Degree-days: an aid in crop and pest management

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Questions such as when to plant, whether the crop is developing on time, and when to initiate pest control actions are particularly difficult to answer, because the timing is not always the same each year. Growth and development of insects and plants can vary as much as two to three weeks from the "normal" time, depending on whether temperatures are above or below the average. In this article we compare different techniques for predicting temperature-related insect population and crop development.

Temperature thresholds

The notion that the growth and development of many organisms is dependent on temperature was formulated as long ago as the middle of the 18th century. Despite its relatively early origins, the concept is still useful in modern agriculture. In general, it holds that the cooler the temperatures, the slower the rate of growth and development of insects and plants. Table 1 illustrates this point, showing the difference in development of cotton during a warm year (1978) and under 30-year temperature averages. Similar differences would be observed with a range of crops as well as pest and beneficial insects.

An estimated temperature/development time curve for the cotton bollworm, *Heliothis zea* (Boddie), shows that an organism takes quite a long time to grow a given amount or to develop through successive stages at low temperatures (fig. 1A). As temperature increases, development time progressively decreases until the temperature becomes high enough to affect that growth and development negatively.

TABLE 1. Cotton development during a warm year (1978) as compared with 30-year average

Growth stage	Date: 1978	Date: 30-year average
Emergence	Apr 24	Apr 22
Square (flower-bud) initiation	May 28	Jun 1
First boll	Jul 10	Jul 13
First open boll	Aug 19	Aug 28
95+% open	Oct 11	Nov 4

NOTE: Dates based on April 15 planting, using Fresno, California, temperatures.

Field weather station records daily temperatures necessary to predict insect and plant development.

Jack Kelly Clark

The concept helps growers time pesticide applications efficiently

Figure 1B illustrates the same relationship in a slightly different manner, this time plotting development rate (1/development time) as a function of temperature. Two parameters are used extensively when referring to the effect of temperature on growth and development. The lower development threshold for a species is the lower temperature at which development stops. In practice, an estimate of this threshold (T_L) is obtained by projecting the straight segment of the curve (fig. 1B) until it intercepts the temperature axis. This "linear approximation" method normally over-estimates the lower development threshold, but this is of small concern since for most crops temperatures are above the estimated threshold during the growing season. The second parameter, the upper temperature (T_U) threshold, is less well defined but is often taken as the temperature at which the rate of growth or development begins to decrease. For many cropping systems upper thresholds are not used, either because they do not sufficiently increase the accuracy of the prediction for growth or development or because figures are lacking to obtain such estimates.

In practice, information such as that in figure 1 is obtained from laboratory experiments in which groups of insects (or mites) and plants are grown at several different constant temperatures and their development times recorded. Figure 2 represents the development of laboratory-reared cotton bollworm (from newly hatched larvae to newly emerged adults) at each of four temperatures. As temperature increased, the time taken to develop decreased, but the heat required to complete development was approximately the same.

The heat accumulation for any one temperature equals the difference between that temperature and the lower threshold (57° F in this example), estimated as illustrated in figure 1B, times the days to develop, commonly referred to as "degree-days" (°D):

$$°D = (T - T_L) \times \text{days to develop}$$

According to this equation, the °D to complete bollworm larval development were 572, 539, 622, and 583, respectively, at the four temperatures.

The °D equation changes slightly when the temperature exceeds the upper threshold:

$$^\circ D = (T_U - T_L) \times \text{days to develop.}$$

The second equation, although a better estimator of development than the first equation when temperatures are high, can under certain conditions overestimate development — for example, when temperatures are consistently extremely high.

Field temperatures normally follow a cyclical pattern as shown for a three-day period in figure 3A. The °D accumulated during this period, of course, depend on the lower and upper thresholds. The lower the lower threshold, the more the accumulated degree-days (fig. 3A vs. 3B); the lower the upper threshold, the fewer the accumulated degree-days (fig. 3A vs. 3C). Two species, such as a pest and its parasite, may differ in their thresholds and the number of °D to complete development. Although it is fairly simple to estimate °D accumulation in the laboratory as illustrated in figure 2, daily cyclical temperature fluctuations as occur in nature (fig. 3A) often necessitate more detailed methods.

Calculating °D

Several methods are available for calculating °D. From the simplest to the most complicated, these include (1) the max + min method, (2) the "saw-tooth" or trapezoidal approximation, (3) the single sine, and (4) the double sine. All of these are called linear methods, because the rate of development is presumed to be linear with temperature, as occurs in figure 1B. Various models that do not assume linear development on temperature have also been formulated, including one that incorporates the notions of Michaelis-Menton enzyme kinetics. This second group of more accurate but also more complicated methods will not be discussed here.

Considerable disagreement exists over the most appropriate method for calculating °D. Unpublished results from analyses conducted by the University of California Integrated Pest Management (IPM) computer group show that, although the °D estimates vary somewhat, and in some areas or for some species a particular method may be more appropriate, in most cases the methods can be interchanged.

The simplest method (max + min) used to estimate the number of °D for one day is the following:

(high temperature + low temperature) ÷ 2 — lower threshold.

The max + min method ignores the upper threshold, which is reasonable for most of the year, since the high temperature is seldom at this level long enough to have any lethal or sublethal effect. Figure 4A illustrates the estimated accumulation of °D for a three-day period. The area or °D represented by "b," which is underestimated by this method, is balanced by the overestimates of "a," resulting in a surprisingly accurate estimate of cumulative °D over several days. Only when the minimum temperatures are below the lower threshold or when the maximum temperatures exceed the upper threshold does any appreciable error result.

This method's normally high degree of reliability is important considering its extensive use by agriculturists without access to computers. Many hand calculators can easily be programmed so that the calculation can be made simply by entering the low and high temperature

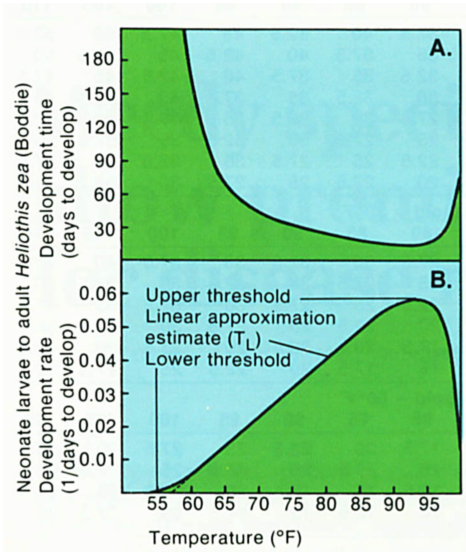

Fig. 1. Cotton bollworm develops more quickly as temperature increases up to a point, after which development slows.

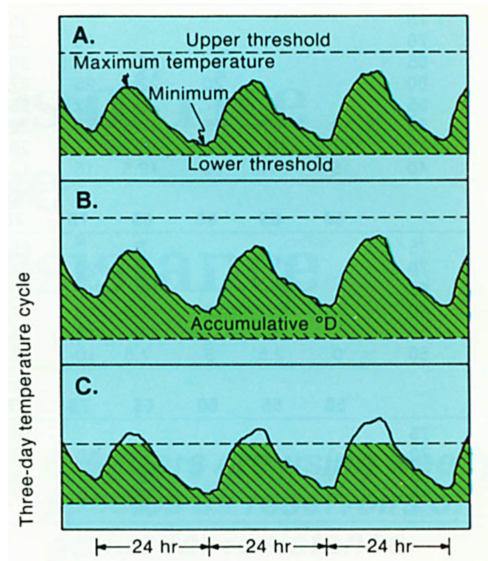

Fig. 3. In daily cyclical temperatures (A), the lower the lower threshold, the more the accumulated °D (A vs. B); the lower the upper threshold, the fewer the °D (A vs. C).

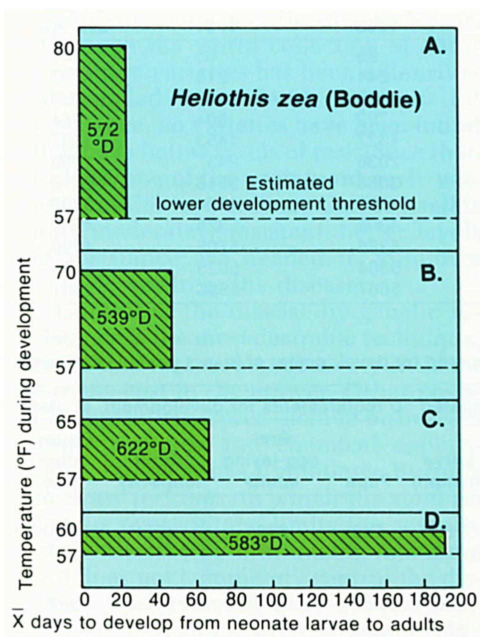

Fig. 2. Heat accumulation, or degree-days (°D), for cotton bollworm was about the same, even though development time differed at different temperatures.

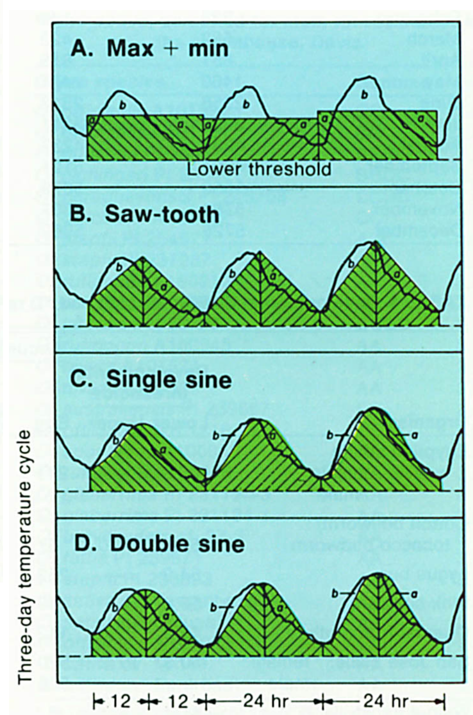

Fig. 4. Four linear methods for calculating °D accumulation, from the simplest (A) to the most complicated (D).

for the day and the lower threshold for the insect or plant. Precalculated tables using these methods are available, where the high for the day is charted across the top and lows down the side. To find the °D accumulated for a day, the user locates the appropriate high and low and crosses to where the two intersect. A different table must be used for species with different lower thresholds (see table 2). All of the linear methods mentioned produce values very similar to those in table 2 when an upper threshold is ignored, except when the temperature falls below the lower threshold, in which case the simple max + min method produces the greatest error.

TABLE 2. Daily cumulative degree-days for the corresponding maximum and minimum temperatures, and developmental thresholds

Minimum temperature	Maximum temperature												
	Threshold = 40°F												
	50	55	60	65	70	75	80	85	90	95	100	105	110
75						35	37.5	40	42.5	45	47.5	50	52.5
70					30	32.5	35	37.5	40	42.5	45	47.5	50
65				25	27.5	30	32.5	35	37.5	40	42.5	45	47.5
60			20	22.5	25	27.5	30	32.5	35	37.5	40	42.5	45
55		15	17.5	20	22.5	25	27.5	30	32.5	35	37.5	40	42.5
50	10	12.5	15	17.5	20	22.5	25	27.5	30	32.5	35	37.5	40
45	7.5	10	12.5	15	17.5	20	22.5	25	27.5	30	32.5	35	37.5
40	5	7.5	10	12.5	15	17.5	20	22.5	25	27.5	30	32.5	35
	Threshold = 50°F												
	50	55	60	65	70	75	80	85	90	95	100	105	110
75						25	27.5	30	32.5	35	37.5	40	42.5
70					20	22.5	25	27.5	30	32.5	35	37.5	40
65				15	17.5	20	22.5	25	27.5	30	32.5	35	37.5
60			10	12.5	15	17.5	20	22.5	25	27.5	30	32.5	35
55		5	7.5	10	12.5	15	17.5	20	22.5	25	27.5	30	32.5
50	0	2.5	5	7.5	10	12.5	15	17.5	20	22.5	25	27.5	30
	Threshold = 60°F												
	50	55	60	65	70	75	80	85	90	95	100	105	110
75						15	17.5	20	22.5	25	27.5	30	32.5
70					10	12.5	15	17.5	20	22.5	25	27.5	30
65				5	7.5	10	12.5	15	17.5	20	22.5	25	27.5
60			0	2.5	5	7.5	10	12.5	15	17.5	20	22.5	25

TABLE 3. Accumulation of degree-days above 50°F for Fresno, California

Month	Year: 1978	1979	1980	1981	30-year average
January	107	53	85	85	31
February	235	175	241	215	133
March	563	423	419	389	328
April	851	819	792	804	654
May	1469	1475	1327	1453	1202
June	2256	2313	2036	2437	1950
July	3260	3311	3088	3516	2912
August	4234	4237	4038	4534	3809
September	4924	5121	4805	5329	4532
October	5550	5678	5388	5705	4999
November	5704	5867	5604	5923	5170
December	5726	5960	5667	5983	5201

TABLE 4. Developmental thresholds (°F) and °D required for development of insect pests in California

Organism	Developmental thresholds: Lower	Upper	Accumulated °D requirements for development, at stage: Egg	Larva (nymph)	Pupa	Pre-egg-laying adults	Adult longevity	Generation time
Egyptian alfalfa weevil: female	45.0	—*	211	85	288	279	495	univoltine?
male				103				
Cotton bollworm/ tobacco budworm	57.0	94.0	67	329	388	117	871	968
Lygus bug	54.0	—	252	371	none	176	—	—
Pink bollworm	50.0	—	149	430	230	50	569	—
Oriental fruit moth	45.0	90.0	142	387	383	50	124	995
San Jose scale: female	50.9	97.2	520	452	58	20	—	1049
male			506	430	95	20	—	1049
Walnut aphid	41.4	—	†	400	—	none	378	572

* — not determined.
? In some areas of California the Egyptian alfalfa weevil now appears to have more than one generation per year.
† Synchronized with bud break regardless of when laid.

Figure 4B illustrates the saw-tooth approximation method using a 12-hour or half-day calculation period. Over a 24-hour period the overestimate area or °D represented by "a" will be balanced by "b." Both this and the other more complicated methods can use other than 12-hour heating and cooling periods to increase the accuracy for a single day, although this increased accuracy is seldom significant. The trapezoidal method can also be based on more than two calculations per day, and as the time intervals decrease the accuracy increases. As the calculation period becomes extremely small, a °D estimate equal to that shown in figure 3A is produced. The disadvantage of using this method in this manner is that weather stations provide only low and high daily temperatures and not hourly or by-minute readings.

Figure 4C illustrates the single sine curve method. This technique uses a day's low and high temperatures to produce a sine curve over a 24-hour period and then estimates °D for that day by calculating the area above the threshold and below the curve. Again, the "a" areas balance the "b" areas, resulting in an accurate prediction of °D. The U.C. IPM computer network uses this method to calculate °D for the various insect and plant growth and development prediction models.

Figure 4D illustrates the double sine method. The only difference between this and the last method is that this one produces a sine curve for the heating period of the day using the low and high temperatures from that day, and then a separate sine curve for the cooling period of the day using the high temperature from that day and the low temperature from the next morning. Although the double sine method appears more realistic for some days than the single sine, it is nevertheless little or no more accurate over a period of several days.

Accumulating °D

Because each species requires a set number of °D to complete development, we are interested in knowing the accumulated °D from a starting date. The date to begin calculating °D accumulation varies with the species. April 1 is used to begin accumulating °D in safflower to treat lygus bugs so that they will not migrate to cotton. Planting date, some other biological event, and traps have all been used to determine the date when °D accumulation should begin. Early in the season, degree-days accumulate slowly, and the rate peaks in July or August.

In Fresno, using a lower threshold of 50° F as an example, each of the four years shown in table 3 was distinct, with 1981 accumulating the most °D and 1980 the fewest. A greater number of °D accumulated in each of the four years than in the 30-year average. A warmer or longer season (more °D accumulation), however, does not mean that yields will be uniformly higher. In some crops, high temperatures can aggravate irrigation management problems and increase crop stress.

Insect and plant population and development models that incorporate thresholds and rates based on degree-days can help growers and pest control advisors to pinpoint biological events. The result is better pest control and crop management decisions. Table 4 lists several insect pests for which °D-based models have been developed and are now being used in California. Some of these models are very simple and provide information on the timing of events such as overwintering emergence and subsequent population buildup. The more detailed models can be used to estimate damage to the crop in determining when pest control is necessary to avoid economic loss.

Using °D to predict insect development makes it possible to minimize conflicts between cultural and pest control operations, such as between irrigation and pesticide scheduling.

Degree-days can tell growers and pest control advisors where they stand in relation to development of a generation of insects or a disease so that they can time pesticide applications more efficiently, thus often reducing costs and damage by insects or disease organisms. For example, pheromone traps might indicate an increase in the number of adults of a pest species. The accumulated °D would indicate whether this is a real or a false peak. If it proves to be false, treatment could be delayed until the next pest generation actually begins, avoiding an unnecessary pesticide application.

Degree-days also can be useful in determining when to do extensive sampling — limiting such activities to times when the pests are present.

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Weedy species of rice show promise for disease resistance

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Breeders are using weedy species as reservoirs of genes for resistance

Weedy or related species of cultivated crops frequently serve as sources of genes for disease resistance, especially when suitable genes cannot be found in the crop. Such a situation exists for the fungal disease stem rot, caused by *Sclerotium oryzae*, in cultivated rice, *Oryza sativa*. Stem rot causes significant rice yield reductions in California each year. Although the world collection of cultivated rice varieties has been extensively sampled in a search for stem rot resistance, no varieties have been found that have better levels of resistance than Colusa, one of the prominent early varieties of California. Since Colusa itself is only moderately resistant, better levels of resistance are needed to minimize yield losses from the disease.

Control of the disease by genetic resistance is the most desirable technique, since this represents relatively little recurring cost to the grower. Other possible control measures include burning of straw residues and chemical applications, but each has limitations. Burning of straw residues, in which the stem rot fungus overwinters, limits the severity of the disease by minimizing inoculum but does not completely control the disease. Also, concern over air pollution caused by smoke from straw burning has led to restrictions on the amount of burning. The chemical triphenyltin hydroxide effectively controls stem rot but is unregistered in California and thus cannot be used commercially.

We began a program in the mid-1970s to develop better sources of stem rot resistance from the related species of

TABLE 1. Disease index (DI) scores of 24 genotypes, representing 13 weedy species of *Oryza* and 4 varieties of cultivated rice, *Oryza sativa*, screened for stem rot resistance in the greenhouse, Davis

Oryza species	Genome	DI*
O. officinalis A101399	CC	2.0
O. officinalis A101121	CC	2.4
O. punctata PI 254570	BBCC	2.4
O. eichingeri PI 233491	BBCC	2.5
O. paraguayensis PI 245708	CCDD	2.4
O. officinalis A101112	CC	2.6
O. stapfii PI 254571	A'A'	2.6
O. stapfii PI 237987	A'A'	2.7
O. rufipogon A100912	AA	3.0
O. rufipogon A100923	AA	3.1
O. latifolia PI 269727	CCDD	2.7
O. rufipogon A100945	AA	3.4
O. nivara A101524	AA	3.2
O. nivara A101512	AA	3.1
O. australiensis PI 239667	EE	3.4
O. officinalis A101116	CC	2.9
O. spontanea A100943	AA	3.2
O. rufipogon A100946	AA	3.5
O. glaberrima PI 231194-3	AA	3.7
O. glaberrima PI 231194-1	AA	3.8
O. breviligulata af. 27-3	AA	3.4
O. fatua PI 239671	AA	3.4
O. stapfii PI 236393	A'A'	3.9
O. sativa cv. Tanginbozu	AA	3.5
O. sativa cv. Colusa	AA	3.7
O. officinalis A101073	CC	3.8
O. sativa cv. M-101	AA	4.0
O. sativa cv. Earlirose	AA	4.0

* DI values are on a scale of 1 to 5, as follows: 1, no infection; 2, fungus attacks outer leaf sheaths only; 3, fungus penetrates all leaf sheaths; 4, fungus infects the culm; 5, culm severely infected (rotted). LSD 0.05 and 0.01 = 0.4 and 0.5, respectively.