

A comparison of phenology models for harvest readiness in walnuts

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Introduction

Phenology models are used in research and farm operations to predict the timing of plant life stages, such as emergence, flowering, and maturity. Phenology models estimate development rates for crop growth simulations that assess the effects of different varieties, management decision, and the environment on productions. Farmers use phenological predictions from these models to prepare for the logistics associated with flowering and harvest, such as pesticide application and equipment rental.

While both temperature and photoperiod can drive plant development, here we focus on temperature driven phenology models. Temperature based models use thermal time, instead of chronological time, to measure plant development. Thermal time summarizes how plants' rates of development change based on the ambient temperature surrounding the plant. These phenology models also use a threshold value to define the most temperature sensitive period of development for the plant in question. We distinguish between two broad types of models based on the unit of this threshold value: thermal time threshold (TTT) and day threshold (DT) models.

Phenology models of annual crops generally use a TTT model. These models set a threshold in thermal time units. Then the model counts the number of days it takes to reach that threshold. The full model we develop in this paper uses the day count to predict the total length of the stage, in days. Annual crops are modeled with a simplified version of the model. In the simplified TTT model, the day count is exactly the stage length. TTT models are generally used to study plant responses to different weather conditions. However, the full TTT models are also used for within season predictions.

Models of perennial crops, specifically trees, generally use DT phenology models. The threshold for DT models is given in days. The model counts the amount of thermal time accumulated during that time. Next, the model uses the thermal time accumulated to predict the length of the stage, in days. This approach is commonly used in fruit and nut phenology models, including peaches, almonds, and prunes, to make in season predictions for farm orchard management. DT modeling is supported by finding that temperature variation within the first 30 to 60 days of flowering have disproportionately large effects on fruit development [mimoun1998; day2007; debuse2008; tombesi2010; ruml2011]

One key component of both model types is the method for converting daily or hourly temperatures into thermal time. This is typically done by using temperature thresholds called cardinal temperatures. The models in this paper use base (T_b), optimal (T_o), and critical temperatures (T_c). Above Thermal time is zero below the base temperature and above the critical temperature. Typical values of T_b and T_c for mediterranean fruit and nut trees are around 4°C and 36°C respectively). Thermal time is highest at the optimum temperature, which may be around 25°C for tree crops [richardson1975]. Growth chamber experiments can determine cardinal temperature values. However, while this is relatively straightforward for annuals, it is impractical for tree crops.

While some effort has been made to compare different DT phenological models [e.g. marra2001; tombesi2010], the performance of DT and TTT models have not been compared. In this paper, we develop the full TTT model and compare the predictive power of 8 DT and 14 TTT phenology models for predicting harvest readiness in walnuts. We use optimization methods to estimate both the amount of thermal time accumulation and the cardinal temperatures used to calculate thermal time. The resulting models can be used for in season walnut harvest date prediction.

Phenology models

There are four steps in specifying a phenology model for in season prediction of harvest readiness or another growth stage: (1) selection of the type of model including whether the full or simplified form is used; (2) selection of the function used to derive thermal time from temperature; (3) estimating the cardinal temperature and thermal time accumulation parameters; and (4) fitting of a statistical model that predicts the length of growth stage of interest from time or thermal time accumulation.

Thermal Time Threshold (TTT) Model

For all the phenology models λ will represent the model threshold. In TTT models, λ_j is the accumulated thermal time threshold for stage j . The independent variable in the TTT model is the number of days necessary to accumulate λ_j thermal time units, which we represent as $x_i(\lambda_j)$ for a given year i . Next, we can use a linear regression model to define the length of stage j , in days, as

$$y_{ij} = \alpha_j(\lambda_j) + \beta_j(\lambda_j) \cdot x_i(\lambda_j) + \epsilon_i \quad (1)$$

where y_{ij} is the length (in days) of stage j during the i th year of observation. This means that $\alpha_j(\lambda_j)$ is the stage length if the plant reaches the thermal time threshold before the first day of j stage is over. Then $\beta_j(\lambda_j)$ is the change in the predicted stage length, in days, if the plant takes one day longer to reach the thermal time threshold (λ_j). The $\alpha_j(\lambda_j)$ and $\beta_j(\lambda_j)$ values depend on the values of x_i based on (citation). Since x_i itself depends on λ_j , so do $\alpha_j(\lambda_j)$ and $\beta_j(\lambda_j)$, if only indirectly. As the above phenological model incorporates the full linear regression, we refer to this model as the Full TTT Model.

Most annual crop phenology models simplify this the Full TTT model by setting λ_j equal to the total thermal time units necessary physiologically for the plant to complete stage j . We will refer to this value as Λ_j . Using the assumption that $\lambda_j = \Lambda_j$, we can make two simplifications.

First, $\alpha_j(\Lambda_j)$ must be zero. If $x_i(\Lambda_j) = 0$, this means that the plant accumulated enough thermal time to reach the thermal time threshold on the first day of the stage. Because the thermal time threshold is also the total thermal time required for the plant to complete the stage, this means $y_{ij} = 0$ as well. Substituting these two equations into the linear regression model produces the following result:

$$\alpha_j(\Lambda_j) = 0 \quad (2)$$

The second simplification implied by the simplified TTT model assumption is that $\beta_j(\Lambda_j)$ equals one. Under the assumption $\lambda_j = \Lambda_j$, thermal time threshold is exactly the number of thermal time units it takes for the plant to complete the physiological development in stage j . If it takes the plant one day longer to reach the thermal time threshold Λ_j , then by definition it also takes one day longer to complete stage j . Since $\beta_j(\Lambda_j)$ is the increase in predicted stage length, given that it took the plant one day longer to reach Λ_j , $\beta_j(\Lambda_j)$ must be one.

$$\beta_j(\Lambda_j) = 1 \quad (3)$$

If we substitute equations (2) and (3) into equation (1), it simplifies the linear model to

$$y_{ij} = x_i(\Lambda_j) + \epsilon_i \quad (4)$$

Conceptually, this model is simply taking the number of days to reach Λ_j thermal time units, x_i as the stage length. As the value of Λ_j itself depends on the the values of the cardinal temperatures, they still need to be estimated for this model. Because this model includes a reduced version of the linear model, we refer to this as the Simplified Thermal Time Threshold Model.

Day Threshold (DT) Model

The Day Threshold model has essentially the same structure as equation (1). The only thing that differs is the interpretations of the variables. The variable λ_j is the threshold in days, instead of thermal time units, and $x_i(\lambda_j)$ is the amount of thermal time accumulated in λ_j days. Like before, y_{ij} is the length, in days, of stage j . Then, $\alpha_j(\lambda_j)$ is the predicted stage length if the trees did not experience any thermal time accumulation during the first λ_j days of stage j and $\beta_j(\lambda_j)$ is the change in stage length due to accumulating one additional thermal time unit during the first λ_j days of the stage. Like before, we refer to this model as the Full Day Threshold Model.

When simplifying the DT model, we set the model threshold to be Λ_j , total the number of days the plant will accumulate thermal time in stage j . This is necessarily the length of stage j , in days. Now, $\beta_j(\Lambda_j)$ is the change in stage length if the plant accumulates one more unit of thermal time in Λ_j days. However, since Λ_j is, by definition, the total number of days that the plant will accumulate thermal time, $\beta_j(\Lambda_j)$ must be zero. This removes the x_i term from the linear regression, leaving the equation

$$y_{ij} = \alpha(\Lambda_j) + \varepsilon_i \quad (5)$$

Since the stage length, y_{ij} , no longer depends on x_i , the model will predict the same stage length for all values of thermal time accumulation, namely the mean stage length, \bar{y} .

Thermal time computation functions

We evaluated five functions for calculating thermal time. While there are additional functions (ex. @marra2001), these five capture a variety of assumptions about tree responses to temperature and are computationally viable options for model fitting on most computers. The simplest “Linear” thermal time function has just one parameter [yang1995].

$$\text{Linear TT} = \begin{cases} 0 & T \leq T_b \\ T - T_b & T_b \leq T \end{cases}$$

where TT is the thermal time accumulated, T is the average temperature for the chosen time period (day or hour), and T_b is the base temperature. We evaluated the Linear function for both hourly and daily temperatures (LinearHour and LinearDay).

The “Plateau” function slightly more complicated function that includes two parameters.

$$\text{Plateau TT} = \begin{cases} 0 & T \leq T_b \\ T - T_b & T_b \leq T \leq T_o \\ T_o & T_o \leq T \end{cases}$$

where T_o is the optimal temperature. The Plateau model caps thermal time at T_o , but still neglects a potential slowdown in development at very high temperatures.

One function that accounts for this is the three parameter triangle function from (citation?), where T_b , T_o , and T_c are the base, optimal and critical temperatures respectively.

$$\text{Triangle TT} = \begin{cases} 0 & T \leq T_b \\ T - T_b & T_b \leq T \leq T_o \\ \frac{(T_c - T)(T_o - T_b)}{T_c - T_o} & T_o \leq T \leq T_c \\ 0 & T_c \leq T \end{cases}$$

A widely used function in tree crop phenology is another three parameter model, called the Asymcur model, from [Anderson1985].

$$\text{Asymcur TT} = \begin{cases} 0 & T \leq T_b \\ \frac{T_o - T_a}{2} \left[1 + \cos \left(\pi + \pi \cdot \frac{T - T_b}{T_o - T_b} \right) \right] & T_b \leq T \leq T_o \\ (T_o - T_a) \left[1 + \cos \left(\frac{\pi}{2} + \frac{\pi}{2} \cdot \frac{T - T_o}{T_c - T_o} \right) \right] & T_o \leq T \leq T_c \\ 0 & T_c \leq T \end{cases}$$

As this function is almost always used with the cardinal temperatures reported by Anderson1985, we use these as well to have a basis of comparison to other studies ($T_b = 4$, $T_o = 25$, $T_c = 36$). We refer to the Asymur function with cardinal temperatures from Anderson1985 as the Anderson function.

One thermal time function uses daily minimum and maximum temperatures data to calculate thermal time accumulation. The widely used Growing Degree Day (GDD) function has only one parameter, the base temperature T_b [Zalom1983; McMaster1997].

$$\text{MinMax TT} = \begin{cases} 0 & T_{max} \leq T_b \\ \frac{(T_{max} - T_b)^2}{2(T_{max} - T_{min})} & T_{min} \leq T_b \leq T_{max} \\ T - T_{avg} & T_{min} \geq T_b \end{cases}$$

Where T_{avg} is the mean of the daily minimum and maximum daily temperature and T_b is the base cardinal temperature. T_{avg} is sometimes replaced with the minimum daily temperature (T_{min}) or the maximum daily temperature (T_{max}) [Ruml2011]. A simpler GDD function is sometimes used as well [Snyder1999]. While there are other models used in the literature [Marra2001], these five capture a variety of assumptions about tree responses to temperature, and are all computationally feasible.

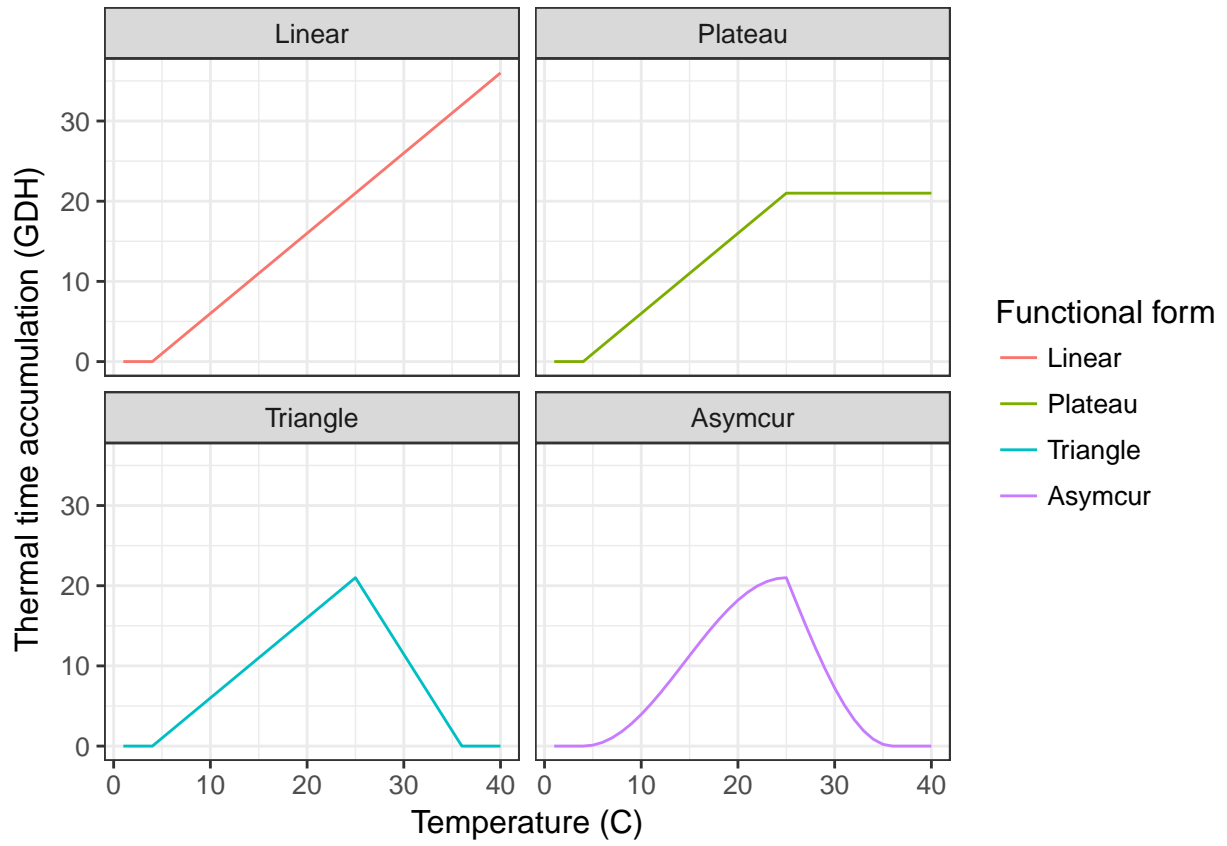


Figure 1: Visual representations of thermal time functions. For all of the functions $T_b = 4^{\circ}\text{C}$, $T_o = 25^{\circ}\text{C}$, and $T_c = 36^{\circ}\text{C}$.