Int J Biometeorol (1999) 42:177–182

METHODS IN PHENOLOGY

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Determining degree-day thresholds from field observations

Received: 26 May 1998 / Accepted: 28 October 1998

Abstract This paper compares several methods for determining degree-day (°*D*) threshold temperatures from field observations. Three of the methods use the mean developmental period temperature and simple equations to estimate: (1) the smallest standard deviation in °*D*, (2) the least standard deviation in days, and (3) a linear regression intercept. Two additional methods use iterations of cumulative °*D* and threshold temperatures to determine the smallest root mean square error (RMSE). One of the iteration methods uses a linear model and the other uses a single triangle °*D* calculation method. The method giving the best results was verified by comparing observed and predicted phenological periods using 7 years of kiwifruit data and 10 years of cherry tree data. In general, the iteration method using the single triangle method to calculate °*D* provided threshold temperatures with the smallest RMSE values. However, the iteration method using a linear °*D* model also worked well. Simply using a threshold of zero gave predictions that were nearly as good as those obtained using the other two methods. The smallest standard deviation in °*D* performed the worst. The least standard deviation in days and the regression methods did well sometimes; however, the threshold temperatures were sometimes negative, which does not support the idea that development rates are related to heat units.

Key words Growing degree-days · Kiwifruit · Cherry trees · Phenology · Threshold temperature

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Introduction

Heat units are often used to predict the rate of phenological development of plant species. Developmental rates increase approximately linearly as a function of air temperature, and heat units are a measure of the time duration at various temperatures. Therefore, heat units [e.g., degree-hours or degree-days (°*D*)] are used to quantify phenological development.

One degree-hour is observed when the air temperature is one degree above a lower threshold temperature for 1 h. Development rates are assumed to be insignificant when the air temperature is below the threshold. If the temperature is more than one degree above the threshold temperature for 1 h, then the number of degree-hours equals the observed air temperature minus the threshold temperature. Therefore, a bigger difference between the air and threshold temperature implies more degree-hours and a faster developmental rate. °*D* are calculated as the total degree-hours for a day, divided by 24.

For some organisms, there is also an upper threshold temperature, above which no further increase in development rate is expected. If an upper and lower threshold temperature are both known, then one °*D* is equivalent to having one degree of temperature over a 24-h period above the lower and below the upper threshold temperature. With hourly data, one could calculate °*D* by subtracting the lower threshold from the observed hourly temperature or upper threshold, whichever is smallest, and dividing the sum by 24 h. Although using hourly weather data offers the greatest accuracy for estimating °*D* values, daily maximum (T_x) and minimum (T_n) temperature data are often used to estimate °*D* by approximating the diurnal temperature trends. A thorough review of the methods available for estimating °*D* with daily data was reported by Zalom et al. (1983).

Although many methods for estimating °*D* from daily data have been reported, a method for evaluating the best threshold temperatures has not received widespread acceptance. For example, Yang et al. (1995) evaluated threshold temperatures using the standard deviation of cumulative °D (°D_c; Magoon and Culpepper 1932; Stier 1939), the standard deviation of days (SD_{day}; Arnold 1959), and the regression method of Hoover (1955). In the Yang et al. (1995) paper, the authors ignored the upper threshold temperature and they used a simple linear model for °D that can provide inaccurate estimates on days when the threshold temperature falls between T_x and T_n.

In practice, °D should be calculated on a daily basis to properly account for lower and upper threshold temperatures. In the Yang et al. (1995) paper, the developmental period mean daily temperature as used to estimate a cumulative °D value as the period mean minus the threshold temperature (x) multiplied by the number of days in the period. They used this model to derive equations to evaluate threshold temperatures without the need for iteration. While this is a creative and simple approach to estimating °D, some error is likely to occur because the heat units are underestimated on days when the threshold is between T_x and T_n, and the °D values are negative on days when the threshold is higher than T_m. This may not be a problem if the threshold temperature is generally lower than T_n during the entire developmental period.

Ring et al. (1983) used the same linear model for °D as Yang et al. (1983), but they calculated daily values and they set the °D equal to zero when the threshold was higher than T_m. This is more accurate than the method of Yang et al. (1995), but there are still some errors when the threshold is above T_n. Ring et al. (1983) used an iterative technique to determine the threshold temperature, giving the best prediction of observed days within a growth period. The most accurate approach for estimating daily °D is to use a method that accounts for thresholds that fall between the daily T_x and T_n (Zalom et al. 1983).

In the paper presented here, several methods to determine °D thresholds were tested using several years of phenological observations for kiwifruit and cherry tree development. An iteration method to determine the smallest root mean square error (RMSE) between observed and predicted number of days was used to evaluate the best lower and upper threshold temperatures using the single triangle method of Zalom et al. (1983) to calculate daily °D. The second method was used by Ring et al. (1983). It also uses an iteration technique to determine the threshold (x); however, the daily °D estimates are calculated as °D=T_m–x, where °D=0 when T_m<x. The third method used the equations from Yang et al. (1995) to calculate the threshold (x). One of the equations from Yang et al. (1995) identifies the x value giving the smallest standard deviation of °D (SD_{dd}), as proposed by Magoon and Culpepper (1932). The second equation finds the x value giving the least SD_{day} as suggested by Arnold (1959). The third equation uses the regression method of Hoover (1955) to identify the x value having the slope of the regression of °D_c versus the T_m equal to zero. The Yang et al. (1995) °D model is the same as that of Ring et al. (1983) except that the °D value is not set equal to zero when °D<x.

Methods

Computing daily °D

In this paper, °D were calculated using one of three methods. The first method was presented by Yang et al. (1995). They defined a case as one season of phenological development and calculated the total °D_c or [f_i(x)] as a function of the threshold temperature (x) for the i^{th} case as:

$$f_i(x)=(T_i-x)d_i \tag{1}$$

Here, T_i is the sum of the daily mean temperatures (ΣT_m) divided by the number of days in the i^{th} case (d_i), and x is the threshold temperature. Using this equation simplifies the methodology to determine the threshold temperature, but it introduces some error because the linear °D model underestimates heat units with $T_n<x<T_x$, and it has negative values when $x>T_i$.

The second method was presented by Ring et al. (1983). In this method, they calculate °D on a daily basis and add up the daily values during the developmental period to determine the total °D_c for each case. The daily °D are calculated as:

$$°D=T_m-x, \tag{2}$$

where

$$T_m=\frac{T_x+T_n}{2} \tag{3}$$

Whenever, the T_m is less than the threshold ($T_m<x$), the °D are set equal to zero (°D=0).

The third method is the single triangle method that is described by Zalom et al. (1983). In that method, °D are calculated on a daily basis as:

$$°D=0 \text{ when } x \geq T_x \tag{4}$$

$$^oD=\left(\frac{T_x-x}{2}\right)\left(\frac{T_x-x}{T_x-T_n}\right) \text{ when } T_n<x<T_x \tag{5}$$

$$°D=T_m-x \text{ when } x \leq T_n \tag{6}$$

It is assumed that development is negligible when the temperature is below the lower threshold and that there is no further increase in developmental rate when the air temperature is above an upper threshold temperature. Therefore, °D between two thresholds are calculated as the difference between °D above the lower threshold and that below the upper threshold.

Determining thresholds

Several methods were used to determine the best threshold temperatures for °D calculations and estimating development. Three of the methods used equations from Yang et al. (1995). The methods include: (1) the smallest SD_{dd} from the mean observed °D_c from Magoon and Culpepper (1932), (2) the least SD_{day} from the mean observed number of days in the period from Arnold (1959), and (3) the regression method from Hoover (1955). Two additional methods that were tested use iterations of the threshold temperature(s) and °D_c to calculate the sum of daily °D to determine the smallest RMSE in days from the observed number of days for all cases. Daily °D were calculated using the linear method of Ring et al. (1983), or °D were calculated using the single triangle method of Zalom et al. (1983). In this paper, the methods are called "Iteration" for Ring et al. (1983) and "Triangle" for Zalom et al. (1983). The results of all models were also compared with developmental predictions using an assumed threshold of x=0. This is referred to as the "Zero" method. In total, there are comparisons of six different methods.

Smallest SD_{dd} method

Yang et al. (1995) reported equations to determine threshold temperatures from field-measured phenological data without the need for daily °D calculations. They used Eq. 1 to calculate the total °D_c [°D_c=$f_i(x)$]. Then the SD_{dd} is calculated as:

$$SD_{dd} = \sqrt{\frac{\sum\left[f_i(x) - f(x)\right]^2}{n-1}} \tag{7}$$

Here, $f(x) = \frac{\sum f_i(x)}{n}$ is the mean of the cumulative °D for all cases and n is the number of cases. They differentiate this equation with respect to x and set the derivative equal to zero to find the inflection point where the slope is zero.

$$x = \frac{\sum T_i d_i \sum d_i - n \sum d_i^2 T_i}{(\sum d_i)^2 - n \sum d_i^2} \tag{8}$$

This value for the lower threshold (x) is the lowest possible value for the SD_{dd}.

Least SD_{day} method

Yang et al. (1995) calculated the least SD_{day} using Eq. 1. Because the mean number of °D per day can be approximated as T–x, where $T = \frac{\sum T_i}{n}$ is the overall mean temperature of all cases, the SD_{day} is calculated as:

$$SD_{day} = \frac{SD_{dd}}{T - x} \tag{9}$$

Again, the smallest standard deviation is found by differentiating the equation with respect to x and setting the derivative equal to zero. Then the equation is solved for x as:

$$x = T - \frac{(\sum t_i d_i)^2 - n \sum t_i^2 d_i^2}{n \sum t_i d_i^2 - \sum t_i d_i \sum d_i} \tag{10}$$

Here, t_i=T–T_i and T_i is the mean temperature for the i^{th} case.

Linear regression method

Yang et al. (1995) also used the regression method from Hoover (1955). In this method, the total °D_c [°D_c=$f_i(x)$] are again calculated using Eq. 1. The resulting °D_c values are plotted versus the T_m during the corresponding developmental stages. A value for x is found by iterating until the slope of a linear regression line (b) equals zero. Yang et al. (1995) used the equation for the slope of a regression line set equal to zero. They solved for (x) as:

$$x = \frac{\sum T_i \sum d_i T_i - n \sum d_i T_i^2}{\sum d_i \sum T_i - n \sum d_i T_i} \tag{11}$$

Iteration method

Both the standard deviation of °D_c about the mean [$f_i(x)$ about $f(x)$] and the standard deviation of number of days about the mean [dp_i about d_m] are commonly used to evaluate threshold temperatures. However, because the aim is to accurately estimate days in the development period of each case, minimizing the RMSE of differences between predicted and observed days in the developmental periods for each case is a better approach.

In practice, when °D are used, daily calculations are accumulated until the sum exceeds some predetermined °D_c value, which is assumed to be independent of T_m. Therefore, the best method to find the threshold temperatures is to select threshold temperature(s) and increment the °D_c value to find the smallest RMSE of the predicted (dp_i) minus observed (d_i) days over all of the cases using the following equation:

$$RMSE = \sqrt{\frac{(dp_i - d_i)^2}{n}} \tag{12}$$

The procedure is repeated for a range of threshold temperatures until the combination of thresholds and °D_c that gives the smallest overall RMSE is found. The RMSE approach was proposed by Ring et al. (1983). In their paper, a low value for x was assumed and daily values for °D were estimated using Eq. 2. The daily values were added to obtain a value for °D_c for each case. After the °D_c is known for all cases, the RMSE is calculated using Eq. 12. The value for x is incremented by 1.0 and the procedure is repeated for a range of x values. The x value with the smallest RMSE is considered to be the best threshold.

Triangle method

In the single "Triangle" method (Zalom et al. 1983), an iteration procedure is used to estimate both lower and upper threshold temperatures. Starting low values for °D_c and the lower and upper threshold temperatures, daily °D values are calculated and summed from the beginning date until the °D_c exceeds the target °D_c.The number of days (dp_i) from the beginning date until the °D_c exceeds the target is noted for each case. When dp_i is known for all cases, the RMSE of the difference between the dp_i and the observed number of days (d_i) is determined. If the new RMSE is smaller than the previous value, then the selected °D_c value is incremented by 5.0 and the procedure is repeated. If the RMSE for the current °D_c is greater than for the previous °D_c, then the previous °D_c value is the best predictor for that set of threshold temperatures. This procedure is repeated for a range of both lower and upper thresholds until the overall smallest RMSE is identified.

Lower threshold equals zero method

In addition to the methods presented by Yang et al. (1995), °D were also calculated assuming x=0 as a comparison with the other methods.

Phenological data

Seven years (1987–1994 w/o 1991) of phenological data were collected from kiwifruit grown near Tempio, Sardinia, Italy. In this paper, two stages were used to evaluate the °D thresholds. The first stage was "Bloom", which is from January 1 until bloom. The second stage was "Harvest", which is from bloom to harvest.

Phenological data for cherry trees were also studied. The dates from bloom to ripening were observed for three cherry tree varieties during 1987 through 1996 near Sassari, Sardinia, Italy. The varieties were: (1) Burlat C1, (2) Burlat, and (3) Forli.

Results and discussion

To ensure that the equations of Yang et al. (1995) work properly, the °D were calculated daily using the linear equation (Eq. 1) for a range of threshold temperatures from x=0 to near the maximum for the period. °D values were accumulated and the SD_{dd} was computed for each threshold temperature. SD_{dd} values about the mean are plotted versus lower threshold for both January 1 to bloom and for bloom to harvest in Fig. 1. Using Eq. 8, the calculated threshold temperatures were 7°C for Bloom and 12°C for Harvest, so the SD_{dd} equation for determining the smallest standard deviation worked well.

Similar plots were produced for the SD_{day} method (Fig. 2). The values from the SD_{day} equation (Eq. 10) were x=2 and x=–10 for the Bloom and Harvest periods, respectively. Although negative values for the lower threshold are not shown in Fig. 2, it does seem reasonable that the lowest SD_{day} would occur at about x=–10 for the Bloom period. However, it is also clear that the difference in SD_{day} is small over the range of lower threshold values up to about 7°C for Bloom and up to about 12°C for Harvest. Consequently, selecting a higher threshold temperature gives acceptable values for the SD_{day}. The negative x value for the Harvest period from Eq. 10 most likely results from use of the linear equation for °D without accounting for when x is higher than the T_m.

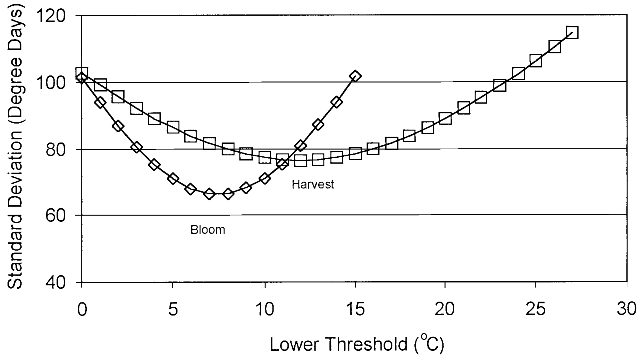

Fig. 1 Standard deviation in degree-days about the mean versus threshold temperature for kiwifruit. Bloom (*open triangles*) represents the period from January 1 to bloom, and Harvest (*open squares*) represents the period from bloom to harvest. Degree-days were calculated using the method of Yang et al. (1995)

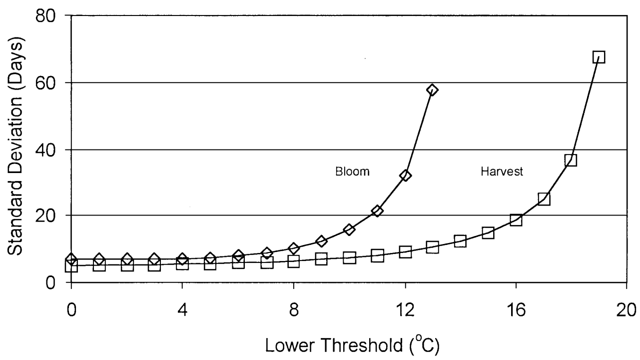

Fig. 2 Standard deviation in days about the mean versus threshold temperature for kiwifruit. Bloom (*open triangles*) represents the period from January 1 to bloom, and Harvest (*open squares*) represents the period from bloom to harvest. Degree-days were calculated using the method of Yang et al. (1995)

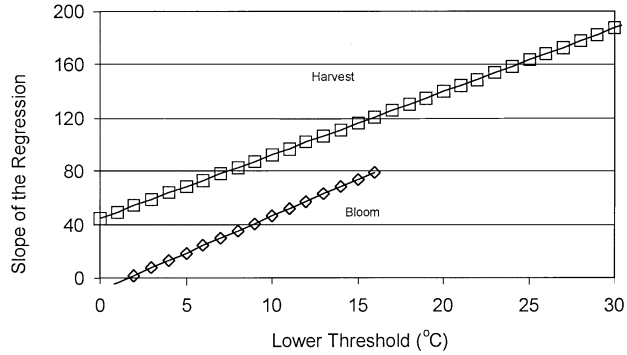

Fig. 3 Slope of the linear regression of $f_i(x)$ versus mean daily temperature (T_i) for the developmental period plotted versus threshold temperature for kiwifruit. Bloom (*open triangles*) represents the period from January 1 to bloom, and Harvest (*open squares*) represents the period from bloom to harvest. Degree-days were calculated using the method of Yang et al. (1995)

Figure 3 shows a plot of the slopes of the regression lines of $f_i(x)$ versus (T_i) against the threshold (x) for the Bloom and the Harvest periods. Recall that $f_i(x)$ and T_i are the °D_c and mean daily temperatures for the i^{th} developmental period. Using the regression method equation (Eq. 11), the best threshold temperatures were x=2 and x=–9 for the Bloom and Harvest periods, respectively. Since Eq. 11 is used to identify the x value at which the slope intersects the x-axis, it seems that Eq. 11 works

Table 1 Best threshold temperatures by period and calculation method, observed and predicted days within the developmental periods, mean cumulative degree days (°D_c), and root mean square errors (RMSE) between observed and predicted days for kiwifruit grown near Tempio, Sardinia (Italy). The developmental periods are: (1) Bloom = January 1 to bloom, and (2) Harvest = bloom to harvest. Mean temperatures were 14.5°C from January 1 to bloom and 20.3°C from bloom to harvest during the 7-year trial. The observed number of days in the developmental periods were 66.4±10.2 and 144.0±5.7 for the January 1 to bloom and bloom to harvest periods, respectively. (SD_{dd} Standard deviation in degree-days, SD_{day} standard deviation in days, dp is the mean predicted number of days for the development period ($\Sigma dp_i/n$), σ_{dp} is the standard deviation of the predicted number of days for the development period)

Period	Method	Lower	Upper	dp	σ_{dp}	°D_c	RMSE
		°C	°C	Days	Days	°D	Days
Bloom	SD_{dd}	7	–	66.9	11.4	499	5.2
	SD_{day}	2	–	66.3	8.1	831	4.7
	Regression	2	–	66.3	8.1	831	4.7
	Zero	0	–	66.4	7.5	964	4.8
	Iteration	8	–	66.7	4.2	470	4.2
	Triangle	2	28	65.6	8.1	800	4.7
Harvest	SD_{dd}	12	–	149.3	33.2	1192	31.6
	SD_{day}	–10	–	144.0	3.7	4360	6.0
	Regression	–9	–	144.0	3.7	4216	6.0
	Zero	0	–	144.9	7.3	2920	8.4
	Iteration	2	–	139.3	6.7	2565	8.8
	Triangle	0	27	142.1	4.8	2815	6.7

Table 2 Best threshold temperatures by variety and calculation method, observed and predicted days within the period, °D_c, and RMSE between observed and predicted days during bloom to ripening for the Cherry tree varieties Burlat C1, Burlat, and Forli grown in Sardinia (Italy). Overall mean temperatures during the periods were 14.2°, 14.4°, and 14.9°C for Burlat C1, Burlat, and Forli, respectively. The observed number of days in the developmental periods were 51.6±6.5, 48.4±7.8, and 52.0±9.4 for Burlat C1, Burlat, and Forli, respectively

Variety	Method	Lower	Upper	*dp*	σ_{dp}	°D_c	RMSE
		°C	°C	days	Days	°D	Days
Burlat C1	SD_{dd}	3		51.9	7.5	578	3.5
	SD_{day}	–3		51.5	5.5	887	2.8
	Regression	–3		51.5	5.5	887	2.8
	Zero	0		51.7	6.3	732	2.9
	Iteration	1		50.7	6.6	650	3.0
	Triangle	3	14	51.7	5.7	460	2.7
Burlat	SD_{dd}	5		49.0	9.0	455	3.7
	SD_{day}	1		48.6	6.8	649	3.1
	Regression	0		48.6	6.6	697	3.0
	Zero	0		48.6	6.6	697	3.0
	Iteration	4		47.7	7.8	475	3.0
	Triangle	7	13	48.2	7.9	230	2.4
Forli	SD_{dd}	8		52.7	11.0	361	5.6
	SD_{day}	2		52.3	7.6	673	4.4
	Regression	1		52.4	7.0	725	4.3
	Zero	0		52.4	6.8	777	4.4
	Zero	0		52.4	6.8	777	4.4
	Iteration	3		51.2	8.0	585	4.3
	Triangle	6	16	52.4	8.5	380	4.2

well. However, again a negative *x* value was identified for the Harvest period.

Kiwifruit

Table 1 shows a comparison of all methods to determine the best threshold temperature(s) for the kiwifruit. The RMSE values indicate how closely the predicted days in the developmental periods match with the observed number of days. For the Bloom period, the Iteration method gave the smallest RMSE; however, all of the methods gave good RMSE values. Big differences were noted for the Harvest period. The SD_{dd} method performed poorly for the Harvest period, whereas the SD_{day} and regression methods gave the *x* values with the smallest RMSE. However, the negative thresholds for the SD_{day} and regression methods do not fit well with the basic concept of heat units. Of the methods with positive threshold values, the Triangle method performed best. However, the additional error from using either the Zero or Iteration methods was small.

Cherry trees

The cherry tree data were analyzed similarly to the kiwifruit data. The overall results are shown in Table 2. In this study, only the period from bloom to ripening was observed for the three varieties. Table 2 shows that the SD_{dd} method predicted development less well than the other methods. The Triangle method did the best overall, although the RMSE differences were small. However, the upper threshold temperatures were close to the mean period temperatures in all cases. This means that including heat units above the T_m did not improve the prediction of number of days in the developmental period. Again, some negative threshold values for *x* were observed for SD_{day} and regression methods.

Conclusions

Based on the kiwifruit and cherry tree results, the Triangle method for determining threshold temperatures provided the smallest RMSE in most instances. However, for the cherry tree data, the identified upper threshold temperatures were close to the period mean temperature, so heat units above the mean were not improving the prediction. The Iteration method of Ring et al. (1983) method generally provided good predictions; however, simply using a threshold temperature of x=0 gave results that were nearly as good. The equations for estimating the threshold temperatures that were reported by Yang et al. (1995) sometimes did well and sometimes did poorly at predicting days for development. In general, using the SD_{dd} was the worst method. The SD_{day} and the regression methods performed well in many instances, but the threshold temperatures were sometimes negative. Although there is nothing wrong with using negative threshold temperatures in terms of modeling phenological development, there is little physiological basis for why negative thresholds should work. However, based on the curves of SD_{day}, considerably higher threshold temperatures provide predictions of similar accuracy. In conclusion, it seems that either using the Iteration method suggested by Ring et al. (1983), or simply using x=0 provides low RMSE values for predicting the number of days in a growing period.

Acknowledgements The authors thank Dr. Sandro Dettori, from the University of Sassari, Istituto di Coltivazioni Arboree for providing the cherry tree phenological data. This experiment complies with current laws of the United States of America.

References

Arnold CY (1959) The development and significance of the base temperature in a linear heat unit system. Proc Am Soc Hort Sci 74:430–445

Hoover MW (1955) Some effects of temperature on the growth of southern peas. Proc Am Soc Hort Sci 66:308–312

Magoon CA, Culpepper CW (1932) Response of sweet corn to varying temperatures from time of planting to canning maturity. USDA Tech Bull 312

Ring DR, Harris, MK, Jackman JA, Henson JL (1983) A Fortran computer program for determining start date and base temperature for degree-day models. The Texas Agricultural Experiment Station Bull MP-1537, The Texas University System, College Station, Texas

Stier HS, 1939. A physiological study of growth and fruiting in the tomato (*Lycopersicon esculentum* L.) with reference to the effect of climatic and edaphic conditions. Ph.D. Dissertation, University of Maryland, College Park, MD, USA

Yang, S, Logan J, Coffey DL (1995) Mathematical formulae for calculating the base temperature for growing degree-days. Agric For Meteorol 74:61–74

Zalom FG, Goodell PB, Wilson LT, Barnett WW, Bentley WJ (1983) Degree-days: the calculation and use of heat units in pest management. University of California DANR Leaflet 21373