables were involved in the models for predicting of tomato fruit yield and fruit number in 1991 than in 1992. There were two reasons for this. First, temperature regimes in the field were different in the two years. Transplants with the same quality might not produce the same fruit yield and fruit number under different climatic conditions. Second and more importantly, transplant conditions were very different for two years. Ranges of transplant height (H), diameter (DI), the length of the first (L1), second (L2), third (L3), fourth (L4), fifth (L5), and sixth (L6) leaf, fresh transplant weight (FRE), dry shoot weight (SWT), and dry root weight (RWT) for two years are shown in Table 8. All measurements in 1991 had larger ranges than those in 1992. From regression theory, it is known that the large the range of independent variables, regression mean squares tend to be larger, therefore, independent variables more likely tend to be significant. This was probably a reason why more transplant condition variables significantly affected fruit yield and fruit number in 1991 than in 1992.

Table 8. Ranges of transplant height (H), stem diameter (DI), the length of the first (L1), second (L2), third (L3), fourth (L4), fifth (L5), and sixth (L6) leaf, fresh transplant weight (FRE), dry shoot weight (SWT), and dry root weight (RWT) of tomato transplants grown in the greenhouse for two years.

Years	H	DI	L1	L2	L3	L4
	(cm)	(mm)	(cm)	(cm)	(cm)	(cm)
1991†	13.9-21.7	3.6-4.4	10.5-14.3	10.6-15.1	9.7-14.7	6.0-12.8
1992†	13.0-17.7	3.5-4.2	9.2-11.8	9.7-12.4	9.7-13.7	6.5-10.8

	L5	L6	FRE	SWT	RWT
	(cm)	(cm)	(gm)	(gm)	(gm)
1991	2.1-6.3	0.2-3.3	56.6-117.1	5.4-13.8	1.81-4.72
1992	2.0-4.9	0.0-2.7	50.2-89.5	5.8-9.6	1.98-2.98

† *Measurements were made at the time of transplanting.*

Individual transplant condition variable such as transplant height or stem diameter may affect fruit yield and fruit number. However, these individual variables can not affect fruit yield separately and must be associated with each other to function holistically. This means that whole complement of variables affecting morphology of tomato transplants is more important than individual variables. The quality of transplants is determined by the combination of variables rather than by individual variables. Additional research is needed in this area.

4. CONCLUSIONS

Results from this study showed that temperature regimes under which transplants were grown in the greenhouse before transplanting significantly affected the subsequent fruit yield and fruit number in the field. Temperature regimes before the second rotation significantly affected fruit yield and fruit number in the first grade in 1991 and in the second grade in 1992. In 1991, temperature regimes before the first rotation significantly affected total marketable fruit yield. Planting dates, temperature regimes between first and second rotation and after second rotation did not significantly affect fruit number and fruit yield. These phenomena indicated that the quality of tomato transplants were more sensitive to temperature regimes before the first and second leaf appearance than at the subsequent states of growth. A sharp change in temperature experienced by tomato transplants in the greenhouse either from high to low or from low to high before the fourth leaf appearance, especially before the second leaf appearance had negative effects on their subsequent performance in the field. For optimum development, temperatures should be in the range of 18-21 C for seedling emergence and 19-22 C for the first and second leaf appearance. However, temperature for seedling emergence should not be 4 C higher or lower than that for the first and second leaf appearance. Regression models suggested that transplants were oversized in 1991. The age of transplants in 1992 was older than that of transplants in 1991, but the size of transplants in 1992 was smaller than that of transplants in 1991. This meant that the rapid growth rate of 1991 transplants had negative effects on transplant quality and the subsequent yield in the field.

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APPENDIX

Table A-1. Seeding dates and temperature levels experienced by tomato seedlings at different periods of times in the greenhouse in 1991.

Seeding date	Seeding code	Temperature levels T1	T2	T3	Treatment
3/19	A	1	1	1	A111
3/19	A	2	2	2	A222
3/19	A	3	3	3	A333
3/22	B	1	2	1	B121
3/24	C	1	3	1	C131
3/22	B	2	1	1	B211
3/24	C	2	2	1	C221
3/26	D	2	2	1	D231
3/24	C	3	1	1	C311
3/26	D	3	2	1	D321
3/28	E	3	3	1	E331
3/22	B	1	1	2	B112
3/24	C	1	2	2	C122
3/26	D	1	3	2	D132
3/24	C	2	1	2	C212
3/26	D	2	2	2	D222
3/28	E	2	3	2	E232
3/26	D	3	1	2	D312
3/28	E	3	2	2	E322
3/29	F	3	2	2	F332
3/24	C	1	1	3	C113
3/26	D	1	2	3	D123

Table A-1 Continued.

Seeding date	Seeding code	Temperature levels T1	T2	T3	Treatment
3/28	E	1	3	3	E133
3/26	D	2	1	3	D213
3/28	E	2	2	3	E223
3/29	F	2	3	3	F233
3/28	E	3	1	3	E313
3/29	F	3	2	3	F323
3/29	F	3	3	3	F333

Notes: T1 (17-19 C), T2 (21-23 C), and T3 (24-26 C) represent temperature levels experienced by tomato seedlings before the first rotation, between the first and the second rotations, and after the second rotation, respectively. Treatment refers to temperature regimes experienced by tomato seedlings in the greenhouse and is designed by the combination of seeding date and temperature level codes.

Table A-2. Seeding dates and temperature levels experienced by tomato seedlings at different periods of times in the greenhouse in 1992.

Seeding date	Seeding code	Temperature levels T1	T2	T3	Treatment
3/12	A	1	1	1	A111
3/16	B	1	2	1	B121
3/19	C	1	3	1	C131
3/16	B	2	1	1	B211
3/19	C	2	2	1	C221
3/21	D	2	3	1	D231
3/19	C	3	1	1	C311
3/21	D	3	2	1	D321
3/16	B	1	1	2	B112
3/19	C	1	2	2	C122
3/21	D	1	3	2	D132
3/19	C	2	1	2	C212
3/21	D	2	2	2	D222
3/23	E	2	3	2	E232
3/21	D	3	1	2	D312
3/19	C	1	1	3	C113
3/21	D	1	2	3	D123
3/21	D	2	1	3	D213
3/23	E	2	2	3	E223
3/23	E	3	3	3	E333

Notes: T1 (18-20 C), T2 (20-22 C), and T3 (22-25 C) represent temperature levels experienced by tomato seedlings before the first rotation, between the first and the second rotations, and after the second rotation, respectively. Treatment refers to temperature regimes experienced by tomato seedlings in the greenhouse and is designed by the seeding date and temperature level codes.

Table A-3. The height (HI), stem diameter (DI), and the length of the first leaf (L1), second leaf (L2), third leaf (L3), fourth leaf (L4), fifth leaf (L5), and sixth leaf (L6) of tomato transplants measured at the time of transplanting in 1991.

Treatment	HI	DI	L1	L2	L3	L4	L5	L6
	(cm)	(mm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)
A111	13.9	3.5	10.5	11.5	12.3	9.4	4.2	1.9
B112	13.5	3.8	10.7	10.6	10.7	8.3	4.1	1.9
B121	18.6	4.1	13.3	13.6	14.6	12.4	6.4	2.7
C113	19.0	4.0	12.6	12.7	12.1	10.9	5.2	2.7
C122	14.0	4.2	11.9	12.0	11.1	8.5	4.0	0.9
C131	15.8	3.8	12.1	12.1	14.2	12.1	5.8	2.2
E133	15.6	3.9	11.1	11.3	12.5	11.4	5.0	0.8
B211	15.1	3.5	11.6	13.0	13.1	10.3	4.8	2.2
C212	13.5	3.7	11.5	12.2	11.8	8.6	3.7	1.3
C221	20.3	4.2	14.3	15.1	14.6	12.8	6.3	2.6
D213	19.4	4.1	11.2	12.6	12.0	9.7	4.8	1.3
D222	16.7	3.7	13.3	13.8	12.2	9.7	4.7	1.7
D231	15.5	4.2	12.8	14.2	15.1	12.7	7.3	3.3
E223	21.7	4.6	12.8	13.8	14.1	11.5	6.1	1.8
E232	21.4	4.4	12.4	12.5	13.2	10.8	5.3	1.8
F233	18.1	4.1	11.9	13.0	14.5	12.2	5.9	1.9
C311	14.2	3.5	10.8	11.5	12.3	9.4	4.0	1.1
D312	12.0	3.6	11.1	11.2	10.1	6.8	2.6	0.7
D321	17.8	4.3	12.8	14.3	14.7	12.3	6.1	2.3
E313	17.3	3.8	11.5	12.0	12.6	9.0	3.6	1.1
E322	14.5	4.2	11.8	11.9	11.2	8.6	3.6	1.0
E331	18.0	3.8	11.7	12.4	13.8	12.2	5.2	1.8
F323	14.1	3.8	10.5	11.2	11.3	8.6	3.1	0.4
F333	18.1	3.7	10.6	11.3	12.3	10.8	4.7	1.5
F332	17.0	3.8	11.6	11.6	11.6	8.7	3.1	0.3
D132	13.8	3.7	11.0	12.1	9.7	6.0	2.1	0.2
D123	18.7	4.3	12.5	13.7	12.5	9.2	3.5	0.6

Table A-4. The fresh weight above the ground (FRE), dry weight (DTW), dry root weight (DRW), and dry shoot weight (DSW) of tomato transplants measured at the time of transplanting in 1991.

Treatments	FRE	DSW	DRW	DTW
	-----------------	--(g/transplant)-----	-----------------	-------
A111	14.4	1.60	0.66	2.26
B112	13.5	1.40	0.48	1.88
B121	19.9	2.14	0.80	2.94
C113	15.3	1.44	0.44	1.88
C122	14.1	1.46	0.44	1.98
C131	18.0	2.00	0.82	2.82
E133	12.8	1.24	0.40	1.64
B211	19.0	2.16	0.94	3.10
C212	15.1	1.98	0.68	2.66
C221	22.2	2.76	0.86	3.62
D213	17.2	1.68	0.52	2.20
D222	18.6	1.66	0.54	2.20
D231	23.2	2.56	0.76	3.32
E223	20.2	1.82	0.52	2.34
E232	19.6	2.66	0.78	3.44
F233	17.2	1.88	0.74	2.62
C311	15.6	1.76	0.80	2.56
D312	15.0	1.96	0.58	2.54
D321	23.4	2.62	0.84	3.54
E313	15.0	1.28	0.52	2.80
E322	14.6	1.86	0.58	2.44
E331	19.6	2.04	0.82	2.86
F323	11.3	1.08	0.50	1.58
F333	16.0	1.74	0.58	2.31
F332	11.8	1.94	0.60	2.54
D132	12.9	1.52	0.42	1.94
D123	12.4	1.22	0.36	1.58

Table A-5. The height (HI), stem diameter (DI), and the length of the first leaf (L1), second leaf (L2), third leaf (L3), fourth leaf (L4), fifth leaf (L5), and sixth leaf (L6) of tomato transplants measured at the time of transplanting in 1992.

Treatment	HI	DI	L1	L2	L3	L4	L5	L6
	(cm)	(mm)	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)
A111	15.6	3.7	10.4	10.7	12.1	10.3	6.1	2.7
B121	14.4	3.5	11.3	12.7	12.3	9.2	4.3	0.7
C131	13.0	3.6	9.4	9.9	12.0	9.6	4.2	2.0
B211	13.2	3.6	9.9	11.5	10.5	9.5	4.4	1.3
C211	14.0	3.5	11.2	11.3	10.6	7.5	5.7	1.1
D231	12.8	3.6	10.8	11.5	12.6	9.1	3.8	0
C311	14.1	3.6	9.9	11.4	11.4	7.6	3.2	0
D321	14.1	4.1	11.1	11.9	11.3	8.0	2.7	0
B112	14.4	3.5	9.3	11.1	11.3	9.4	4.2	1.6
C122	17.7	3.8	11.5	12.4	12.9	9.9	4.9	2.2
D132	13.7	3.7	9.7	10.9	10.8	8.3	3.8	1.2
C212	13.7	3.6	9.7	10.7	11.8	9.1	3.8	0
D222	17.0	4.2	11.8	12.4	13.7	10.8	5.4	2.4
E232	12.5	3.7	11.0	12.1	10.8	6.6	2.6	0
D312	14.1	3.7	10.3	11.6	11.4	8.2	3.4	0.6
C113	14.6	3.5	10.5	11.6	11.9	8.5	4.1	1.2
D123	15.5	3.8	10.0	11.8	11.9	8.6	4.7	2.1
D213	10.5	3.5	9.2	9.7	9.7	6.7	2.7	0
E223	13.0	3.5	11.4	11.8	10.3	6.5	2.0	0
E333	13.1	3.5	10.6	12.2	11.3	7.4	3.2	0

Table A-6. The fresh weight above the ground (FRE), dry weight (DTW), dry root weight (DRW), and dry shoot weight (DSW) of tomato transplants measured at the time of transplanting in 1992.

Treatments	FRE	DSW	DRW	DTW
	---(g/transplant)---			
A111	17.9	1.92	0.60	2.52
B121	15.5	1.82	0.55	2.37
C131	14.8	1.63	0.50	2.13
B221	15.0	1.52	0.47	1.99
C221	13.5	1.46	0.46	1.92
D231	15.5	1.78	0.59	2.37
C311	14.9	1.59	0.51	2.10
D321	13.6	1.49	0.50	1.99
B112	13.6	1.31	0.46	1.77
C122	17.9	1.88	0.51	2.39
D132	13.8	1.38	0.41	1.79
C212	13.7	1.36	0.48	1.84
D222	18.1	1.83	0.51	2.34
E232	12.8	1.23	0.41	1.64
D312	14.0	1.41	0.51	1.92
C113	15.2	1.71	0.55	2.26
D123	15.6	1.80	0.50	2.30
D213	10.1	1.16	0.47	1.63
E223	12.4	1.31	0.40	1.71
E333	14.6	1.65	0.48	2.13

Table A-7. Temperature accumulations (base temperature is 0 C) for transplants in the greenhouse from sowing to seedling emergence (TE), from seedling emergence to the first and second (T12), from the first and second to third (T3), from the third to fourth (T4), from the fourth to fifth (T5), and from the fifth to sixth leaf appearance (T6) in 1991.

Treatments	TE	T12	T3	T4	T5	T6
	GDD					
A111	231	113	145	78	103	117
B112	216	116	136	79	76	101
B121	216	118	99	65	149	117
B211	153	100	180	70	125	117
C113	241	77	146	59	177	48
C122	241	85	147	64	82	116
C131	235	68	175	51	182	41
C212	163	112	130	73	134	134
C221	163	112	106	84	146	37
C311	166	124	164	85	162	79
D123	242	63	172	64	155	No
D132	242	74	209	89	119	No
D213	208	68	180	39	64	134
D222	208	68	144	92	78	120
D231	208	68	96	102	80	56
D312	162	103	194	76	176	No
D321	158	158	91	103	88	119
E133	221	69	205	98	104	No
E223	201	109	150	116	82	53
E232	201	47	181	51	148	100
E313	197	59	184	74	90	103
E322	197	57	151	73	112	169
E331	197	57	186	69	103	96
F233	185	95	153	79	99	153
F323	208	57	172	105	95	77
F332	208	57	151	104	113	No
F333	208	57	151	104	128	123

No means the sixth leaf did not show up at the time of transplanting.

Table A-8. Temperature accumulations (base temperature is 0 C) for transplants in the greenhouse from sowing to seedling emergence (TE), from seedling emergence to the first and second (T12), from the first and second to third (T3), from the third to fourth (T4), from the fourth to fifth (T5), and from the fifth to sixth leaf appearance (T6) in 1992

Treatments	TE	T12	T3	T4	T5	T6
	------------------	------------------	------------------GDD	------------------	------------------	------------------
A111	159	124	188	101	88	86
B112	159	113	167	112	86	93
B121	159	115	139	95	108	87
B211	168	109	162	133	89	121
C113	160	130	135	95	74	114
C122	160	128	129	99	63	97
C131	160	128	134	75	85	114
C212	170	105	156	109	74	137
C221	170	106	151	112	95	131
C311	179	101	151	106	97	No
D123	165	111	135	81	62	114
D132	165	111	142	92	74	127
D213	164	119	135	105	117	No
D222	164	119	124	100	68	91
D231	164	117	134	75	113	123
D312	157	120	123	114	65	134
D321	157	118	109	113	119	No
E223	168	120	132	99	101	No
E232	172	116	116	116	123	No
E333	167	117	126	90	125	No

No means the sixth leaf did not show up at the time of transplanting.

Table A-9. Total fruit yield (TY), total marketable fruit yield (MY), fruit yield in the first, second, third, and fourth grades (Y1, Y2, Y3, and Y4) of tomatoes in the field at Knoxville, TN in 1991.

Treatments	TY	MY	Y1	Y2	Y3	Y4
	($Mg\ ha^{-1}$)					
A111	74.1	69.2	38.6	20.3	8.3	2.0
B112	68.9	64.3	36.3	19.1	7.3	4.0
B121	62.0	59.1	26.2	21.3	7.4	3.6
B211	73.9	68.9	33.9	20.9	9.9	4.0
C113	74.2	71.2	34.8	23.3	9.0	3.8
C122	75.4	72.4	35.3	24.3	10.5	2.1
C131	76.9	71.9	36.3	21.9	8.8	4.2
C212	75.1	68.9	30.4	27.7	7.4	3.1
C221	70.2	65.0	34.1	18.5	9.1	3.0
C311	75.9	72.7	36.6	22.7	10.3	2.9
D123	71.4	68.2	26.7	27.0	11.3	3.2
D132	62.8	57.6	25.7	19.9	9.3	2.3
D213	77.6	69.9	37.1	20.3	9.1	3.4
D222	72.7	68.5	34.4	20.9	8.9	3.3
D231	85.0	83.0	44.2	22.8	9.7	3.2
D312	63.8	54.4	24.5	17.9	8.1	3.6
D321	69.7	65.9	27.9	23.7	10.4	3.8
E133	66.9	62.8	32.4	18.2	8.9	3.2
E223	77.6	71.2	29.5	20.8	6.4	4.0
E232	81.1	75.9	39.0	24.9	9.0	2.5
E313	81.5	75.1	36.1	26.5	9.8	2.9
E322	73.6	70.7	37.6	23.3	6.4	2.9
E331	65.5	60.1	27.6	21.0	7.7	3.3
F233	76.4	70.2	39.3	19.1	8.3	2.4
F323	65.5	59.6	28.7	19.4	7.5	4.8
F332	63.8	58.6	29.9	17.9	7.8	2.9
F333	76.4	69.7	39.5	19.5	7.3	3.4

Table A-10. The number of total fruit (TN), total marketable fruit (MN), and fruit in the first, second, third, and fourth grades (N1, N2, N3, and N4) of tomatoes in the field at Knoxville, TN in 1991.

Treatments	TN	MN	N1	N2	N3	N4
	($1000 ha^{-1}$)					
A111	450	395	167	131	73	25
B112	428	373	165	122	66	21
B121	408	376	116	138	67	48
B211	467	415	148	131	88	47
C113	491	428	156	148	77	49
C122	479	425	160	149	91	25
C131	499	430	164	138	77	45
C212	484	413	133	171	67	38
C221	465	395	152	118	79	46
C331	487	442	168	152	94	36
D123	472	429	120	170	99	41
D132	425	353	116	127	82	27
D213	484	402	158	130	80	38
D222	472	420	152	136	80	37
D231	514	460	190	144	86	39
D312	457	351	110	120	69	51
D321	470	425	129	154	93	47
E133	420	361	134	116	77	36
E223	494	425	175	135	60	47
E232	499	430	165	157	79	29
E313	529	452	158	164	89	38
E322	487	432	168	159	54	35
E331	437	376	127	134	70	41
F233	482	413	176	124	77	31
F323	430	368	129	127	68	45
F332	398	338	122	112	70	34
F333	492	398	168	124	68	39

Table A-11. Total fruit yield (TY), total marketable fruit yield (MY), fruit yield in the first, second, third, and fourth grades (Y1, Y2, Y3, and Y4) of tomatoes in the field at Knoxville, TN in 1992.

Treatments	TY	MY	Y1	Y2	Y3	Y4
	(Mg ha^{-1})					
A111	95.9	86.2	28.4	38.8	16.3	2.6
B112	95.4	86.7	27.9	39.0	15.3	4.6
B121	83.5	74.4	27.9	32.1	13.2	2.6
B211	96.1	90.2	26.2	44.2	16.1	3.4
C113	109.2	100.8	42.0	38.8	16.2	3.6
C122	90.7	81.3	29.4	36.3	14.3	1.5
C131	88.7	76.4	30.0	31.1	15.1	4.2
C212	72.2	63.3	15.8	29.4	14.2	3.6
C221	77.1	68.7	21.0	28.4	15.3	3.9
C311	70.7	62.3	19.5	27.9	11.8	2.9
D123	84.8	79.8	25.2	38.1	11.2	5.2
D132	76.4	67.7	24.7	23.3	14.0	5.4
D213	98.8	85.5	35.8	29.2	17.9	2.9
D222	106.0	96.1	41.0	37.3	16.3	1.8
D231	84.3	75.1	26.2	33.1	12.8	2.8
D312	87.7	78.3	28.7	30.9	15.8	2.9
D321	79.8	70.4	26.9	29.4	10.1	4.2
E223	67.7	60.3	18.0	25.7	12.2	4.4
E232	101.1	90.7	32.4	38.3	16.8	3.3
E333	89.2	78.6	26.2	34.1	15.0	2.9

Table A-12. The number of total fruit (TN), total marketable fruit (MN), and fruit in the first, second, third, and fourth grades (N1, N2, N3, and N4) of tomatoes in the field at Knoxville, TN in 1992.

Treatments	TN	MN	N1	N2	N3	N4
	($1000 ha^{-1}$)					
A111	541	455	101	198	129	27
B112	531	467	94	209	117	48
B121	467	383	101	162	100	19
B211	531	474	93	228	126	28
C113	556	494	144	201	122	28
C122	479	400	99	174	110	19
C131	524	425	86	157	142	41
C212	442	358	55	154	106	43
C221	445	371	67	144	118	43
C331	413	336	69	144	87	36
D123	460	415	89	196	88	43
D132	477	393	103	124	103	62
D213	534	445	121	155	137	31
D222	526	457	137	180	121	19
D231	442	371	92	155	93	31
D312	514	415	100	162	121	30
D321	430	368	91	151	82	46
E223	398	341	65	134	93	50
E232	534	462	109	198	119	35
E333	477	402	89	173	110	32

Table A-13. Daily average temperature from planting to seedling emergence (TE), from seedling emergence to the first & second (T12), from the first & second to the third (T3), from the third to the fourth (T4), from the fourth to the fifth (T5), and from the fifth to the sixth (T6) leaf appearance in 1991.

Treatment	TE	T12	T3	T4	T5	T6
	----------	----------	---------- ^{0}C	----------	----------	
A111	19.6	18.2	19.3	19.4	17.4	19.2
A222	23.1	19.9	21.5	22.5	21.4	21.2
A333	26.6	22.8	25.0	25.7	24.1	24.9
B112	19.6	18.7	17.9	19.8	18.9	19.1
B121	19.6	19.6	20.7	21.6	21.3	19.1
C113	18.5	19.3	18.5	20.5	25.3	24.2
C122	18.5	21.3	21.4	22.0	20.5	19.3
C131	18.1	22.6	25.7	26.7	20.1	20.5
D123	18.8	21.6	21.8	20.7	25.8	No
D132	18.4	25.6	26.1	22.3	19.9	No
E133	18.8	23.0	25.9	24.1	25.9	No
B211	22.8	19.5	20.0	18.0	17.9	19.0
C212	21.2	21.1	19.0	19.2	18.9	18.9
C221	21.2	21.1	21.9	21.5	20.8	17.6
D213	20.8	22.8	18.5	19.7	16.2	25.8
D222	20.8	22.8	21.2	22.4	20.0	20.0
D231	20.8	22.8	25.2	25.5	26.7	19.3
E223	20.5	21.8	21.8	23.2	26.3	25.1
E232	20.6	24.9	25.9	26.4	24.1	25.5
F233	20.6	24.9	25.9	26.4	24.1	25.5
C311	24.0	25.2	20.0	18.1	17.8	19.7
D312	23.4	24.9	19.6	19.6	19.5	19.6
D321	23.3	25.4	22.9	21.4	19.5	18.3
E313	22.4	25.8	19.0	17.5	23.8	26.0
E322	22.4	25.8	21.4	22.1	19.8	19.9
E331	22.4	25.8	25.6	26.1	22.4	18.6
F323	23.7	26.0	22.3	21.1	22.0	25.9
F333	23.7	26.0	25.6	26.5	24.7	25.7
F332	23.7	26.0	25.6	26.5	23.6	25.0

Notes: TE, T12, T3, T4, T5, and T6 were average daily temperature accumulations from planting to emergence, first and second, third, fourth, fifth, and sixth leaf appearance, respectively. No means the sixth leaf had not show up at the time of transplanting.

Table A-14. Daily average temperature from planting to seedling emergence (TE), from seedling emergence to the first & second (T12), from the first & second to the third (T3), from the third to the fourth (T4), from the fourth to the fifth (T5), and from the fifth to the sixth (T6) leaf appearance in 1992.

Treatment	TE	T12	T3	T4	T5	T6
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A111	17.7	17.8	18.6	21.5	21.5	22.1
B121	17.5	19.9	19.9	23.1	21.5	22.8
C131	17.6	18.5	23.1	24.1	21.9	22.0
B211	19.0	21.8	18.2	21.5	22.3	21.2
C221	19.3	20.4	21.6	23.4	22.5	21.4
D231	20.2	19.8	23.1	24.3	22.1	21.2
C311	19.7	20.6	19.6	21.2	22.5	No
D321	19.7	20.4	21.4	23.1	22.4	No
B112	17.5	19.9	18.5	21.6	23.2	23.2
C122	17.6	18.5	21.7	23.2	23.1	23.6
D132	18.5	17.9	23.7	24.8	23.7	22.3
C212	19.3	20.2	20.0	21.4	23.7	22.4
D222	20.2	19.8	21.7	23.1	23.3	23.4
E232	21.2	19.6	24.1	23.7	23.6	No
D312	19.7	20.4	20.2	21.5	23.4	22.4
C113	17.6	18.5	20.3	21.5	25.4	23.7
D123	18.5	17.9	22.4	22.4	25.7	23.2
D213	20.2	19.8	20.1	21.5	26.6	No
E223	21.2	19.6	22.7	23.0	25.9	No
E333	20.6	20.4	24.2	23.9	25.4	No

Notes: TE, T12, T3, T4, T5, and T6 were average daily temperature accumulations from planting to emergence, first and second, third, fourth, fifth, and sixth leaf appearance, respectively. No means the sixth leaf had not show up at the time of transplanting.

Table A-15. Regression models of total marketable fruit yield (MY), fruit yield in the first grade (Y1), fruit yield in the second grade (Y2), total marketable fruit number (MN), fruit number in the first grade (N1), fruit number in the second grade (N2), and marketable fruit size (MS) of tomatoes in the field at Knoxville, TN 1991.

	Regression models*	Adjusted R^2
(1)	$MY=-53.4+17.1L_3-0.616L_3^2-2.956L_4+2.656L_5$ $+0.438L_6^2-2.872NL$	0.63
(2)	$MN=-288.28+86.01L_3-12.17L_4+20.07L_6-2.979L_3^2$ $-81.45R_2+623.02R_3-13.80NL$	0.71
(3)	$MS=0.160-0.0004L_4^2+0.0178L_5-0.0102FRE$ $+0.1237R_2-0.0006HD+0.0241DWT$	0.67
(4)	$Y1=4.448-0.284L_4^2+0.289L_5^2-1.178NL$	0.98
(5)	$Y2=3.334+0.885L_3+1.968L_6-0.225L_5^2-7.421R_2$ $-3.197NL$	0.99
(6)	$N1=38.91+11.90L_5-0.321L_4^2$	0.38
(7)	$N2=20.81DI+5.297L_3-1.382L_5^2+12.14L_6-49.48R_2$ $-9.208NL$	0.99

* *all intercepts and regression coefficients were significant at P=0.05 significant level.*
Notes: L_3, L_4, L_5, *and* L_6 *were the length (cm) of the first, second, third, fourth, and fifth leaf at the last measurement, NL was the average number of leaves per transplant,* R_2 *was the growth rate of seedling height (cm/day),* R_3 *was the growth rate of seedling diameter (mm/day), FRE was fresh weight of 5 transplants (gram), HD was the product of transplant height and transplant diameter, DWT was dry weight of 5 transplants (gram), and DI was transplant diameter. All these variables were measured at the time of transplanting.*

Table A-16. Regression models of total marketable fruit yield (MY), total marketable fruit number (MN), and marketable fruit size (MS) of tomatoes in the field at Knoxville, TN 1992.

	Regression models*	Adjusted R^2
(1)	$MY=0.181L_2^2+4.618L_6-5.345SWT+18.23RWT$	0.98
(2)	$MN=167.3-11.57HI+1.075L_2^2+37.3L_6-26.4SWT+75.9RWT$	0.44
(3)	$MS=0.098+0.0003L_2^2+0.0199RWT$	0.51

** all intercepts and regression coefficients were significant at P=0.05 probability level.*
Note: L_2 and L_6 were the length (cm) of the second and sixth leaf, HI was transplant height; SWT and RWT were dry shoot and dry root weight.

PART V

OVERALL SUMMARY

1. SUMMARY OF PARTS II-IV

In this research, four mathematical formulas of calculating the base temperature in heat unit systems were proposed, proven, and tested. Effects of temperature regimes or temporal temperature distributions experienced in the preceding developmental stage on the succeeding developmental stage were studied in the greenhouse. Effects of temperature regimes for tomato transplants in the greenhouse before transplanting were investigated on the subsequent fruit yield in the field.

The four mathematical formulas proposed are capable of calculating the base temperature simply and more accurately than current procedures. Unlike the previous procedures with which the base temperature must be selected with a number of attempts, using the proposed formulas the base temperature can be calculated with only one attempt. These mathematical formulas are applicable to any crop and any developmental stage for calculating the base temperature. Comparing the prediction of tomato seedling development with four proposed formulas, it was seen that the least standard deviation in growing degree days method was the least accurate. Other three methods provided similar results.

Since current methods of predicting crop development need to be improved, detecting effects of temperature regimes in the preceding developmental stage on the succeeding developmental stage may be means of doing so. Results from this study considering effects of temperature regimes in the preceding developmental stage on the succeeding developmental stage suggested that the prediction of crop development could be possibly improved by this approach. This research was done only on tomato seedling development. Additional research is needed in a complete growing season and on selected crops in order to obtain more substantial data base of growth and development information.

The quality of tomato transplants is important to the subsequent yield in the field. Transplant quality is determined by transplant size, age, and morphology, however, the quality of transplants is influenced greatly by temperature regimes. Therefore, attempts of investigating effects of temperature regimes for transplants before transplanting on the subsequent performance in the field are well justified. The results from this investigation showed that transplants which did not experience a sharp change in temperature as crop development progressed produced higher yields. Temperature of 18-21 C for seedling emergence and 1-2 C lower than that (20-21 C) for the first and second leaf appearance appeared optimum for seedling development. Temperatures for the following developmental stages should be slightly, but not more that 3-4 C higher. The findings from tomato transplants may be applicable to other vegetable crops such as green pepper and eggplant. Temperature regimes for producing high quality transplants may vary with crops, but the principle is the same for all crops

VITA

Senshan Yang was born in China in 1953. He received a Bachelor of Science degree in agriculture with a major in agronomy from Shenyang Agricultural College (China) in 1982 and a Master of Science degree in agriculture with a major in agroecology from Nanjing Agricultural University (China) in 1985. In 1986 he worked at North Carolina State University as a visiting scientist for about a year and half. He started his doctoral degree program in 1988 at the University of Tennessee, Knoxville. During his graduate program he was employed as graduate research assistant. He completed the requirements for a Doctoral degree with a major in Plant and Soil Science in 1993.