6-1983

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Pruess, Kenneth P., "Day-Degree Methods for Pest Management" (1983). *Faculty Publications: Department of Entomology*. 689.
http://digitalcommons.unl.edu/entomologyfacpub/689

Published in *Environmental Entomology* 12:3 (June 1983), pp. 613–619; doi: 10.1093/ee/12.3.613

Submitted July 23, 1982; accepted November 18, 1982.

Day-Degree Methods for Pest Management

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Abstract

Recommendations are made for reporting day-degree methods which may have practical applications. Standardized thresholds (40, 50, and 60°F, or 5, 10, and 15°C) should be used. Day-degrees may be either sine wave approximations or exact units determined by instrumentation. Methods are proposed for converting current day-degree models to standardized thresholds and, ultimately, to actual day-degrees.

Many day-degree (often, perhaps improperly, heat unit) methods have been proposed for predicting insect development (Taylor 1981). The purpose of this paper is to suggest reporting and computational procedures which will enhance present and future practical applications of day-degree models. Toward that end, I am presenting a review of existing methods for calculating day-degrees. Then I will discuss proposals for a standardized day-degree model and methods for converting existing models to that standard. My intent is not to criticize specific models but to make comments which I feel apply to most day-degree models. Recent volumes of this journal contain many articles which could be used to support almost any desired argument, and I will cite only selected papers, obviously chosen to support my viewpoint.

Recent models for insects usually employ sine wave approximations of day-degrees above precisely defined thresholds (bases). Models typically deal with a single species, and authors often suggest excellent predictability. Although attempts have been made to compile data in a form that can be used for multiple pests (Butler and Henneberry 1976), at this time it appears that only computer-based programs (Welch et a1. 1978) use day-degree methods when multiple pests are involved. Why?

Agronomists have found many practical applications for simple, imprecise (in the sense that actual day-degrees are not used) methods (Neild and Seeley 1977). For plants, sine wave estimates are commonly used only in theoretical models (Stapleton et al. 1973); even if sine wave estimates are used for modeling physiological processes, simpler methods may be used in the model for predicting crop phenology (Schreiber et al. 1978, Tscheschke and Gilley 1979). I am not suggesting that agronomists are either less precise or more practical than entomologists. But if day-degrees are to achieve their potential for practical applications, some compromise may be necessary between precision and utility. Pest management involves interactions between insects and their hosts, with duration and timing of those interactions often of major concern. If day-degrees are the best mechanism for predicting those interactions, then it would seem desirable that similar models be used for both insects and plants. Is this possible?

There are excellent reasons why all proposed insect development models have not found practical applications. One reason may be that they provide no more accuracy than the use of calendar dates. Even models which appear to offer a dramatic increase in predictability often are not compared with calendar date predictions. Most models have been developed from limited data, often from a single location, and may not hold at other locations. An agronomic crop, selected by humans, is likely to respond more similarly to temperature wherever grown than insects which may have a genetically based geographical gradient in their response to climate (Tauber and Tauber 1976). However, it is not the possible invalidity of insect development models which is disturbing but rather the meager evidence that validation has even been attempted.

A primary limiting factor to both application and validation may be the very complexity of many models. For example, models based on microenvironmental day-degrees, no matter how accurate, may not be used because comparable temperature data are unavailable at other locations. Use of the sine wave approximation, and a different threshold for each insect, do not tempt many potential users to test models. Even with the aid of a computer program (Allen 1976), computations are time-consuming if many different estimates are required. Pest management is not an exact science, and practitioners must accept errors in almost all other tools employed (e.g., scout sample data). New techniques are readily adopted only if affording increased precision at little or no increase in cost. Welch et al. (1981) make an eloquent argument (with which I concur) that we may not have implemented models already adequate for many pest management purposes because of demands by researchers on an unattainable, and unneeded, degree of accuracy.

Admittedly, there may be good reasons why imprecise predictors of actual day-degrees will work for plants but even the most precisely computed models fail for insects. But I believe day-degree models do have a place in pest management. I also believe there are acceptable models for both insects and plants and that those models may be identical. To reach a stage of full compatibility will require some compromise, but that compromise will not be based on either utility or precision, yet will incorporate both. It will not be achieved by some process of arbitration but dictated on specified terms. This model will arise from the rapid increase in automated weather stations that can provide actual day-degrees computed by using a few standardized thresholds. As entomologists, we have nothing to fear from this technology; many of us already use such equipment. In anticipation of the future, I suggest we explore means of preparing day-degree models compatible with both immediate validation and application as well as future technology.

Methods for Computing Day-Degrees

Many methods have been devised for computing day degrees. I will limit this discussion to a few in common use or recently proposed. There are good reasons for the development and application of each method, ranging from strictly utilitarian to the ultimate in mathematical precision (unfortunately, not synonymous with biological predictability). We might consider these models to represent an evolutionary sequence.

Historical Method

Day-degrees accumulated on a single day are computed simply as the difference between the arithmetic mean temperature, (max + min)/2, and the threshold. Authors variously refer to this as the historical, simple, or mean-minus-base method. Most practical applications use only two thresholds, 40°F for cool-season (alfalfa, wheat) and 50°F for warm-season (com, sorghum) crops.

For many crops, much of the total development occurs during a portion of the year when minimum temperatures are above the assumed threshold. Under this condition, computed day-degrees are identical to sine wave estimates, and no precision is lost. Days on which actual accumulations are underestimated contribute so little to total plant development that loss in precision is negligible.

Weather Bureau (86/50) Method

This modification of the historical method recognizes both a lower and upper threshold for crop development and assumes that some crop growth occurs on days when the mean temperature is below the threshold so long as the maximum is above. Often called the 86/50 method, temperatures below 50 or above 86°F are simply set at those limits, and computation is otherwise identical to the historical method. Initially developed for rating maturity of corn varieties, this method has been adopted for computation of growing degree-days reported in Weekly Weather and Crop Bulletin (U.S. Department of Commerce 1969).

This method somewhat overestimates actual day-degrees when the daily temperature curve intersects the assumed threshold, whereas the historical method underestimates under that condition. The major advantage is that this method recognizes an inhibition of crop growth during hot weather. It is unimportant that it may not be temperature itself but moisture stress or other factors associated with high temperatures that cause this inhibition.

Sine Wave

This method assumes that the daily temperature curve approximates a sine wave and, like the 86/50 method, recognizes that development may occur if only a portion of the day lies above the threshold. For most locations it more closely estimates actual day-degrees than the preceding methods if the minimum temperature is below the threshold. If temperatures are between the thresholds, the sine wave provides estimates identical to the preceding methods. For an excellent discussion of the method and computational procedures, see Allen (1976).

The primary advantage of this method is for organisms responding to temperature during the spring in temperate climates. Such is the case for many insects and a logical argument for the use of this method by entomologists. Entomologists take pride in precise definition of developmental thresholds, a wide array of which are in use or proposed. Without a computer, computation is not easy, but tables have been published for specific thresholds (Wedburg et al. 1977).

Bias-Corrected Sine Wave

It has long been recognized that the sine wave is only an approximation of actual day-degrees and that the bias in those estimates varies geographically. For a lucid description of the problem and a possible solution, see Allen (1976). The problem will be further dealt with in this paper. The major difficulty lies not in methodology but in lack of published information from which accurate bias correction terms can be calculated. Bias correction may be necessary in the near future, not because it will provide significantly better predictions, but because presently used day-degrees will need to be transformed to actual day-degrees to make use of predictions developed using past technology.

Actual Day-Degrees

Previously discussed methods only estimate, with varying degrees of precision, actual day-degree accumulations. With the increasing establishment of automated weather stations, usually with the ability to integrate temperatures at frequent intervals above several thresholds, I anticipate that actual day-degrees will soon be reported for selected base temperatures for many locations. These values will not be precisely the same as those currently used by either agronomists or entomologists, but for practical purposes, should be used by both disciplines.

Response of Organisms to Temperature

I am using the term "actual," or "true," day-degrees in a mathematical sense only. Methods discussed in this paper make the assumption that developmental rates are proportions to temperature above the threshold. This assumption is often false, and models have been constructed for nonlinear responses (Logan et al. 1976). At this time, their use seems limited to theoretical simulations. Even if temperature responses are nonlinear, good predictions for practical applications may be obtainable by using linear models by judicious choice of effective, rather than true, developmental thresholds. The Weather Bureau (86/50) method is a good example of the use of a linear model for dealing with the nonlinear development of com (Newman 1971). I strongly suspect that many precisely defined thresholds, empirically derived, do not represent true developmental thresholds, and the incorporation of this unintended error is in fact necessary to the use of a linear development model.

As additional factors are determined which influence the response to temperature, practical solutions become more difficult. Some crops (corn and soybeans) are known to differ in growth during the photophase vs. scotophase, and Canadian workers often use the so-called Brown or Ontario method (Aspiazu and Shaw 1972, Brown 1960). The added computation, though not difficult, combined with only a slight gain in predictability, has militated against wider adoption of this method. Future models may well deal more precisely with additional factors influencing development rates, but too few data on either insects or crops are available at this time to justify further consideration in this paper.

Starting Date for Accumulation

Agronomists working with annual crops commonly use the planting date as a precise time at which to begin day-degree accumulations. Insect models which employ observations on one active growth stage to predict some future stage are usually quite successful. But many models of potential value lack information as to when development after dormancy begins. Thus, it is common practice to select arbitrary dates, often 1 January or 1 March, on which to begin accumulation. If the latter date is used, the justification is that day-degree accumulation before that date is negligible. Seldom is a biological basis cited. Mistakes in choice of starting date, though perhaps unavoidable, may be a major source of error in current models. This error cannot be corrected by mathematically precise day-degree calculations.

Methods

To investigate the feasibility of converting day-degrees as currently computed to a standardized method (to be proposed), a data set was obtained from National Weather Service (U.S. Department of Commerce 1963). Data from 1963 were used, because hourly temperatures were then reported for many stations. Locations used were Phoenix, Arizona; Orlando, Florida; Lansing, Michigan; and North Platte, Nebraska. The first three stations were chosen to provide data comparable to that used by Allen (1976). For each station, 60 days were chosen to represent the full temperature regime over which day-degrees for biological purposes would normally be desired. To obtain data bases of equal size, temperatures for alternate months (January to November) were used for the first two stations, each month (March to August) for the latter two. If possible, 10 consecutive days beginning the 17th of each month were used. A few substitutions were made for days on which the maximum temperature did not exceed 40°F, the lowest threshold studied.

Daily and accumulated day-degrees were computed, using all methods previously discussed. Actual day-degrees were computed from hourly temperatures, using the triangulation method of Sevacherian et al. (1977). Temperatures recorded at Mead, Nebraska, at 5-min intervals to the nearest 0.01°C were used to determine the accuracy of the triangulation approximation.

Results and Discussion

Bias Correction

The regression method proposed by Allen (1976) proved a good technique for estimating actual day-degrees from sine wave approximations. Allen and I found similar geographical trends toward over- or underestimation, but coefficients for the regression equations were somewhat different. These differences may have resulted either from microenvironmental differences in our data sets or the methods employed to compute actual day-degrees. Allen's planigraph measurements could result in a small error (< 1%) (Allen, personal communication) of unknown direction because of mechanical bias. In my data set, on a few occasions hourly temperatures did not incorporate the true maximum or minimum reported during the 24-h period. Analysis of data taken at 5-min intervals revealed that this error was also small (± 0.1°C). The triangulation method slightly underestimates day-degrees during the warmer part of the day when the temperature curve is convex but overestimates when the curve is concave. These errors tend to cancel when minimum temperatures are above the threshold, but actual day-degrees may be slightly underestimated when the minimum is below the threshold.

Allen correctly recognized that some improvement in estimating day-degrees for a single day can be achieved by computing day-degrees as the sum of 2 half days having different minimum temperatures. To use a standard sine wave, he made the necessary assumption that each half day was of equal duration. Such is not the case (Fig. 1). From morning low to afternoon high is typically 9 to 10 h; from maximum to the following low is 14 to 15 h. The exact duration varies daily, seasonally, and geographically. Parton and Logan (1981) propose a generalized model for dealing with these problems. A truncated sine wave is used to estimate daytime temperatures, an exponential function for night temperatures. This model may be an alternative to bias correction, but it was not considered in the present study. But the false assumption that each half day is of equal duration results in errors which more or less cancel for the day as a whole, and the estimate for the entire day may actually be better than if correct durations were used. Thus, I concur with Allen that bias correction applied to the day as a whole, rather than its component parts, is a satisfactory procedure.

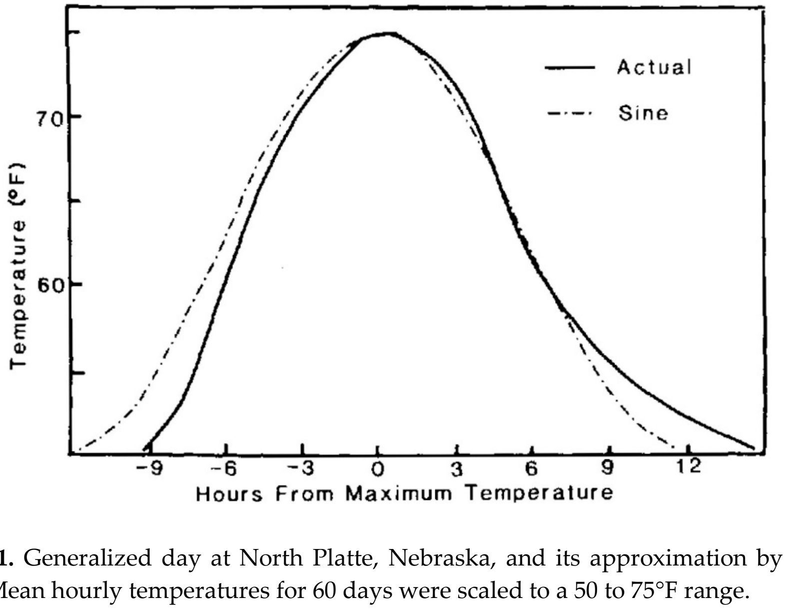

Figure 1. Generalized day at North Platte, Nebraska, and its approximation by a sine wave. Mean hourly temperatures for 60 days were scaled to a 50 to 75°F range.

However, I would argue that no real advantage accrues from computing each part of the day separately. Although the mean prediction for individual days will be slightly improved, and maximum errors reduced, smaller errors may be increased. In 25, 37, 52, and 57% of the observations, bias correction actually gave poorer estimates for Phoenix, Orlando, Lansing, and North Platte, respectively. Over a period of even 3 days, there was no advantage for accumulated day-degrees over those found by using a single high and low for each 24-h period. Although it is not wrong to compute by half days, I am concerned that this extra computation implies a gain in precision which does not exist. If precise day-degrees are required for individual days, I suggest they be found by direct means and not estimated. Bias correction is useful only for accumulated day-degrees, those estimates being significantly improved.

Allen's statement that "deviations will be unaffected by choice of thresholds as long as the threshold does not cut the curve" could prove misleading. He was not computing day-degrees above specific thresholds as is the usual practice, but day-degrees above minimum observed temperature on any day. If the temperature curve does intersect the threshold, deviations may even change in sign, depending on the threshold used (Fig. 2). Since the sine wave is advantageous only under the latter condition, a different set of deviations would be required for each threshold. If desired, a generalized regression equation for each location can be written using the same approach to be suggested for converting to standardized thresholds.

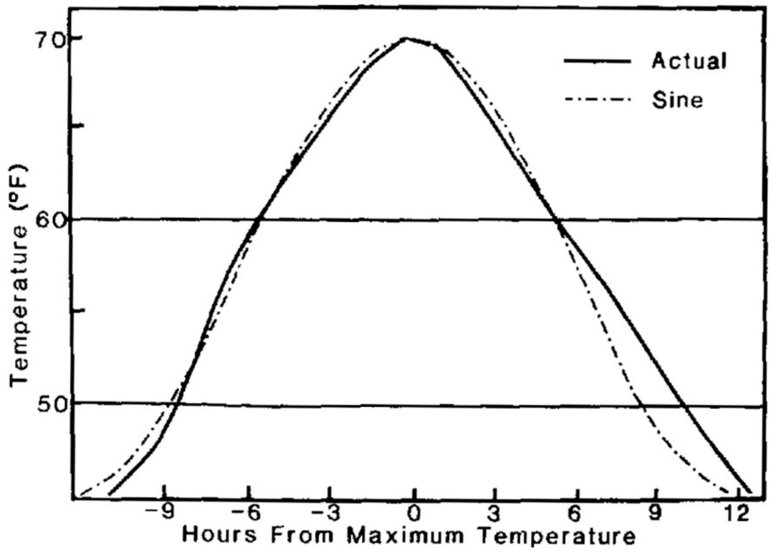

Figure 2. Hypothetical diurnal temperature curve showing overestimation of actual day-degrees by sine wave at base 60°F, underestimation at base 50°F.

How Good Is Bias Correction?

Bias correction is not especially useful for estimating day-degrees for individual days. For accumulated day-degrees over longer time intervals, bias correction, properly applied, will be a potentially useful approach for converting sine wave estimates to actual day-degrees. Because of possible errors (admittedly small), I would not suggest using coefficients found by either Allen or myself in making those corrections.

The ultimate bias correction must be computed by using data obtained from instruments and locations which will be employed in the future to report actual day-degrees. When such data become available, one might say a bias correction is no longer needed. However, by then so many models will have been developed by using current technology that conversion to the new standard will be mandatory if they are to achieve, or maintain, practical applications. There seems no point, however, in applying only approximate conversions at this time. Consequently, I consider bias correction a future rather than immediate need.

Converting to Standardized Thresholds

In the near future it is my belief that not only will we use actual day-degrees but these will also be reported for a few standardized thresholds. Because of existing agronomic applications, 40, 50, and 60°F seem logical candidates for immediate adoption. Since most insect models now use sine wave approximations without bias correction, it would be most convenient to make a direct conversion from an existing base, B_o, to actual day-degrees at the nearest standardized base, B_s.

Using sine wave estimates for bases 40 to 60°F by 2°F intervals, linear regression equations were computed for converting those estimates to actual day-degrees at base 50°F. Conversions for North Platte from 40, 50, and 60°F are shown in Figure 3. All correlations were highly significant ($r^2 > 0.98$). Equal accuracy was found for other locations, but the conversions differed slightly in both intersect and slope. Although it is apparent that linear regression may not provide the best attainable fit for individual observations, errors for accumulated day-degrees would be small.

If a single equation is desired for any possible conversion, this is multivariate. Let the difference between thresholds, D, = $B_o - B_s$. If X = day-degrees at B_o, then actual day-degrees, Y_a, for B_s can be estimated from $Y_a = b_o + b_1D + b_2D^2 + b_3X + b_4DX + b_5D^2X$. For North Platte ($n = 647$, $r^2 = 0.993$, SE = ± 1.31°F) all included parameters were significant ($P < 0.01$) with coefficients $b_o, b_1, \ldots b_5$ = –0.4469, 0.5874, –0.0074, 1.0350, 0.0131, 0.005, respectively. Using the difference between thresholds, D, rather than actual thresholds, effectively removed intercorrelations otherwise inherent in quadratics. Results are shown in Figure 3 for comparison with linear regressions. This analysis included conversions up to ± 10°F. One might expect even better estimation working with changes of base of only ± 5°F, the maximum required to convert to nearest proposed standardized threshold. However, improvement was slight, since most of the error was due to individual days rather than magnitude of the conversion.

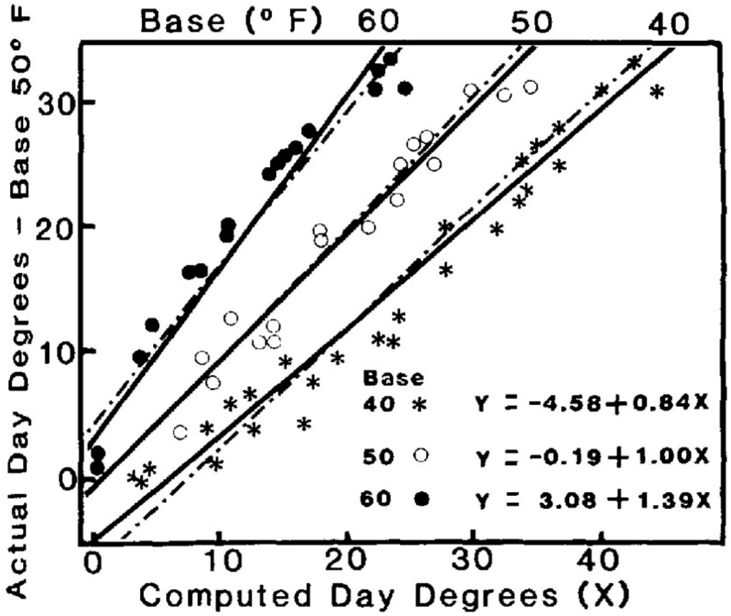

Figure 3. Linear regressions of actual day-degrees (base 50°F) on sine wave estimates at other bases, North Platte, Nebraska. Only observations deviating > ± 1.5 day-degrees from predicted values are plotted. Broken lines show fit to multivariate model.

Even two-step conversions can be made with considerable confidence. One might first convert to a standardized base on the current F° temperature scale and later to the nearest equivalent base in C°. The final conversion would be by a simple linear regression of the form $Y_{a(C^\circ)} = b_o + b_1 X_{a(F^\circ)}$. The simple conversion, C° day-degrees = 5/9 F° day-degrees, applies only if C° is the exact equivalent of F°, the reason being the next problem to be discussed.

In making such conversions, much of the error arises when few, or zero, day-degrees are computed at one base. When converting to a higher threshold, small accumulations will sometimes result in a negative estimate. Theoretically, there might be some justification for summing these negative estimates for computing accumulated day-degrees. From a practical viewpoint, it may be more convenient to set any negative estimates to zero and slightly reduce the accumulated day-degrees required in a prediction. The opposite problem can arise in converting from a higher to a lower threshold. Then zero computed day-degrees at the higher threshold can be a varying number (0 to D) at the lower threshold. These problems arise only under conditions of very small accumulations, and errors may often be biologically unimportant.

Alternative Methods for Present Needs

Although the conversions already suggested can be used solely for changing data to standardized bases, a somewhat simpler regression approach may fulfill applications involving only a change of base. That is to regress accumulated day-degrees, A_s, at a standardized base B_s, on accumulated day-degrees A_o computed at B_o. Such can be done by using only daily maximum and minimum temperatures for a single "typical" year and computing accumulated day-degrees for all bases of interest. Data were used for two dissimilar years at North Platte to test this approach. The spring of 1975 was exceptionally cool with 937 day-degrees accumulated to 30 June at $B_o = 50°F$ (sine wave without bias correction). Accumulation for the same time span in 1963 was 1,300 day-degrees. The generalized equation is $A_s = b_o + b_1A_o + b_2A_o^2$. Regressions, computed from combined data for the 2 years, for converting accumulated day-degrees at $B_o = 40$ and 60°F to $B_s = 50°F$ are shown in Figure 4. Even use of the regression equation derived from 1 year to predict day-degrees for the other year resulted in a maximum error of ± 30 day-degrees (base = 50°F) and only before 150 day-degrees would any error have been greater than 2 days. With a change of base of only ± 5°F, the maximum required to convert to nearest standardized base, this error would have been reduced to 1 day. This quadratic is valid only during that part of the year when minimum temperatures frequently fall below the threshold. If daily minimum temperatures are constantly above both B_s and B_o, a constant, $B_o - B_s$, is added to each daily accumulation to make the conversion, and the regression then becomes linear.

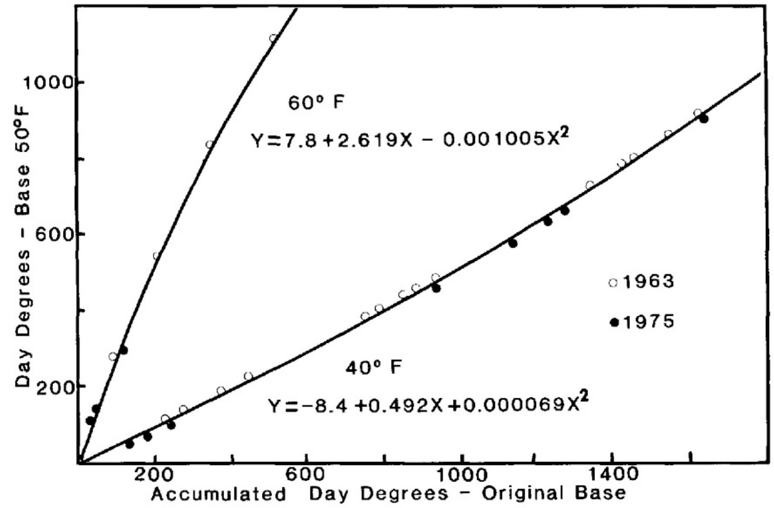

Figure 4. Regression of accumulated day-degrees at base 50°F on day-degrees calculated at bases 40 and 60°F. Sine wave estimates without bias correction, North Platte, Nebraska. Only most deviant observations plotted.

During midsummer we are rarely interested in predicting a process which began in early spring. More often we are concerned with predicting some future developmental stage from another observed stage, e.g., a damaging larval instar from the observation of eggs. An alternative approach is then available. Given accumulated day-degrees, A_o, required at B_o and mean daily day-degrees, M_o, then time, T, in days = A_o/M_o, and since T cannot be changed by arithmetic manipulations, $T = A_s/M_s$. If daily minimum temperatures are above both B_o and B_s, then $M_s = M_o + B_o - B_s$ and $A_s = A_o(M_o + B_o - B_s)/M_o$. For example, given a mean of 20 day-degrees accumulated per day at $B_o = 52°F$ with an event requiring

200 day-degrees (T = 10 days), then at B_s = 50°F mean daily accumulation would be 22 day-degrees, and the event would require 220 day-degrees.

These approaches are suggested primarily for persons trying to utilize published literature immediately and should prove satisfactory in the majority of cases, assuming the model has wide geographical application. The ultimate precision, however, is not quite as great as that offered by bias correction, which does not seem very seasonally dependent.

Not all present day-degree models use sine wave approximations. However, all of the techniques suggested apply equally well to conversion of day-degrees computed by the mean-minus-base or 86/50 methods. Accumulated day-degrees computed by all methods are highly correlated, even if different thresholds are used. Thus, for immediate applications there can be no objection to any conversion which will enhance validation of a day-degree model. I would only caution that the conversions do vary geographically and that for the area of intended use a "typical" year be employed for deriving the conversion for that location.

Recommendations

All day-degree methods with potential application in pest management should be reported to standardized thresholds. Appropriate thresholds are 40, 50, and 60°F, or 5, 10, and 15°C.

Either actual day-degrees or sine wave estimates may be reported. Bias correction should not be used at this time an estimate of actual day-degrees unless derived from data obtained with instruments recording actual day-degrees.

All models should use air temperatures obtained with equipment and locations comparable to temperatures reported by the National Weather Service.

All models should clearly state the date on which accumulation was begun. No assumption should be made that this was the correct date unless so specified by the author.

Any claim that a day-degree model is better than simple calendar date predictions should include deviations in actual days from mean calendar dates for comparison.

If an upper threshold is employed, that threshold should be stated. No recommendation is made at this time for standardization of upper thresholds, though future standardization may be desirable. If not resulting in decreased predictability, 86°F (30°C) would be consistent with current agronomic practice.

These recommendations emphasize practical applications and are not meant to discourage determination of true thresholds or their application in theoretical models. When known, such information should be reported in addition to standardized accumulations. Likewise, reporting of soil or other microenvironmental accumulations is encouraged. A comparison of the "standardized" model with models using additional information would be appropriate.

The suggested procedures should enhance the application of day-degree models of proven predictability, encourage validation of theoretical models, and be consistent with future technology.

Acknowledgments – Shashi Verma provided Mead, Nebraska, weather data recorded at 5-min intervals. I thank Jon Allen, Ivan Berry, Thomas Holtzer, and Ralph Neild for their constructive criticism of the manuscript. Philosophical differences were not entirely reconciled, and I assume full responsibility for opinions expressed.

Published with approval of the Director as paper no. 6934 Journal Series, Nebraska Agricultural Experiment Station. Research reported was conducted under project 17-029.

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