The 2010 Degree-Day Phenology Model Quandary and Antidote -

A Biological Model Assessment White Paper © by Richard G. Stuff, Climate Assessment Technology, Inc.

Summary

Complacency and misusage of the world’s first and still most widely employed biological model, the degree day (DD), now fetter its original purpose – clerical phenology – and to a even broader extent the many follow-on agricultural applications (models) that use or incorporate degree-day quantities. This paper summarizes the general background and nature of the degree-day model limitations and their solution through a basic algorithmic “morphogenesis” to emend a next-generation phenology model (XP). Various XP examples and implementation tools have been drafted and are at least partially available. Justification for fomenting the overdue phenology model revision lays in its potentially vital role in securing a second agricultural green revolution, making sustainability assessments, etc. and value-added contribution to the world’s natural resource knowledge base. Propelling model upgrades into rapid scientific-technical development and agricultural user adoption phases may require implementation leadership by major plant industry members.

Background

With its introduction in 1735 by René-Antoine Ferchault de Réaumur during the natural-philosophy or European Renaissance phase of modern science, the degree day (DD) is for all practical purposes the western world’s first biological simulation model. Its basic mathematical derivation as a phenology model consists of trial-and-error estimation of one or two calibration parameters (lower and upper threshold temperatures) and a variable coefficient (total number of degree days required to reach a particular plant stage) using empirical observations mostly from natural environments.

The model appears unorthodox in today’s simulation world since the results of integration are almost always left expressed in terms of the independent variable (number of degree days rather than the biological stage response variable), but it provided a way to do bio-calculus before the invention of electronic calculators by simply adding a day’s temperature to a running total. Records of significant applications of the model suggest they were few and gradual until the employability of electronic calculators and computers generated an exponential type growth during the second half of the 20th century.

Most of the early (pre1935) degree day model related research was about the “correct” lower threshold temperatures and if they could be the same for many different plant species. Scientific publications and other documentation associated with the early degree-day work consistently included recognition of the limiting assumptions and restrictions. Mainly, the model should be successful (statistically more accurate than an average number of days) for predicting the duration plant development phases where the average rate (1/duration) is:

1. Monolithically driven by temperature (not significantly influenced by other factors or conditioned, by previous temperatures etc.)
2. Unaffected by temperatures outside the thresholds (rates remain “flat” at their higher of lower threshold value)
3. Composed of temperature response rates that are linear above or between the threshold values
4. “ “ “ “ “ “ the same from beginning to end of the biological phase
5. Based on observed air temperatures that are in some way spatially and temporally standardized relative to the temperature exposure of the observed (sampled) plants.

Another critically important but seldom recognized implied assumption (#6) is that coefficient and parameter estimates used for different applications of the model are statistically unbiased. In cases where natural spatial and temporal covariances and other interdependencies have not been properly taken into account when deriving model coefficients and parameters, limits on this assumption causes models to be overly localized or poor predictors in new seasons, or both.

Over the last 75 years, base temperatures and DD calculation methods for simulating the phenology of hundreds of insect and plant species and plant varieties have been published in both scientific and technical literature. Successful related biological applications of DD models include labeling varieties in the seed industries, scheduling “field” management practices, et cetera , and each quantity has been or could be extended to corresponding climate parameters, classifications, and maps. The proliferation of the DD model is certainly a credit to its simplicity and utility – virtuous characteristics for any mathematical representation of nature, and no other model even comes close to its widespread usage.

Also, beginning about 75 years ago, degree days began to be used in the heating and air conditioning industries to monitor and predict building energy needs as a statistical function of outdoor air temperatures. The new heating an cooling DD naming conventions probably lead to affixing the word “growing” to degree day models used for botanical applications. Other versions that became important are chilling degree days for plant vernalization and insect degree days used in entomology. Overall, dozens of other versions have been devised and named to reflect the causative variable, mathematical twist, or the subject. The term “thermal units” also became used as a moniker across the board.

During the modern-electronic era surge to find additional crop applications for the DD model, many proposed new versions were introduced with less assumption testing and apparently in some cases without even giving theoretical consideration as to how well particular derivations met any of the six assumptions.

Some of the foremost validation relaxations entered into procedures to incorporate daylength into phenology models for species known to be photoperiod sensitive. A common formulation was to multiply individual daily temperature isolates by daylength (photo-thermal units). This form installs the additional assumption that daylength affects development by parabolically interacting with (substituting for) temperature and/or days.

Incorporation of an additional variable or other model modification magnifies a major structural restriction of the model that stems from its "outside" integration of the causative (temperature) variable. With only time integrated response data available, the performance of daily aging rates cannot be tested. This data "gap"places exorbitant exactitude on the correctness of the assumed biophysical function and overall unbiasness in measuring biological and environmental variables corresponding to the integrated data points. If multiple variables are compounded into an interaction-only function in order to maintain model integration by addition of causative variables, the relative amount of biophysical correctness sacrificed and points where the model "breaks down" should be identified.

Other shortcomings of rapid proliferation era DD applications may be related to failures to distinguish between plant growth in size vs stage in ontogeny. The corresponding technical and scientific publications are weakened by descriptions, analyses or discussions that casually interchange growth and development variables and terminologies. In some cases the general acceptance of the DD model and its "growth" label may have been a contributing factor in allowing developers and reviewers to compromise assumption testing.

Probably the worst assumption neglect and corresponding abject models emerged from analyses where single-season growing DD accumulations are correlated with the cumulative growth of leaf area, plant height, biomass, etc. In most of these cases the addition of ball scores, traffic counts, or any other positive random variable can be used in place of temperature addition and usually provide equally high correlations with the particular in-season growth variable. Also in this category would be linear statistical models for correlating grain yield or other individual seasonal growth measure with some proposed compounded (thereby confounded) DD variable.

Phenology deals with the relationships between environmental factors and plant ontogeny - biological "aging" in terms of advancements (development) through identifiable life-cycle stages and/or phases. Stage transition points usually correspond to visible morphological or anatomical changes such as codledion emergence and floral initiation. In other cases plant age is expressed in terms of phases (dormancy, seedling, vegative, reproductive, senescence, et cetera) between stage points. In the life cycle of most higher plants growing in adapted environments, their ontogeny can be observed or measured independently of their growths in size, but they also can be interrelated.

Crop phenology model output is used directly for certain field management scheduling, used in conjunction with other models such as pest epidemiologies, or used indirectly to translate astrological chronologies (ISO8601 class calendar times) into plant ontological-biological age for orchestrating other physiological processes in composite model systems. In this last role the outputs often provide temporary-standin information for projections ahead of actual measured environments or residual fill-in values if actual ontogenies cannot be measured as seasons unfold. Composite model systems range from plant growth and yield models to field, best management practice assessments, to global ecosystem sustainability models.

The basic needs for phenology models that are more accurate than DD forms arise from the multitude of cases where prediction accuracy for independent years or locations is simply less than desired. Often the inaccuracies are associated with year, location, moisture, nutrient or other stresses – where it is obvious that the ontogeny-environment relationship involves something more than just linear temperature. Net inadequacy awarenesses are heightened by impacts of model errors when predicted stages are used in high-stakes crop management decision support systems (DSS) – whether for assessing in-season field level precision agriculture practices or long-range global food production.

The most demanding or absolute need for better alternatives to the degree day model occur in biotechnologies where gene-phenotype associations involve attempts to link quantitative trait loci (QTL) to phenological model response parameters and coefficients. Since actual gene-phenotypic expressions are universal in pure seed lines, the pursuit of these simulation model linkages simultaneously elevates the greater model universality objectives.

The overall economic importance of seasonal information and forecasts has increased in proportion to the rapidly growing monitoring requirements related to the earth's food supplies and natural resources. After climate forecasts and weather forecasts, the critical connecting role of the phenology model in the management of crops, other biological resources, environmental quality, recreation, et cetra makes the maximum possible ontogeny accuracy paramount. The combined realities add up to a profound, urgent need for phenology model improvement.

Transcendence to a more correct, accurate, and universal solution

A definitive plant ontogeny based quantification and functioning is the crux of the rectifying, next-generation phenology (XP, local acronym in this paper) models or model approach. In XP, rate functions and integration are expressed in floating point plant stage quantities and ISO8601 time becomes a separate interval-timing index that is a common to both the dependent and independent variables. While XP appears as a slight tactical change from the DD approach, it represents a major strategical change in model premise-inference framework. More data ciphering, open-ended formulation options, reduced assumptions, and straightforward operational products are key parts of XP phenology's needed scope.

The main data difficulty is the acquisition of short-interval differential measures (the mathematical ***dy*** pieces of the derivative function) of ontological change (aging is still one of natures best kept secrets). The daily time step is a practical, common denominator for higher plant species with long (>30 day) life cycles since photoperiod and circadian factors may be involved. But since most of the causative variables (mathematical independent variables) have large diurnal changes, it may be pragmatic to also integrate hourly functions into XP models.

Most of the best quality "***dy*** estimates" to date are indirect phase average rate data that are derived from controlled environment experiments. If phase averages are derived from natural environment sources, the range of location-years should be maximized through global locations, multiple plantings each year, and statistically accounting for spatial-temporal multicollinearities in the causative variables. Global ecosystem monitoring and phenology networks can be valuable data sources. Some response signal detail will be lost in data from natural environments since it is almost impossible to get sufficient homogeneous blocks of driver variables over intervals longer than a couple hours or days.

Regardless of the source of the rate response measurements, there is the primary and important task of defining the stage points between which assumption #4 holds and establishing a standardized method for recognizing the occurrence of those "cardinal" points. Defined sets of plant stages like the BBCH and precise descriptions of the corresponding morphology and anatomy such as those established by the Plant Ontology Consortium are available for selecting cardinal stages and deriving assumption #4 compliant average rates. These same resources allow simulated rates and integrated stage fractions of the model's internal scale to be translated to digital values on any user required output scale.

Given ontological rates as fractions of cardinal unit stages and the corresponding environmental variables, a full array of mathematical functions can be assembled to specify comprehensive, robust, multivariate relationships with core driver variables (model builds). The functions should represent the truest possible integrated knowledge of plant ontological processes and tissue functioning and their associations with QTL's and other physiological processes in terms of empirical, phenomenological, and verifiable mechanisms and subjected to statistically correct parameterizations and calibrations.

A significant part of the pioneering and prototypical work is in place or under way, in terms of initial data logging, model constructions, and implementation tools. Two noteworthy and early efforts were the bio-meteorological time scale (1968) by George Robertson and the digitized base 10 decimal scale of Jan Zadoks (1974).

Like most new technologies, XP phenology models must demonstrate practical application benefits for end users in order to be adapted and proceed to replace an ingrained method. Compared to DD models, XP requires more science and computing (ICT) resources on the development side but in most applications the underlying technology can remain totally out of user's sight. Daily plant stage outputs can be directly related targeted field observations and prediction schedules for the remainder of the season.

In addition to the indirect and intangible advantages of the XP format, it should offer a 2 to 10 fold accuracy increase to achieve rapid adoption. For example, if a standard DD model is converted to its XP equivalent that is limited to a linear temperature function over the same range, the end-point schedules (resulting dates of the cardinal stages) will have the same values and accuracies. The XP advantages in this case start with improved intelligibility of outputs and likely immediate appearance of ways to improve the model.

Phenological applications related to maturity classifications of agronomic crops have large economic values and may present the greatest returns for early XP adaptors. A simple value added service that dynamically lists and charts optimum planting and projected stage schedules for remaining current season dates and for local (at least to a U.S. zip code equivalent level) average season dates is made feasible for farm managers through the internet, networked mobile devices, or preprogrammed hand calculators. The model outputs could also display statistical probabilities (early and late ranges) of stage events, etc. At regional monitoring, advisory, and forecast application levels, geographic information systems (GIS) make it feasible to dynamically and interactively map this information and more.