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J. Amer. Soc. Hort. Sci. 111(1):11–16. 1986.

Predicting Harvesting Date of Processing Tomatoes by a Simulation Model

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Additional index words. Heat units, physiological day

Abstract. **A computer program was developed for predicting the times of emergence, flowering, turning stage, and harvesting of processing tomatoes. The program was validated and calibrated by using 1972-1980 tomato data from 44 fields at 2 locations in Israel. Predictions are based on accumulation of heat units defined in terms of "physiological days", where 1 physiological day is equivalent to a calendar day with a constant temperature of 26°C. The growing season was divided into 4 stages: from sowing to emergence, from emergence to flowering, from flowering to turning stage, and from turning stage to harvesting. Accumulation of physiological days during the first 2 stages is based on a linear function. During the last 2 stages, a quadratic function is used to calculate daytime heat units wherever the daily average temperature is above 20°. The maximum rate of development is at 26°. In the last stage, soil stress index also is taken into account. Use of the model makes it possible to predict the day of harvest with a precision of ±3 days, as compared with ±9 days when a daily mean systems is employed.**

The efficient operation of tomato processing plants requires the steady supply of tomatoes over an extended period of time. Planting on different dates can extend the harvest period. Knowledge of the influence of environmental factors on vegetative growth, fruit development, and ripening rate will permit a more precise manipulation of planting dates in different areas in order to ensure the continuity of fruit supply.

Prediction of plant development is based mainly on heat unit accumulation (3, 4, 11, 12, 13). The common method of calculating heat units is by means of the daily mean method, in which a day is the time unit and each degree above a base temperature has a linear effect on plant growth and on the accumulation of heat units. This can be expressed as:

$$HDU = (TMAX + TMIN)/2 - THMIN$$

where HDU is the daily accumulation of heat units, TMAX is the daily maximum temperature, TMIN is daily minimum temperature, and THMIN is the base temperature. By this method, negative values are ignored, and the minimum daily accumulation is zero.

In all predictive methods, it is assumed that the plant must accumulate a certain number of heat units in order to complete a developmental stage. Reports differ, however, with regard to the base temperature required for predicting the harvesting date of processing tomatoes (4, 13). None of these methods shows any significant advantage over the actual counting of days. These methods do not take into account the possibility of different base temperatures for different developmental stages. Optimum,

Received for publication 29 Oct. 1984. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

Table 1. Analysis of variance of sum of heat units on the basis of different assumptions for growth during the vegetative growth stage. Data were collected from 16 fields at 2 locations.

Analysis no.	Base temp. (celsius)	Temp range that advances blooming	Advance blooming factor	Variance: Between locations	Variance: Within a location	Variance: Total
1	8	TMIN[z] 8-15	constant	59.86	17.38	20.92
2	8	TMIN 8-15	variable	59.75	23.94	26.93
3	10	TMIN 10-15	constant	69.01	17.55	21.84
4	10	TMIN 10-15	variable	67.40	15.07	19.43
5	8	TNYT[y] 8-15	constant	42.86	13.79	20.12
6	8	TNYT 8-15	variable	35.22	29.42	29.90
7	8	TNYT 10-15	constant	43.19	13.55	16.02
8	8	TNYT 10-15	variable	35.97	25.29	26.18
9	10	TNYT 10-15	constant	49.40	12.35	15.44
10	10	TNYT 10-15	variable	41.65	20.93	22.65

[z]TMIN = minimum temperature.
[y]TNYT = average night temperature.

minimum, and maximum temperatures also can vary for different stages.

Brown (5) developed a formula that expresses the relationship between temperature and the sum of heat units for sweet corn development until ripening. This relationship is a quadratic function, with an optimum at 30°C and a minimum base temperature of 10°, below which no heat unit accumulation occurs. In Brown's model, heat units are calculated separately during the day and the night.

Since the temperature changes during the day closely follow a sine curve, Allen's model (1) calculates the area under the sine curve and above a base temperature. By definition, this area represents heat units, since it is a multiple of time and temperature.

A commonly used concept is the "physiological day". For cotton, 1 physiological day is equivalent to a calendar day with a constant temperature of 26°C. Heat accumulation is calculated separately for the day and the night and is weighted according to day length and night length respectively (9).

In attempting to predict the harvesting date for processing tomatoes by determining the number of heat units accumulated, it is necessary to consider the effect of temperature during each stage of plant development. A minimum threshold temperature of 10°C is considered for growth, even though there are reports of growth at lower temperatures (12, 13, 14). Less information is available regarding the maximum threshold. Temperatures above 30° have a negative influence on flowering, fruit set, and ripe tomato quality, but no evidence exists of a temperature above which growth ceases (6, 10).

Table 2. Influence of water tension in the soil on the period of fruit development, expressed as physiological days, from flowering to final weight. B_0, B_1, and R^2 for the respective sigmoid curves.

Location and irrigation treatment	Physiological days	B_0	B_1	R^2
Gilat				
20 KPa	29.69	−4.05	0.22	0.98
40 KPa	29.51	−5.07	0.24	0.92
60 KPa	28.03	−4.93	0.25	0.88
Akko				
20 KPa	30.98	−2.62	0.17	0.86
50 KPa	29.57	−2.26	0.16	0.85
80 KPa	27.86	−1.90	0.14	0.85
Mean	29.27			

Table 3. Number of physiological days in the ripening period from breaker stage to harvesting (95% changing color) under different irrigation treatments at two locations.

Irrigation treatment	Location: Gilat	Location: Akko
20 KPa	28.09	29.04
40/50 KPa	26.67	25.78
60/80 KPa	25.86	24.60
SE	1.46	0.85
	NS[z]	**

[z]Nonsignificant (NS) or significant at 1% (**) level.

In recent years, several reports have been written on the simulation of growth of a few crops. These include studies on the influence of environmental factors such as temperature, radiation, air humidity, and soil water status on dry weight accumulation, partitioning, and final yield (11).

The purpose of this study was to develop a model that would predict that length of the developmental stages of processing tomatoes. Such a model would make it possible to plan harvesting dates on the basis of temperature data from previous years and could be updated during the actual year of use.

Materials and Methods

Data were collected from 44 tomato fields at 2 stations in Israel during the years 1972–1980. One station (AKKO) is situated near the coast in the north and the other (GILAT) is located in the Negev. Climatic data included daily maximum and minimum temperatures. Field data included dates of planting, emergence, flowering, final irrigation, and harvesting.

During 1980, 3 drip irrigation treatments were applied at each location. Planned water tension in the soil was −20, −40, and −60 KPa in Gilat and −20, −50, and −80 KPa in Akko. The differences in water tension at the 2 locations are due to different soil water retention curves. Water tension in the soil was measured with 2 tensiometers placed beside the irrigation line between 2 drippers, about 20 cm from each dripper, 30 and 60 cm in depth.

Stress day index (SDI), ranging from 0 to 1, was determined according to tensiometer readings and soil types. In Akko, a water tension of −20 KPa was defined as 0 SDI and a water tension of −90 KPa as 1 SDI. It was assumed that a decrease in water tension caused a linear increase in SDI over this range. In Gilat, a water tension of −10 KPa was defined as 0 SDI and a water tension of −70 KPa as 1 SDI.

In order to study fruit development rate, clusters were tagged 3 times during the flowering period: early (1–3 days from the 1st flowering), medium (8–10 days from the 1st flowering), and late (16–18 days from the 1st flowering). Clusters were tagged when their 1st flower had opened. Fruit that developed from the tagged clusters were sampled every 6–8 days and their fresh and dry weights determined.

During the fruit ripening period, new sections (1 m in length) were sampled in the field every 3–4 days. To determine the ripening rate, fruit were divided into 2 groups: 1) green fruit; and 2) fruit at the turning stage and beyond. Fresh and dry weights were determined for each group. The weight accumulation rate was found by determining the difference in weight between 2 successive samples, each containing 8 fruits. Ripening rate at each sampling date was determined by the percentage of fruit which were at the turning stage and beyond.

The model was based on the GOSSYM cotton algorithm, as modified by Marani and Baker (unpublished). In this algorithm, a physiological day is calculated in 3 stages: 1. Day length is calculated from the latitude and the Julian date (chronological day of the year) (9). 2. Day and night mean temperatures are calculated separately according to the following formulae:

$$TDAY = TMIN + (TMAX - TMIN) \cdot DAYFAC$$
$$TNYT = TMIN + (TMAX - TMIN) \cdot NYTFAC$$

where TDAY is the daytime mean temperature; TMIN is the daily minimum temperature; TMAX is the daily maximum temperature; TNYT is the nightly mean temperature; DAYFAC, NYTFAC are empirical factors (0.77, 0.19, respectively), based on thermograph charts in Israel, for estimating daily and nightly mean temperatures respectively. 3. A "physiological day" in this model is equivalent to a day with a constant temperature of 26°C. This is an arbitrary value which is near the average daily temperature during the main growing period. Heat units contributed during the day and during the night are calculated according to the formulae:

$$DDAY = (TDAY - THMIN)/(26.0 - THMIN) \cdot (DL)/24.0$$
$$DNYT = (TNYT - THMIN)/(26.0 - THMIN) \cdot (24.0\text{-}DL)/24.0$$

where DDAY are heat units accumulated during the day; THMIN is the threshold temperature; DNYT are heat units contributed during the night; and DL is day length in hours. The sum of heat units that are accumulated during 24 hours (PHD) is DDAY + DNYT, discarding negative values.

The tomato cultivar used in all experiments was VF-134-1, except in the 1980 experiment in Gilat, when the cultivar was M82-1-8.

Results

The plant development period was divided into 4 stages. Assumptions regarding the influence of temperature on growth at each stage were incorporated into the model and tested against the growth data obtained from the fields. The sum of heat units was calculated separately for each stage.

Planting to emergence (Stage 1). The number of physiological days to emergence was calculated from data for emergence dates from 31 fields. The minimum temperature threshold was assumed to be 8°C, as in earlier reports (12, 13, 14). The number of physiological days was calculated on the basis of the GOSSYM model. The mean value for the sum of heat units was found to be 4.91 physiological days. Prediction of the emergence day for these fields on the basis of 4.91 physiological days showed a mean deviation of 1 chronological day later than the actual emergence date. During the usual emergence period of March and April, 1 chronological day at both places, Akko and Gilat, is equivalent, on the average, to 0.39 physiological day. This later value was substracted from the mean value of 4.91, and the resulting value 4.52 was taken as the number of physiological days from planting to emergence.

Emergence to 1st flowering (Stage 2). The effect of temperature on development rate according to the model was examined by an analysis of variance of the sum of heat units. If the model indeed reflects development in the field, one would expect the variation of sum values between the 2 stations and within each station to be minimal.

Night temperatures in the range of 10° to 15°C at this stage result in early flowering (14). This effect was expressed in the model by adding physiological days to the sum of heat units, causing a rapid accumulation towards the value at the end of this stage. Two methods of measuring this "advance blooming factor" were examined (Table 1). A constant effect (FX) added 0.25 physiological day to the sum when minimum day temperature (TMIN) or average night temperature (TNYT) were in the range of 8° to 15° or 10° to 15°. A variable effect (FXX) was inversely related to the temperature, according to the following: $FXX = 0.25 \cdot (15.0 - TMIN)$.

Data from 16 fields were analyzed 10 different ways (Table 1), based on various combinations of base temperatures, blooming range, and constancy of blooming factor. Analyses of variance computed for each combination were based on a hierarchial model with locations as main effects. Analyses 7 and 9 yielded

Table 4. Comparison of mean deviation and mean square deviation (days) from the actual dates, in the prediction of emergence date, flowering date, and harvesting date by three prediction models. Data were collected from 44 fields at 2 locations.

	Model					
	TOMMOD		Allen's		Daily mean	
Growth stage	Mean deviation	Mean sq. deviation	Mean deviation	Mean sq. deviation	Mean deviation	Mean sq. deviation
Emergence	2.35	8.23	6.03	96.74	3,20	23.06
Flowering	5.14	47.68	8.59	139.95	6.05	59.05
Harvesting	3.14	14.45	12.75	234.35	9.20	118.15

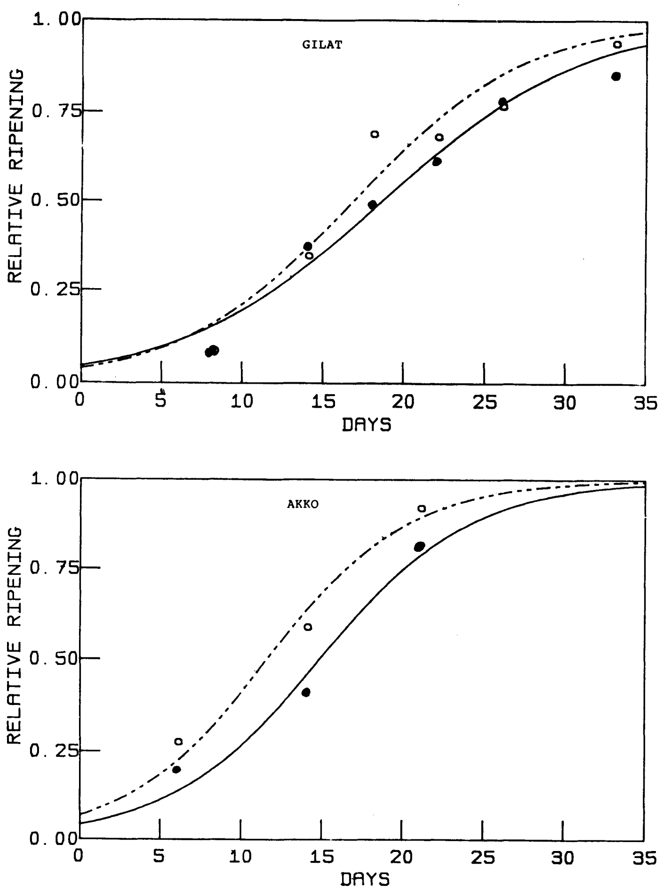

Fig. 1. Actual and predicted ripening rates for different irrigation treatments. Actual: ● 20 KPa; ○ 60/80 KPa. Predicted: —— 20 KPA; - - - - 60/80 KPa.

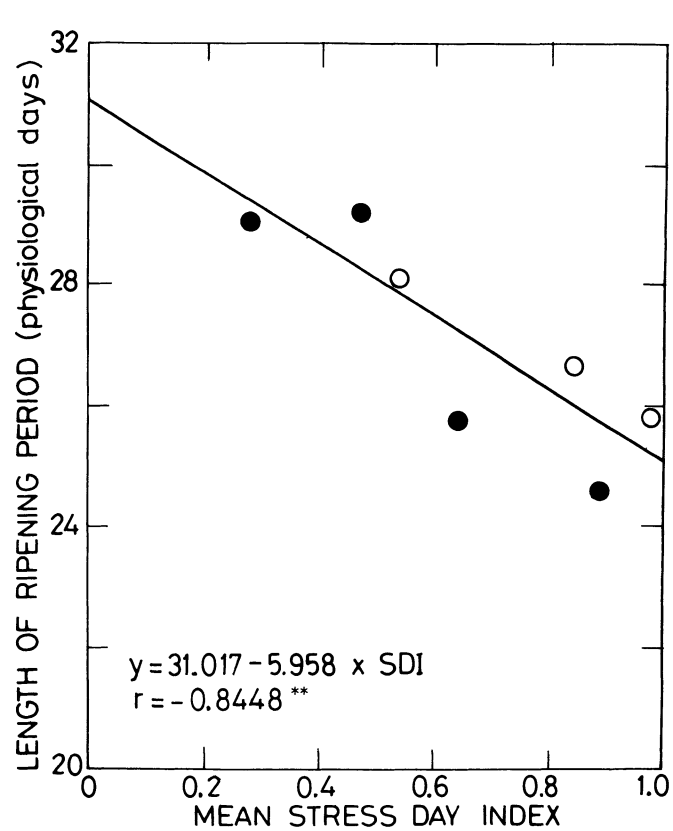

Fig. 2. Influence of mean stress day index on length of ripening period (physiological days). ○ – Gilat; ● – Akko.

the lowest values for total variance. Analysis 9 was preferred because it showed the highest consistency with previous findings (13). The minimum threshold temperature was taken as 10°C. A constant factor of 0.25 physiological day thus reflects the effect of average night temperatures in the range of 10° to 15° on early flowering. The mean value for the sum of heat units was calculated according to the data obtained from 22 fields and was found to be 28.62 physiological days.

Prediction of the flowering day for these fields on the basis of the value of 28.62 physiological days showed a mean deviation of 2 chronological days later than the actual flowering date. During the flowering period of April and May, 2 chronological days at both stations are equivalent, on average, to 1.22 physiological days. Accordingly, 1.22 was substracted from the mean value, and the resulting value of 27.40 was taken as the number of physiological days from emergence to flowering.

Fruit development period. The period of fruit development in Israel, from the 1st flowering to the day of harvest is from May to September. During this time, the mean temperature in Gilat is higher than that in Akko. In spite of this, the fruit development period is not shorter in Gilat. This fact is in contrast to the assumption about a constant number of heat units that the plant accumulates to finish a developmental stage. It is assumed that the effective temperature for growth during this stage is 10° to 40°C, but it is possible that an optimum temperature exists above which development rate is reduced (13).

This stage could be described by a quadratic function assuming the following conditions: 1) Maximum growth at a daytime mean temperature of 26°C (this value gave the least variation in predicting harvesting dates); 2) a day on which the mean temperature is 26° is contributing 1 physiological day [according to the definition of McKinion et al. (9)]; 3) a day on which the mean temperature is 20° contributes 0.625 of a physiological day. This value was calculated from the linear function (9). For higher temperatures, the following quadratic function was derived which gives a value of 0.625 at 20°, and a maximum value of 1.0 at 26°:

$$DDAY = (-6.0304 + 0.5408 \cdot TDAY - 0.0104 \cdot TDAY \cdot\cdot 2) \cdot (DL)/24.0;$$

where DDAY is the number of physiological days in a chronological day, TDAY is the daytime mean temperature, and DL is day length. When the daily mean temperature is below 20°, the number of heat units is calculated according to the linear function (9).

The fruit development period was divided into 2 stages: from the beginning of flowering to the turning stage, and from the turning stage to harvesting (ripening).

Flowering to turning stage (Stage 3). The change in color from green to red occurs when the fruit reaches its maximum weight. Dry weight accumulation in fruit that had started to develop on 3 different dates during the flowering period can be expressed as a sigmoid curve. A sigmoid function was fitted for each treatment (7), and the dry weight accumulation period was defined as the time from flower opening until the fruit reached 95% of its final dry weight. The function is $Y = EXP(B_0 + B_1 \cdot X)/(1 + EXP(B_0 + B_1 \cdot X)$; where Y is the proportion of the maximum value of dry weight, X is the number of days, B_0 and B_1 are coefficients.

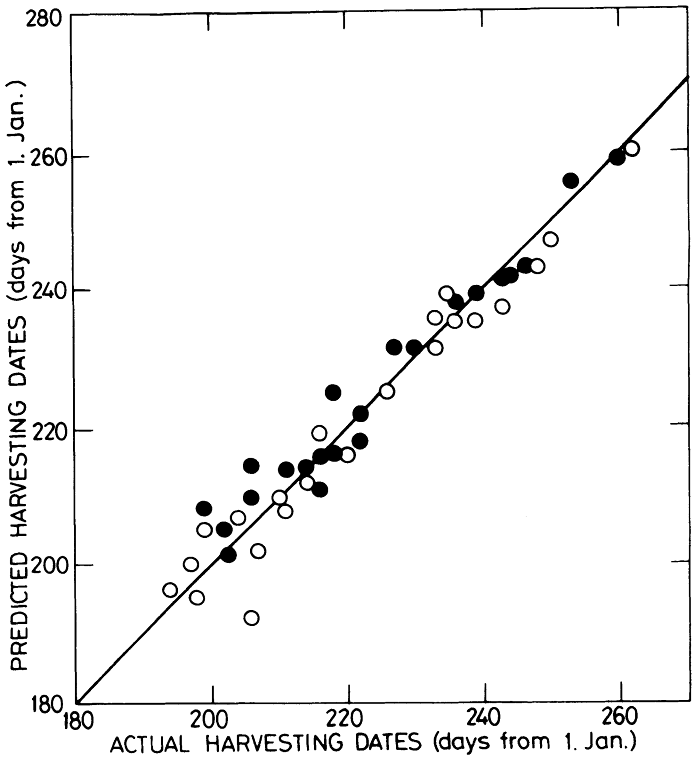

Fig. 3. Relationship between the actual date of harvesting and the harvest date predicted by data from 44 fields. ○ – Gilat; ● – Akko. 1:1 line of actual and predicted data. Actual regression slope = 0.92 ± 0.03.

The turning point occurs when the early fruits complete dry weight accumulation and start to change color. The mean length of early fruit development for all treatments was 29.27 physiological days, and this value was used for predicting the fruit development period (Table 2).

Turning stage to harvesting (Stage 4). Ripening rate, expressed as the percentage of fruit that had changed color per unit time, also was represented by a sigmoid curve (Fig. 1). Fields were harvested when 95% of the fruit had changed color. Examination of the influence of irrigation treatment on fruit ripening showed a definite relationship between drought stress and length of ripening period (Table 3). Mean stress day index (SDI) was found to be significantly correlated with length of ripening period (Y) (Fig. 2). The regression function is:

$$Y = 31.017 - 5.958 \cdot SDI.$$

Predicting the harvesting date in terms of physiological days, without considering the water status, would be of limited usefulness at this stage. The variation resulting from different irrigation treatments indicates that soil water status must be taken into account to improve prediction accuracy. After incorporating the function expressing the relationship between water status in the soil and length of ripening period into the program, the ripening period was found to vary between 25 and 31 physiological days.

On the basis of data obtained during the years 1972–1980 a simulation model (TOMMOD) was developed for predicting the developmental stages of the tomato plant. The model accumulates physiological days (heat units) and takes into account the water status in the soil during the ripening stage. Predictions are based on the following input data: latitude, daily maximum and minimum temperatures, planting date, and soil moisture stress indices based on tensiometer readings.

The model is used to predict expected dates of emergence, flowering, turning stage, and harvesting.

Discussion

Reports from California refer to difficulty in predicting plant development stages and harvesting dates of processing tomatoes by calculation of the sum of heat units (3, 13, 14). In England, however, the procedure has met with greater success (8). The basic assumption made in this method is that the plant must accumulate a certain number of heat units in order to complete a given developmental stage. High temperatures thus accelerate growth and earliness. This assumption probably holds in the English climate, where the daily mean temperatures range from 10° to 17°C, but not in California where the range is 15° to 30°. The fact that the growing season in Gilat is not shorter than in Akko supports the assumption that daily mean temperatures above 25° to 27° do not advance growth at all stages and do not shorten the growing season (2, 14).

A comparison between 3 methods of prediction, namely, the daily mean system, Allen's model, and our own TOMMOD model, reveals that the TOMMOD model has a number of ad- (Table 4). Its main advantage lies in predicting the length of the period from flowering to harvesting. Warnock and Isaacs (14) reported reduced rates of development during fruit setting and ripening in an especially warm year. The prediction gained precision by using a quadractic formula, with an optimum at 26°C, for calculating physiological days during this stage, is supported by previous reports (2, 14).

Water stress during the last stage accelerates ripening. Our results suggest that by controlling the water status of the soil, it is possible to control the ripening rate and hence the date of harvesting.

Using the TOMMOD model, the emergence date can be predicted with a precision of 2–3 days. Variability in the results is mainly a function of the response of the emerging seedlings to soil temperature, soil moisture, soil aeration, depth of planting, and soil compaction. Further data on these parameters and their incorporation into a mathematical model could improve emergence date prediction.

Prediction of flowering date also has a relatively wide precision range. It is known that low night temperatures during the vegetative growth stage can result in early blooming, but no quantitative information exists and it is therefore difficult to include in a computer program.

Prediction of the harvesting date on the basis of data from 44 fields shows a mean accuracy range of 3–4 days (Fig. 3). This range of precision is narrow enough to improve projection of weekly supplies of tomatoes to factories. Studies of the effects of other parameters, such as fertilizing, radiation, and translocation of assimilates could improve precision in simulating plant growth.

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J. Amer. Soc. Hort. Sci. 111(1):16–20. 1986.

Effect of Night Interruption on Cold Acclimation of Potted 'Concord' Grapevines

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Additional index words. hardiness, *Vitis labruscana*, root conductance

Abstract. **Two photoperiod regimes, natural daylength (ND) and night interruption (NI) of ND with a white light source, were used to test the importance of photoperiod on growth parameters, cold acclimation, and root conductance of potted 'Concord' grapevines (*Vitis labruscana* Bailey). By 3 Sept., NI-treated plants had a greater percentage of shoots with actively growing apices and a greater number of nodes per shoot than those untreated. No differences were seen in effect of light treatment on the extent of shoot maturation, as evidenced by shoot color change from green to brown. No consistent differences in hardiness of primary buds or canes of the first 12 nodes could be attributed to light regime. Apical tissues were less hardy than basal tissues for all regimes early in the acclimation period (10 Sept.). Root conductance, measured as suction-induced water flow, decreased throughout the acclimation period but did not differ between light treatments. Results are discussed in light of current hypotheses and of evidence of interrelationships among photoperiod, shoot growth cessation, shoot maturation, and cold acclimation.**

Reports on dogwood and other woody plants have suggested strongly that the first stage of cold acclimation is initiated by short days (SD) (6, 20) and mediated by phytochrome (13, 22). Leaves are the site of reception (6, 9) and must be present to facilitate full hardening (6). SD leaves produce a hardiness promoter (5) and long day (LD) leaves produce a hardiness inhibitor (11). Plants split between the inductive (SD) and noninductive (LD) photoperiods are intermediate in hardiness (8), suggesting an interaction of regulators rather than a single override control mechanism.

An important aspect of cold acclimation appears to be the SD-induced decline in tissue water content (14), a portion of which results from pith senescence and dehydration (3, 14). McKenzie et al. (14) and Parsons (15) claim overall plant water decline may be facilitated, or even controlled, by increased root resistance and decreased stomatal resistance. If root suberization is the cause of increased resistance to water flow, then it may account for observations that plants acclimate regardless of the amount of water present in the root environment (16, 21). This is likely a too simplistic explanation in view of reports that water stress can promote (4) and inhibit (19) cold acclimation.

Previous research on cold acclimation of 'Concord' grapevines has detailed the close relationship of acclimation to tissue maturation and loss of water (24), but whether SD photoperiod can trigger the initiation of these events is not known. Shoot growth cessation in grapevines is not brought about by the formation of a terminal bud, as in other woody plants, thus the need for growth cessation as a prerequisite for cold acclimation has not been shown. Although tissue water loss is related closely to the first stage of acclimation in grapevines, the involvement of roots and their resistance to water uptake has not been investigated.

The objectives of this study were to investigate whether night interruption would delay the importance of photoperiod cold acclimation of grapevines and to determine if root resistance plays a role in the process.

Materials and Methods

'Concord' plants were used in this study. They were purchased in 1980 from a commercial nursery as 1-year-old rooted cuttings and planted singly into 11 liter plastic pots containing a steam sterilized medium of 1 loam soil : 1 sand : 1 peat (by volume). Plants were thinned to 2 shoots per pot, tied to bamboo stakes, and grown without treatment throughout the year. After fall frost, plants were transferred to a protected lathhouse and mulched over winter. In spring of 1981, 55 vines were assigned at random to each of 2 blocks and equally spaced on a 5 m × 15 m flat concrete area. Plants were trained to 2 shoots, 1 on each of the 2 branches which grew the previous year, tied to

Received for publication 7 May 1984. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

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