Almond Fruit Phenology Model

Project No.: **09-HORT10-Gradziel**

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Objectives:

A. Recover as complete a data set as possible from Dr. Kester's almond bloom and fruit phenology studies. Attempt to complete the development of a fruit/embryo growth or phenology model for the variety Nonpareil in a form useful to Farm Advisors and other almond researchers and as a possible extension publication.
B. Test the proposed model for its value as an early predictor of developmental times for full bloom, seed development and in particular, hull-split for *Nonpareil*
C. Evaluate seed development data from the 1980s and more current research to assess the role of incomplete seed fill as a determinant in final variety yield potential.

Interpretive Summary:

Almond production in California is an exceptionally complex undertaking in the best of times, and has become increasingly difficult due to the rapid changes in agrochemical, water and insect pollinator availability, and climate change. Modeling the potential consequences of these changes allows some insight concerning the ramifications of different cultural practices and provides a rational foundation for the development of effective recommendations. An ambitious effort is currently underway for a comprehensive modeling of almond crop production under the primary direction of Bruce Lampinen and Ted DeJong, which utilizes recent technological advances to allow the gathering of immense amounts of field data and its subsequent analysis through advanced computer programs.

An equally ambitious attempt at modeling almond fruit development or 'phenology' was undertaken in the early 1980s by Dr. Dale Kester and cooperating Farm Advisors including Joe Connell, Mario Viveros, and Mark Freeman, and while extensive and detailed data was collected for several varieties including *Nonpareil*, final analysis and information extension was never completed. In our current efforts to complete this analysis, most of the data has had to be transferred manually or through statistical summaries, since the original data collection was undertaken before standard computer spreadsheet programs were established. A complete

printout of 1982, 1983, and 1984 data has now been recovered and made available to other researchers/crop modelers. In addition, a nearly complete set of 1983 and 1984 field data/summaries has been recovered on old format diskettes (5 1/4 in.) but in an obsolete computer format (Kaypro CPM). This data has also been made available to the current Lampinen/DeJong penology modeling project along with web sources useful for translating CPM data to an Excel spreadsheet format.

The ultimate objective of this early research was the use of accumulated degree days to develop a better prediction of the time of hull-split initiation for facilitating navel orangeworm control. While this approach (using 1980's data) provides only a relatively good prediction of kernel development, its ability to predict hull-split initiation was even poorer than the much less tedious approach of predicting hull-split based solely on calendar date (Julian date). The poor correlation between accumulated degree days and key almond phenological stages such as hull-split appeared to be the consequence of sizable regional differences in cultural practices, particularly fruit set, and level of fertilization and irrigation.

The apparent failure of this type of preliminary model is, in fact, one of its benefits since when the model fails in predicting real-world responses it directs us to specific limitations in our knowledge. In this way models have the capacity to evolve; the model inherently identifies information-deficiencies precluding its effectiveness, leading to sequential improvements in its accuracy until it achieves 'expert-systems' status where predictions can be trusted. A more accurate model of almond orchard and tree productivity, such as that currently being developed by Lampinen and DeJong, would have valuable benefits (for example, predicting the optimal balance between fertilizer and/or water use and crop yield). Since these more complex models depend on large amounts of detailed data, the availability the 1980's data results could also be of value. In addition, comparison of production trends based on current field data with comparable trends from the 1980's can help gauge the extent of improvements in critical cultural practices, including pollination, fertilization, irrigation and orchard design over this time period.

Materials and Methods:

The original data was collected from the Kern County Farm, Bakersfield, the Buekelman Farm, Dixon as well as early regional variety trials in Butte, San Joaquin, Merced, and Fresno counties. Data was collected /evaluated by Dale E. Kester, L. M. Klungness, M. Viveros, J. Connell, D. Rough, M. Freeman, S. Fidel, L. Hendricks, Warren C. Micke, and S. A. Weinbaum. Multiple cultivars, including Nonpareil, were sampled in pre-1983 data, with only Nonpareil sampled in 1983 and 1984 data. All measurements were made twice per week at Kern County Farm, and Buekelman Farm, Dixon, while cooperating farm advisors took bloom, embryo, nut filling, and hull splitting data in Butte, San Joaquin, Merced, and Fresno counties once per week. Early 1982 and 1983 data was collected for defined development stages analogous to the biofix stages in insect development as presented in **Table 1**. The BASETD computer software (IBM mainframe) which was initially used by IPM (Integrated Pest Management program) to develop the successful phenology model for predicting navel orangeworm development based on accumulated degree days, was then used to determine the most effective temperature parameters for determining developmentally relevant degree day accumulation (i.e. defying the minimum and maximum thresholds to include in the model;

for example, temperatures below freezing (32°F) were found to have no effect on development rate and so excluded from the model). After recognizing the inappropriateness of the biofix approach to modeling the more incremental plant development, 1984 data was more quantitative (i.e. measuring the incremental changes in development rather than the attainment of fixed, developmental and points; for example, measuring the increase in embryo length at each test period, rather than simply determining whether the early embryo was visible or the full-sized embryo (i.e. filled the ovule) 'biofix' stage had been achieved). Measurements in 1984 were as follows: 1) Bloom was estimated as the percent of open flowers; 2) Embryo development was estimated by embryo length relative to ovule length; 3) Late kernel filling was also measured as kernel dry weight; 5) shell hardness was measured as the force required to puncture through the shell to the hull; 6) Hull splitting was measured as the percent of nuts in each of six standard stages of dehiscence.

Results and Discussion:

Table 1. Optimal minimum and maximum temperature thresholds for modeling discrete developmental stages (biofix) as characterized by the minimum coefficient of variance and as determined by the BASETD IPM program.

Nonpareil Development Stage	Optimal Threshold Temperature (°F)	Coefficient of Variance
Bloom=10 %	32 to 62	0.034
Bloom= 100%	32 to 66	0.033
Shell puncture force=lKg	32 to 56	0.005
Kernel wt. reaches 0.5g.	32 to 60	0.029
Enbryo presence = 100%	32 to 72	0.125
Full embryos= 100%	32 to 78	0.046
Shell puncture force=2Kg	32 to 76	0.024
Presuture nuts= 0%	32 to 78	0.027
Kernel wt.=1.0g.	32 to 78	0.031
Dehisced nuts=100%	32 to 90	0.021

1982/1983 data.

The BASETD IPM program allowed the otherwise very tedious calculation of the optimal degree day model to use for predicting attainment of each of the targeted developmental stages (**Table 1**). This was achieved by the rather brute force, trial and error approach of calculating mean degree day interval for a range of minimum and maximum temperature thresholds extending from freezing to approximately 100° F. Threshold showing the best agreement with observed crop development among the different evaluation sites were selected as the most appropriate for analyzing that developmental stage of the phenology model (**Table 1**). While early results showed promisingly low coefficient of variances for the targeted development stages, application of the subsequent model for predicting specific developmental stage based on accumulated degree days showed unacceptably high confidence intervals (**Table 2**). For example, the confidence interval was almost 30 using of the derived degree day model for predicting 100% nut dehiscence and so would be of little value for accurate field predictions. Similarly while the calculated Mean Degree Days are informative relative to the overall development, the accumulated degree day values calculated for individual evaluation sites often differed considerably from each other, undermining the regional predictive value of this mean, as presented. While part of the failure of the 1982/1983 modeling exercise resulted from the wide cultural and environmental differences among sites, a greater source of error was perceived to be the biofix approach to characterizing development level. While biofix stages work well in characterizing insect development because of their discrete developmental stages, plant development is more incremental and so more vulnerable to misclassification. For example, under the biofix model approach, early embryo development was characterized either as present (visible) in all nuts evaluated on that date or completely developed in all nuts evaluated on the given date. Because sampling was relatively infrequent (weekly or biweekly), many developmental stages were between biofix intervals on the date evaluated, yet the biofix approach used did not allow any opportunity to characterize the extent of that development between those intervals, resulting in a high coefficient of variance and so a large probability of error.

Table 2. Calculated Mean Degree Days and associated confidence interval for the attainment of targeted developmental stages (biofixes) as determined by the BASETD IPM computer program.

Nonpareil Development Stage	Coefficient of Variance	Mean Degree Days	Confidence Interval (alpha = 0. 05)
Bloom=10%	0.034	516.00	5.35
Bloom=100%	0.033	801.17	7.58
Shell puncture force=IKg	0.005	1551.32	3.49
Kernel wt.reaches 0.5g.	0.029	2244.23	30.71
Enbryo presence=100%	0.125	2882.20	72.21
Full embryos=100%	0.046	3468.67	34.85
Shell punctureforce=2Kg	0.024	3585.78	39.67
Presuture nuts=0%	0.027	4573.03	28.08
Kernel wt.=1.0g.	0.031	4343.32	61.99
Dehisced nuts=100%	0.021	6109.82	28.15

1984 data.

To better characterize the incremental progression of development in almond, 1984 data collected was more quantitative than qualitative (i.e. measuring the extent of development versus the attainment of well defined development stages (biofix approach)). New sampling procedures were also implemented in efforts to avoid sampling bias. The five regional orchard plots were again used in which 10 Nonpareil trees were randomly selected for sampling. On each sampling date 20 nuts were evaluated, which, given the approximately 40 sampling dates employed, and resulted in approximately 40,000 measurements. The principal parameters measured were kernel (embryo) length, nut fresh and dry weight, and width and length of suture split during dehiscence.

As with 1983 data, while a large amount of sampling data was obtained by the principal investigators as well as cooperating Farm Advisors, only approximately 60 to 70% of the data appeared to be compiled on either the IBM mainframe computer databases or Kaypro CPM files. This apparently was the consequence of the recognition by the principal investigators of the still poor performance of the 1984 model based on preliminary 1984 data analysis. Results from about 50% of the 1984 kernel dry weight data (i.e. approximately 20,000 data points) is presented in **Figure 1** where combined regional site means are plotted against either time (Julian days) or accumulated degree days. While both plots show good sample data agreement with the predicted weight (centerline) particularly early in development, sample deviation from prediction increased significantly with increasing time, so that by the time of hull-split, multiple sample means deviate well beyond the 5% confidence intervals (outer lines). More importantly, while the plot based on the accumulated degree days showed better agreement with the prediction line early in the season, predictions based solely on Julian days were more accurate during the crucial late-season sampling when hull- split would occur. [Final regional site sampling occurred only to the end of August, 1984 with further sampling either not performed or not recorded in the final documents/files]. In short, despite the Herculean efforts to develop an accumulated degree day model based on extensive Central Valley field data, the results were inferior to predictions based solely on calendar date.

More comprehensive evaluation of the 1984 data identified two major causes for the model failure. 1) Several other factors besides heat units (degree days) influence almond development, particularly at the inherently variable hull-split time. 2) These factors include environmental and cultural conditions which were found to vary greatly among sites. For example, crop conditions varied from record yields in Kern County to yields that were only 1/3 normal in Dixon (due probably the inclement weather at pollination). Large differences were also recorded for maximum day/night temperatures, irrigation levels, fertilizer inputs, and soil types, and these differences were often in conflict (for example, Kern County had some of the highest heat units but the lowest levels of irrigation water). While many of these differences and local trends were identified and evaluated in the final 1984-85 statistical analysis of the project data, most are inherently speculative given the extensive differences between locations and the failure to identify a useful common denominator (i.e. the model) to unify developmental process among the different sites. The combined data, however, can still be useful for data mining in more focused areas as demonstrated in the following analysis.

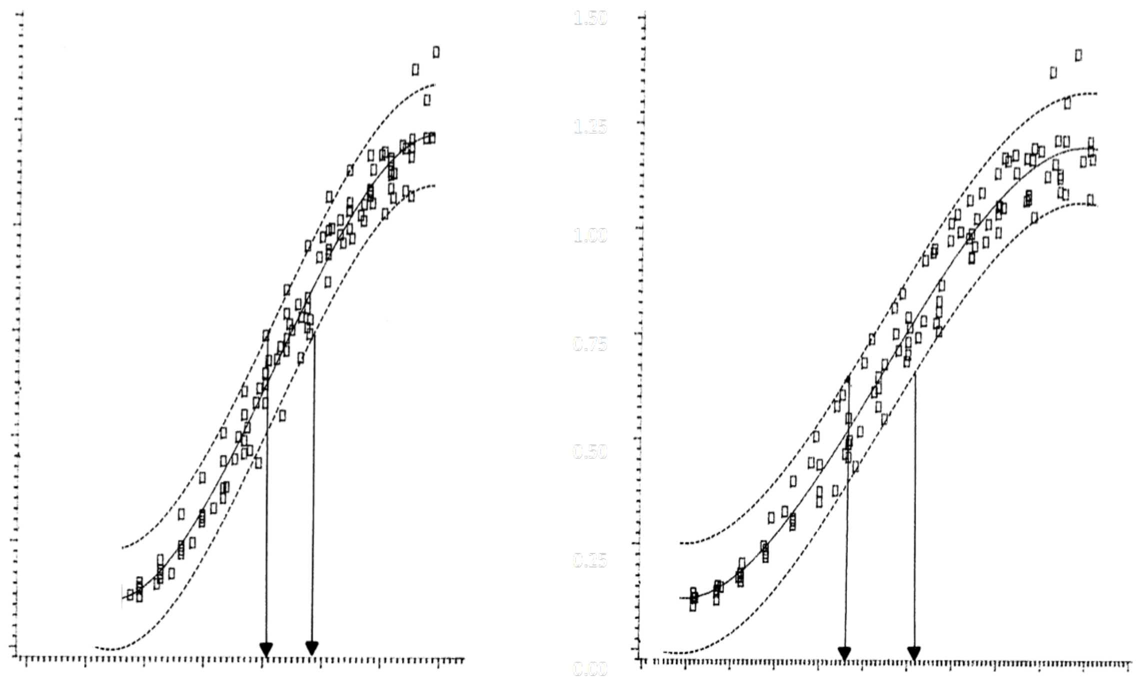

Figure 1. Nonpareil kernel development as characterized by change in kernel dry weight with time, calculated either as Julian days (days from January 1) or as accumulated degree days as calculated using the temperature thresholds developed in **Table 1**. Arrows denote confidence interval at the least variable midpoint of the curves showing less variability (and so greater predictive potential) for Julian days relative to the accumulated degree day model used.

Data mining using 1983 and 1984 flowering/nut set data.

The extensive database on flower numbers and bearing habit (shoot versus spur) and final nut sets was evaluated from 1983 and 1984 field data to determine the relative importance of bearing habit on final yield. In mature, bearing Nonpareil trees, spur production accounted for the majority of effective fruit bearing units contributing to yield (**Figure 2**) as spurs are more efficient than shoots in balancing fruit renewal with the more carbohydrate-costly vegetative growth. In addition, in a highly productive cultivar such as 'Nonpareil', spurs were found to have a higher fruit-set efficiency than flowers on shoot presumably because of a greater availability of spur-stored carbohydrates in the more flower-limited spurs compared with the much higher flower density shoots.

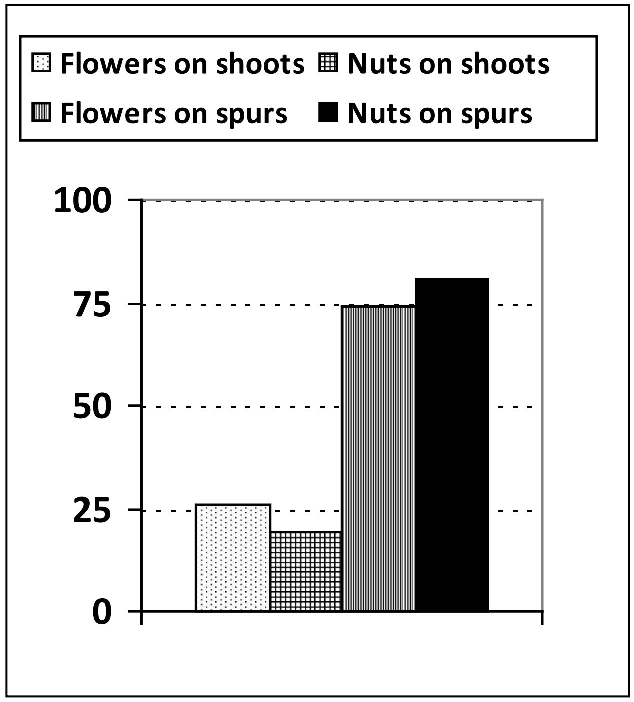

Figure 2. Predominance (as %) of shoot-flowers to spur-flowers on 10 year old Nonpareil trees and the ultimate predominance of spur borne nuts to final yield.

Interestingly, results also indicated that spurs with high initial flower counts (3-4) have higher fruit-set efficiencies than spurs with only 1 to 2 flowers. The initial number of flowers developing per spur is probably an indication of the total carbohydrate reserves locally available to that spur at the time of flowering (and prior to leaf development) with greater carbohydrate winter reserves facilitating higher levels of flower initiation/development.

This is consistent with the current DeJong Development Model where flower/fruit carbohydrates come primarily from nearby leaves with more distant transport of much less importance]. These preliminary results would suggest that a useful indicator of early cropping potential (even prior to flowering) would be the relative number of flowers per spur. Greater flower numbers might indicate greater local carbohydrate reserves available to that spur and so greater ultimate flower fecundity (i.e. higher final nut sets). Thus, this 25 year old data still has value both for helping answering old production/pest control questions as well as identifying potentially important new questions.

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