USE OF PHENOLOGY MODELS FOR PEST MANAGEMENT

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Phenology models are one of the major components of pest management programs which allow researchers to decide on optimal timing of pesticide applications in a system with multiple pests present. These models do not operate on a calendar day basis, but instead, operate on a heat unit scale, which insects respond to in a very predictable manner. The model is generally started from some easily detected event, such as first flight of codling moth, and used to predict something that is important, but not easily sampled (e.g., 3% codling moth egg hatch). In this chapter, I will discuss the basis of phenological models, how they are developed, which ones are available, and give examples of proper and improper use of them.

How and Why They Work
Metabolic rates of animals are related to the temperatures at which those metabolic reactions occur. In biological (enzymatic) reactions, there is generally a temperature at which the reaction goes fastest.
you raise the temperature above the optimal temperature, the precise fit of the enzyme on its substrait is disrupted, and the reaction rate rapidly decreases. If the temperature remains high, the enzyme is generally permanently disrupted, and death occurs. If you decrease the temperature below the optimal temperature, the rate of the reaction drops rapidly until it stops, but death is rarely the result unless freezing and ice crystal formation occurs in the animal’s cells. In warm-blooded animals, body core temperatures rarely vary more than a few degrees, and the animal’s enzymes tend to be operating at peak efficiency near the animal’s normal body temperature.

This means the rate of enzymatic reactions is fairly constant and that development of warm-blooded animals can therefore be readily predicted by calendar time. However, for invertebrates like insects and mites, there are no physiological mechanisms which regulate body temperatures closely. This means that, in general, their body temperatures are directly related to ambient temperatures and therefore, their development can best be predicted from heat accumulations and not calendar time.

Formally, the idea of heat accumulation being used to predict development is known as the law of constant thermal summation. Basically, it says the total number of heat units required to complete a given physiological process is constant (within the upper and lower limits described above). The rate at which the heat units accumulate, whether quickly or slowly, is immaterial. The heat unit scale is often called a physiological time scale.

A good analogy to the law of constant thermal summation would be the filling of a gallon container. It doesn’t matter how fast or how slow you fill the container, it still takes a gallon to fill it. If you consider the gallon container to be a physiological process, like the development through the egg stage, the amount of heat required is the same whether the heat is accumulated quickly or slowly (within certain bounds).

The temperature limits on physiological reactions are termed the upper and lower developmental thresholds. When the temperatures drop below the lower threshold, no development occurs; conversely, when the temperatures rise above a certain temperature, at first development stops, and if temperatures continue to rise, thermal death occurs. To measure the number of heat units accumulated, degree-days are used. A degree-day is defined as the heat experienced by the organism when the temperature is one degree above the lower threshold for development for a period of 24 hours.

Most models use a sine-wave to approximate the daily temperature cycle from night to day. The lower threshold is frequently called K1, from the terminolog developed the sine wave a have at least two forms (se heat unit accumulations do upper threshold for develop where once the upper thr units are accumulated. Th area under the curve with
K1, from the terminology developed by the individuals who developed the sine wave approximation. The upper threshold can have at least two forms (see Figure 1): 1) a horizontal cutoff, where heat unit accumulations do not rise above a maximum rate at the upper threshold for development (K2); and 2) a vertical cutoff (K3), where once the upper threshold is surpassed, no additional heat units are accumulated. The heat accumulated is calculated as the area under the curve within the upper and lower thresholds (dark

**FIGURE 1**

Heat unit accumulation using (A) vertical cutoff and (B) horizontal cutoff. Dark areas are the heat accumulation for each type.
areas in Fig. 1 are the heat units accumulated). The first condition does not appear biologically reasonable in light of this explanation, but it does seem to provide better predictions in certain circumstances. A table is often generated which allows the end-user to merely look up the maximum and minimum temperatures for a day and obtain the number of heat units accumulated during that period for a particular insect. These daily heat units are accumulated from the biofix and are used to predict when the critical event occurs.

Biophenometers are also used to accumulate heat units. They are programmed with the desired upper and lower thresholds for development and placed in the orchard at a particular time. The grower can then just go to the weather shelter and, at the press of a button, get the accumulated number of heat units. The Omnidata® biophenometers allow up to five different upper-lower threshold accumulations to be stored on a single biophenometer. The Omnidata biophenometer allows the upper cutoff to only be of the horizontal variety.

The starting point for the heat accumulation is the “biofix.” The biofix is some easily observed event, such as the first moth catch, which is used to synchronize the model with the field populations.

**FIGURE 2**

Plot of developmental rate versus temperature. This plot is used to determine the total degree-days to complete a stage and the lower threshold for development.

\[ y = -0.0542 + 0.0086x \quad R = 0.95 \]

Threshold is 6.5°C
Degree Days for development = 1/slope of line
\[
= \frac{1}{0.0085} \\
= 117.6
\]

Occasionally, it is a calendar time, such as you generally get no heat unit accumulation. However, if you need to estimate the season change in biological interest, it is a useful tool.

**DETERMINING DEGREE-DAYS AND**

How are the number of degree-days for development determined? Normally, groups of 30 or more are selected at a constant temperature, and the length of time to complete each stage (organ, egg, etc.) recorded. This is repeated at four or more locations. The developmental rate (development rate per degree-day) is then multiplied by linear regression (see Figure 2). The lower threshold is the line drawn through the points on the lower axis (where developmental rate is zero), and the upper threshold is equal to 1/slope of graph (the slope is the average rate of proportion development per degree-day). Therefore, 1/slope determines how long it takes to complete the stage in question.

**MODELING EMERGENCE**

Now that we know the upper and lower limits of heat units to complete each stage, we can model how the insects emerge. This information is typically mentioned above and pattern for our laboratory populations. Data at this point, we generally choose which is adaptable enough to adequately fit several treatments that have been used, such as Erlang distributions, however, the key is to use the model that best fits the chosen population emergence. For deciduous fruits, the PATE model and its co-workers use the Erlang distribution because it is skewed to the right population emerges quickly, but a smaller and also because by changing a single value, the emergence curve can take on many different shapes. This adaptability means that by simply changing a few parameters, the model can be adapted without changing the base principles.
Occasionally, it is a calendar time, such as March 1, before which you generally get no heat unit accumulation. This allows you to set up your weather equipment later and to save time and effort early in the season when little of interest in the insect life cycle is occurring.

DETERMINING DEGREE-DAYS AND THRESHOLDS
How are the number of degree-days for development of the insects determined? Normally, groups of 30 or more insects are reared in the lab at a constant temperature, and the length of time required for each individual to complete each stage (egg, larva, pupa, and adult) is recorded. This is repeated at four or more temperatures with different groups of insects. The developmental rate (= 1/average time to complete development) is then plotted versus temperature and fit using linear regression (see Figure 2). The lower threshold for development is where the line drawn through the points intercepts the temperature axis (where developmental rate = 0), and the degree-days required to complete the stage are equal to 1/slope of the line drawn through the graph (the slope is the average rate of development in terms of proportion development completed per day at a given temperature; therefore, 1/slope determines how long [in degree-days] it takes to complete the stage in question).

MODELING EMERGENCE
Now that we know the upper and lower thresholds and the number of heat units to complete each stage, we need to be able to model how the insects emerge. This information is taken from the same laboratory experiments mentioned above—we know the emergence pattern for our laboratory populations from the way we took our data. At this point, we generally choose some statistical distribution which is adaptable enough to adequately model the laboratory data. Several distributions have been used, such as the Weibull and the Erlang distributions, however, the key point is not which distribution is used, but how well the chosen distribution predicts the field population emergence.

For deciduous fruits, the PETE model developed by Brian Croft and his co-workers uses the Erlang distribution. This distribution was used because it is skewed to the right (i.e., a large portion of the population emerges quickly, but a small part tends to emerge later) and also because by changing a single parameter of the model (k), the emergence curve can take on many different shapes (see Figure 3). This adaptability means that by simply changing k, a wide variety of insects can be modeled without changing the underlying distribution upon which it is based.
Differing shapes of the emergence curves possible using the Erlang distribution. The mean emergence time is the same, only the shape parameter \((k)\) has been changed.

With our laboratory information now modeled, we take the model to the field. Development times per se are rarely measured, instead, we measure the portion of the population in each developmental stage and compare it to the temperatures observed in the field. The process of validation can take several forms, but for IPM, the idea of an "indifference band" validation is frequently used. The indifference bands are a period in time about the predicted event where if the model is off during this period of time, it will make no difference to the pest management program. These bands are set depending on the biology of the pest and the effect of applying the management tactic early or late on its eventual success.

To determine the failure rate of the model, you plot the date an event was predicted to occur and when it actually occurred in the field population. If the point falls outside the indifference band, it is considered a failure, otherwise, it is a success. The percent of the time the model fails is thus an indication of how useful the model is at predicting pest management decisions. Of course, this must be done over a period of several years and in a number of different orchards to ensure success. This sort of plot is shown in Figure 4 for the Western cherry fruit fly information from both Utah and Washington.
Indifference band validation for Western cherry fruit fly on cherries in Utah and Washington.

**FIGURE 4**

Examples of successful models

There are at least nine insect models applicable to deciduous fruits: codling moth, white apple leafhopper, Western cherry fruit fly, San Jose scale, peach twig borer, Oriental fruit moth, tentiform leafminer, apple maggot, and oblique-banded leafroller. Most of these are available in Washington State or will be soon.

Probably the most successful model is the codling moth model. It is used in most fruit growing regions of the United States to time the first and third cover sprays. The model is used to predict when egg hatch occurs, based on the amount of heat accumulated since the first consistent flight of codling moth (i.e., the biofix). The goal of the cover sprays is to kill the young larvae before they begin to bore into the fruit, and, secondarily, to kill adult moths present in the orchard. The use of the codling moth model allows us to get the maximum effective longevity of the cover sprays.

It is critical that the sprays be applied as close to the time predicted as possible. Putting the spray on too early means the residue has weathered that much before the larvae emerge and must be applied that much sooner. Putting them on late means more larvae have entered the fruit than desired. A mistake of applying the pesticide too late results in damaged fruit at harvest or early fruit drop. Using the older methods of 21 days after first bloom, Beers and Brunner have found the first cover spray went on an average of seven days before egg hatch began (and up to 18 days early), thus...
wasting a significant portion of the 21-day longevity of the Guthion residue.

Current recommendations in Washington State call for the first cover spray to go on 250 degree-days after the biofix. This corresponds to approximately three percent egg hatch. The second spray goes on based on the 21-day longevity of the Guthion residue, and the third spray goes on at 1260 degree-days or when about seven percent egg hatch of the second generation has occurred. Why apply at seven percent instead of three percent again? Well, if your first two applications were properly timed, then the in-orchard population will be considerably smaller and seven percent egg hatch will still not be that much damage at harvest.

In Utah, growers were complaining of codling moth resistance problems in the early 1980s. The recommended rates of Guthion were increased to about one-and-a-half to two times higher than the rates used in Washington State, but damage did not decrease. Instead, mite problems became much more severe, and predator mites were rarely found following a cover spray. When I arrived in 1985, I surveyed several of the orchards for resistance, but did not find any. A close look at the timing of the sprays revealed that the timings from the codling moth model were very far off from predictions from New York and Washington State (see Table 1). A misinterpretation of the model had caused the extension service to recommend the apple maggot model I worked on maggot has been a pest in the East for the subject of many papers which look at the average time of emergence years worth of data, you find the median is June 23. However, the average emergence hosts/years can vary from June 24. Obviously, calendar dates don't prove for IPM.

Use of the heat unit concept is not as much as we'd like to think. Traditions since the first of March for in Utah, emergence varies from 563 degree-days (Oregon). This is not due to the biofix, but is probably a result of conditions (particularly soil moisture), or between regions, and, possibly, in overwintering pupae that have entered the soil. Simply using a model developed is a major mistake. We found that the emergence curve (i.e., the rate of New York, Washington, and Oregon, Wisconsin emergence curve. The results in a 77.5 percent failure rate in York for validation. However, the model appears to predict population to some of Jay Brunner's observations.

So far, I have basically been doing this for timing purposes. However, looking at the interactions between second codling moth cover spray order emergence in Utah. Although apple apples in Utah, we investigate two pests in preparation for the apple. The two insects have different seasons in emergence time changes with each year and between locations. By using real-time weather conditions, we could adjust slightly to result in one less cover sprays. This can be expanded further to see how the different control measures differ.

In summary, models are tool

<table>
<thead>
<tr>
<th>% Egg Hatch</th>
<th>Utah Old</th>
<th>New York</th>
<th>Washington</th>
<th>Utah New</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>280 (4.4)*</td>
<td>209</td>
<td>220</td>
<td>225</td>
</tr>
<tr>
<td>5</td>
<td>420 (30)</td>
<td>273</td>
<td>270</td>
<td>285</td>
</tr>
<tr>
<td>10</td>
<td>490 (47)</td>
<td>304</td>
<td>320</td>
<td>320</td>
</tr>
<tr>
<td>25</td>
<td>625 (73)</td>
<td>382</td>
<td>380</td>
<td>400</td>
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*Numbers in parentheses indicate the % egg hatch according to new interpretation.
of the Guthion all for the first fix. This corre-
se second spray on residue, and 
en amount seven occurred. Why 

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the in-orchard cent egg hatch 
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interest is the 

apple maggot model I worked on for Utah tart cherries. Apple maggot has been a pest in the East for about 100 years and has been the subject of many papers which mention its phenology. If you look at the average time of emergence from 152 different location/years worth of data, you find the mean calendar date of emergence is June 23. However, the average emergence time in different locations-hosts/years can vary from June 2 (Canada) to July 18 (Oregon). Obviously, calendar dates don't provide accurate enough predictions for IPM.

Use of the heat unit concept should clear this up, right? Well, not as much as we'd like to think. If you look at the heat accumulations since the first of March for studies where it is available, first emergence varies from 563 degree-days (New York) to 965 degree-days (Oregon). This is not due to accumulations occurring before the biofix, but is probably a result of differences in growing conditions (particularly soil moisture), orchard aspect, and ground cover between regions, and, possibly, in the stage of development of the overwintering pupae that have entered diapause.

Simply using a model developed in one location without validation is a major mistake. We found that the model could be used to predict the emergence curve (i.e., the rate of emergence) in Utah, Canada, New York, Washington, and Oregon, but failed to predict the Wisconsin emergence curve. The model developed for Utah flies resulted in a 77.5 percent failure rate when using data from New York for validation. However, the apple maggot model developed in Utah appears to predict populations emerging in Washington State, according to some of Jay Brunner's data.

So far, I have basically been discussing the importance of models for timing purposes. However, they are also excellent tools for looking at the interactions between different pests. For example, the second codling moth cover spray occurs very close to apple maggot emergence in Utah. Although apple maggot does not currently attack apples in Utah, we investigated the interaction between the two pests in preparation for when apple maggot moves over to apple. The two insects have different thresholds for development, so the difference in emergence times between the two populations changes with each year and between different geographical locations. By using real-time weather data, we found that in most years and locations, we could adjust the spray schedule for both pests slightly to result in one less cover spray in areas where both would occur. This can be expanded further by looking at more pests to see how the different control measures interact.

In summary, models are tools which help decide when the
optimal time of pest control occurs. They are based on the insects' growth being closely correlated with the ambient temperature and are best used to predict when some difficult-to-observe event has occurred. It should be noted, however, that models are not a replacement for sampling. In fact, when used to predict the optimal time for sampling (e.g., when second generation of tentiform leafminer has begun), it can add to the information received by sampling and further provide information on what the population may look like if little predation occurs or no controls are applied (e.g., if you expect 10% to have emerged by a given time and you've caught nothing in your traps, it will probably be a light year for that pest).

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