
Developing a Carbon Budget, Physiology, Growth and Yield Potential Model for Almond Trees

Project No.: 13-PREC1-DeJong

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Objectives:

This project has two objectives. The main objective is to develop a comprehensive functional-structural tree model of almond tree architectural development and growth, carbon partitioning/source-sink interactions, annual and multi-year carbon budgets and yield potential of almond trees. This model will simulate growth and physiological responses to light distribution within the canopy and daily temperature and water potential changes as well as respond to user imposed pruning practices.

A second objective is to complete collection of data on almond tree growth, standing orchard biomass and orchard productivity. These data will then be used to estimate the amount of carbon sequestered in the standing biomass of almond orchards as well as to provide data for validating the long-term biomass accumulation projections of the L-Almond model that is being developed in the main objective.

Interpretive Summary:

Objective one. Almond tree growth and yield is dependent on a complex set of interactions involving the plant genotype, the physiological and developmental processes that occur within the tree, the interaction of these processes with the environment that the tree grows in, and responses to horticultural manipulation of the tree by the grower. Understanding carbon budget, growth and yield responses of

perennial crops like almond are even more complex than most crops because the effects of all these factors are carried out over multiple years.

Recent advances in computer technology have made it possible to develop functional-structural plant models that simultaneously simulate whole plant photosynthesis, tree architectural growth and carbon partitioning within the structure of the tree, and to display tree structural development in three dimensions on a computer screen. The most advanced of these types of models is the L-Peach model (Allen et al. 2005, 2007; Lopez et al. 2008). One objective of this project is to convert the L-Peach model to an L-Almond model.

The first step for conversion of L-Peach to an L-Almond model was to develop statistical models to describe patterns of buds that occur along Nonpareil almond shoots of different lengths. Development of these statistical shoot bud fate models for Nonpareil are now complete. The second step was to begin converting the L-Peach model into an L-Almond model by inserting leaf photosynthetic characteristics of almond trees and the statistical models of almond shoots into the L-Peach model. This has been done and we began to validate the architectural aspects of simulated trees with pictures of actual orchard trees of various ages. However we ran into difficulties with doing simulations of tree growth over periods longer than three years in almond trees because running simulations according to current grower practices required not pruning after the first year. This caused the tree structure to become too complex because all shoots were maintained indefinitely. To address this we have incorporated a new canopy light distribution program into the model and also have developed a new sub-model for the shedding of leaves and stems that are located in the excessively shaded areas of the canopies. We are now beginning to test the functioning of the leaf and stem shedding functions.

In 2013 we also completed upgrading the simulation of annual carbohydrate storage and mobilization in woody tissues so that the tree growth and development can be simulated over multiple years (DaSilva et al. 2014). The primary work on the model that remains is validation of both the quantitative and visual outputs of the model. This is mainly being done by comparing model outputs with data and pictures previously collected in Dr. Lampinen's laboratory.

Objective two. A review of available literature on tree growth; dry matter partitioning and biomass productivity of almond trees over multiple years indicated that there is not enough published data to make reliable estimates of the amount of carbon contained in the standing biomass of mature almond orchards from published literature. However in the past several years it has become standard practice to engage professional tree removal companies to remove almond orchards at the end of their productive life. Since these companies haul and weigh the chippings subsequent to the removal of an orchard, reasonable estimates of orchard standing biomass are available from these operations. Tree size and density vary greatly among orchards so it was necessary to develop a way to estimate the standing biomass in an individual orchard in a relatively simple manner. To develop a simple method for estimating standing biomass in existing orchards we began surveying specific orchards prior to removal to determine

the average tree trunk cross sectional area (TCSA) per acre. We then attempted to develop a mathematical relationship between TCSA/acre and the amount of biomass removed in the clearing process. Preliminary data shows that survey measurements of trunk cross sectional area are useful when the orchards being removed are mainly in tact (few missing trees) but of more limited use in some old orchards. We recently began working with the LandIQ Company to determine if aerial images of orchards can be useful for addressing this problem.

Corollary efforts associated with this project have been the analysis of data from Regional Variety Trials and the spur dynamics study carried out by Dr. Lampinen's laboratory from 2001 to 2007, in order to develop data on long-term spur behaviour that can be used in the L-Almond model. Research by a PhD student not directly involved with this project but associated with Dr. DeJong's laboratory has also provided valuable insights into the chilling requirements of almond trees that will be valuable for modelling tree growth and yield of almond trees over multiple years. Collectively the research associated with this project has provided valuable insights into the fruit production behaviour of almond trees that are useful for general understanding of almond tree productive behaviour as well as for developing the L-Almond model.

Materials and Methods:

Objective one: Development of an L-Almond Model. Developing a model of almond tree growth began with statistically analyzing the structural patterns of various sizes of almond shoots using Hidden Semi-Markov Chain (HSMC) analysis techniques (Guedon et al. 2001). This work began in 2010 in a commercial 4-year-old almond orchard located near Sutter. This orchard had three cultivars ('Nonpareil', 'Aldrich', and 'Winters') exhibiting different tree architectures. Trees in the orchard were minimally pruned after the first year after planting, when the main scaffolds were chosen, so that trees developed their own architecture. Details of this study are presented in Negrón et al. 2013. Two additional studies of almond shoot architectural structure were completed. One investigated the influence of water stress on shoot architecture (Negrón et al. 2014a) and another investigated the effects of pruning severity on subsequent shoot structure (Negrón 2014b)

Shoot structural models from these studies were inserted into the L-Almond model in the same way as previously done for the L-Peach simulation model (Smith et al. 2008). Previously collected data on almond leaf and fruit growth characteristics (Esparza et al. 1999) were also used to convert the photosynthesis and fruit growth sections of the latest versions of the L-Peach model (Da Silva 2011 and 2014) into an L-Almond model.

When the current L-Almond model was run with the updated shoot Markov-chain models the model crashed in the 3rd or 4th year of simulated runs due to excessive canopy complexity. We believe that this is due to an inadequate within-canopy light simulation model and the related inability to program leaf and shoot death due to internal canopy shading. An L-systems computer programming expert from the Computer Science Department at the University of Calgary (Dr. Mik Cieslak) has recently been hired on a short-term contract to address this issue with new canopy light

simulation and stem shedding sub-models. Since this is ground-breaking research it is too early to determine the success of this approach.

Objective two: Assembling Data on Whole Tree Biomass. We have developed a working relationship with G & F Agricultural Services Inc. and have cooperated with them to compile data on recently removed orchards. While we were doing this data compilation, we realized that we needed to develop a surveying method that would allow us to relate biomass removal data with average tree size prior to tree removal. Since tree trunk cross sectional area (TCSA) is a common method to estimate tree size used in horticulture as well as forestry we tested a linear plot sampling method to quickly determine the mean TCSA/acre of specific orchards slated for removal, prior to their actual removal. This method allowed good biomass estimations for intact orchards but was not adequate for orchards with numerous missing trees or a wide range of trees sizes. We have recently begun working with Land IQ to determine if use of aerial photographs of orchards slated for removal can be used simply to provide adjustments to address this issue.

Associated Studies. A corollary effort associated with this project has been the analysis of data from the Regional Variety trials sponsored by the Almond Board (1993-2005) and from the spur dynamics study carried out by Dr. Lampinen's laboratory from 2001 to 2007. This was done to develop an understanding of factors controlling bearing and long-term spur behaviour needed for developing and validating the L-Almond model. We published one research paper from this effort in 2010 and another in 2011. We are working on one additional paper concerning factors that influence fruit set at the spur and tree level.

Results and Discussion:

Objective one: Development of the L-Almond Model. The L-Peach model has been successfully converted to an L-Almond model. Physiological functions describing the behavior of almond fruits and leaves needed to make this conversion came mainly from the DeJong laboratory (Grossman and DeJong 1994, Esparza et al 1999, Esparza et al 2001a). Statistical shoot models for describing the architecture and bud fates of Nonpareil, Winters, and Aldridge shoots were developed (Negron et al. 2013).

At present only the Nonpareil shoot models have been inserted into the L-Almond model in the place of statistical models describing peach shoots. Eventually, after the Nonpareil version of L-Almond has been satisfactorily validated, it will be relatively easy to adjust the model to simulate the growth of the Winters and Aldridge cultivars.

The L-Almond model is capable of making reasonable simulations of architectural tree growth and cumulative biomass during the first three or four years after planting. Initial runs of the model indicated that additional work was necessary on the over-wintering storage and spring mobilization of carbohydrate in the stems and roots. Preliminary adjustments have been made on the model but future data collection on this aspect of the physiology of almond will be necessary to insure that modeled behavior is accurate.

Currently, simulations of unpruned trees beyond four years are not possible because the model keeps track of every plant part at the node level and when the simulated tree gets large, the simulations get bogged down because of physical limitations in computer hardware. We have enlisted the help of a computer scientist to install a shadow propagation light model into the L-Almond model (**Figure 1**) and are now in the process of testing a new leaf and stem shedding model that will be driven by simulated lack of light in the more dense areas of the canopy. It is too early to report results of this leaf and stem shedding sub-model.

Objective two: Developing a database on standing biomass in almond. Since relatively little published data are available on whole tree biomass accumulation in almond trees, we have worked with professional orchard removal companies to obtain data from them on the weight of chippings they obtain subsequent to the removal of an orchard. While this has been more difficult than anticipated, we have made good progress on this objective. Data from 61 removed orchards representing 2034 acres indicated that orchard standing biomass varies greatly among orchards. In this set of removed orchards the amount of dry biomass removed varied from 4 to 63 dry tons per acre with the mean and median dry tons per acre removed being 27.7 and 26.3, respectively. Based on our orchard removal data it is likely that a standing orchard that is 20 years old or older and has a limited number of missing trees contains between 30 and 40 dry tons of biomass per acre. This would represent approximately 12 to 16 tons of carbon per acre.

In order to more accurately estimate the standing biomass of specific orchards we began ground surveying orchards to estimate orchard mean trunk cross sectional area (TCSA) prior to orchard removal and we correlated mean TCSA/acre values with standing biomass data collected upon orchard removal. While there was a good correlation between mean orchard TCSA in orchards with few missing trees the majority of orchards being removed had substantial numbers of missing trees, or trees with highly variable sizes, so we have begun collaborations with the Land IQ company to determine if aerial photography can be effectively used to provide covariate data in order to more accurately estimate standing biomass on non-uniform orchards.

Associated Studies. Studies associated with this project and a previous project were based on an analysis of data from the Regional Variety trials sponsored by the Almond Board (1993-2005), data from the spur dynamics study carried out by Dr. Lampinen's laboratory from 2001 to 2007 and research of a PhD student (Katherine Pope) in Dr. DeJong's laboratory

Developing an Integrated Understanding of Almond Tree Productivity

This project and the studies associated with this project have provided a better quantitative understanding of the factors determining the productivity of almond trees. Previous research by Dr. Lampinen's laboratory (Lampinen et al. 2012) indicated that an orchard that intercepts 85% of solar radiation at mid-day should be capable of producing approximately 5000 lbs. of almond kernels. If an individual kernel weighs 1 gm, then at a standard planting density of ~120 trees per acre, each tree must produce

~19,000 nuts per tree. The almond spur studies indicate that this will require ~15,000 bearing spurs per tree. However, on average only ~15% of the total spurs population bears fruit in any one year, so the total population of spurs in a tree is ~100,000. Of these, ~15,000 spurs bear fruit in the current year, another ~15,000 bore fruit last year (our data shows that spurs very rarely bear fruit in two subsequent year), ~10% (10,000) will die (and need to be replaced), ~20% (20,000) flowered but did not bear fruit, and another ~30% (30,000) spurs rested in the current year potentially because they did not have enough leaf area to stimulate flower production (Lampinen et al. 2011, Tombesi et al. 2011).

The key to maintaining high yields would appear to be maintaining healthy spur populations and doing whatever is possible to stimulate increasing numbers of the 100,000 spurs to flower and set fruit in a given year. However it should be kept in mind that if abnormally high numbers of spurs fruit in any one year the percentage of spurs resting in the following year, due to previous year production will increase and the numbers of spurs in the potentially productive spur pool will decrease. It is likely that the upper limit of the number of healthy spurs that a tree can maintain is a direct function of the amount of light the tree canopy intercepts to supply adequate photosynthate to the spurs in conjunction with adequate nutrients and water in the tree.

Our modeling studies also indicate that there is an upper limit to the number of nuts that a tree can support, particularly during the period between 30 to 50 days after bloom. During this period potential fruit growth is very rapid (~1300 g/tree/day for 19,000 fruit or ~ 0.07 g/fruit/day). The estimated tree photosynthetic rate for this period is 400 – 800 g/tree/day and thus fruit growth is partially dependent on a dwindling supply of stored carbohydrates (the estimated total supply of available stored carbohydrates during the whole winter and spring season is ~14,000 g/tree/season) (based on Da Silva et al. 2014 and Esparza et al. 1999).

More research needs to be conducted to understand what limits the percent of spurs that produce flowers, factors that determine the percent of flowering spurs that set fruit (other than factors affecting pollination) and the rate of depletion of stored carbohydrates during the first 50 days after bloom.

Publications

Overall, this project and studies directly or indirectly associated with this project have resulted in eight significant publications related to almond tree growth and productivity.

- 1) The first provided an understanding of the relationship between Spring temperatures and the timing of hull-split.

Fruit development in almond is influenced by early Spring temperatures in California
S. Tombesi, R. Scalia, J. Connell, B. Lampinen and T.M. DeJong
Journal of Horticultural Science and Biotechnology (2010) 85:317-322.

Abstract: The period from full bloom (FB) to fruit maturity for individual cultivars of peach, nectarine, plum, and prune is influenced by daily temperatures between the start

of FB and 30 d after FB (DAFB). Typically, warm Springs accelerate fruit development. Almond is closely-related to peach, but the date of fruit maturity is not always closely related to the date of harvest. Normally the date of “hull-split” (HS) signals the beginning of fruit maturity. The aim of this study was to determine if the length of the period between FB and HS in several important Californian almond cultivars was related to temperatures shortly after the start of FB. Data on the dates of FB and HS from three locations in the Central Valley of California (North, Central, and South) were analyzed over 8 years to determine the effect of Spring temperatures on the duration of fruit development. Data on 28 cultivars were evaluated, but only the results for 12 of the most important cultivars are reported here. The length of the period of fruit development from FB to HS was negatively correlated with the accumulation of degree-days between FB and 90 DAFB (mean $R^2 = 0.51 \pm 0.3$), with generally poorer correlations with degree-days to 30 or 50 DAFB (mean $R^2 = 0.31 \pm 0.02$ and 0.36 ± 0.3 , respectively). These results suggest that temperatures in the first 90 DAFB are the primary factor influencing the time of nut maturity in almond cultivars in California.

Data from this paper have been used to develop a web-based model to help growers predict hull-split in their orchards by late May of each year. See: Hull-split Prediction Model at

http://fruitsandnuts.ucdavis.edu/Weather_Services/almond_hullsplit_prediction/Hull_Split_Calculator/

- 2) The second publication provided insight into the factors that influence individual spur productivity and mortality in almond tree canopies.

Spur behaviour in almond trees: relationships between previous year spur leaf area, fruit bearing and mortality

*Bruce D. Lampinen, Sergio Tombesi, Samuel Metcalf and Theodore M. DeJong
Tree Physiology (2011) 31: 700-706*

Abstract: In mature almond (*Prunus dulcis*) orchards the majority of crop is borne on spurs (short, proleptic shoots) that can live for several years and can produce from one to five fruit. Previous research has led to the hypothesis that spur longevity is related to spur light exposure, cropping and age. However, limited quantitative data are available to substantiate these hypotheses. The objective of this study was to determine spur characteristics that were most highly correlated with spur productivity and longevity in mature, bearing almond trees. We particularly focused on characteristics related to the spur light environment and spur crop load. Previous year spur leaf area was strongly related to spur viability and flowering; the greater the leaf area in the previous year, the higher the probability of spur survival into the next year and the higher the probability for the spur to bear one or more flowers. Previous year bearing also appeared to influence viability and return bloom, especially in spurs with low leaf area. These results suggest that spur source-sink balance is basic to the life cycle of almond spurs. Furthermore, the results are consistent with the hypothesis that spurs are semi-autonomous organs with respect to carbohydrate balance for much of the growing season. The models developed from this work will provide the basis for developing a functional-structural almond crop model that simulates cropping at the spur level. Finally, this information

provides general thresholds for maintaining spur viability and productivity that will be useful for developing and evaluating tree training systems and orchard management practices.

- 3) The third publication increased understanding of the potential for almond orchards to yield large crops in two successive years.

Relationships between spur- and orchard-level fruit bearing in almond (Prunus dulcis)
Sergio Tombesi, Bruce D. Lampinen, Samuel Metcalf and Theodore M. DeJong
Tree Physiology (2011) 31:1413-1421

Abstract: Almond is often considered to be a moderately alternate-bearing species but historical yield data typically do not exhibit clear patterns of alternate bearing at the orchard level, while research has indicated that spurs (the main fruit bearing unit in almond trees) rarely produce fruit in two subsequent years. The objective of the present work was to analyze the bearing behavior of almond trees at both the orchard level and the individual spur level over multiple years to explain this apparent paradox. The 10-year yield patterns of three almond cultivars grown at three different sites within California were analyzed for tendencies of alternate bearing at the orchard level. At the individual spur level, data on spur viability, and number of flowers and fruits per spur were collected on 2,400 individually tagged spurs that were observed over 6 years to characterize bearing at that level. At the orchard level one cultivar (Nonpareil) did exhibit a tendency for alternate bearing at one site (Kern), but other cultivars and sites did not. The orchard and the individual trees in which the spur population study was conducted showed tendencies for alternate bearing but the spur population did not. Only a relatively small percentage of the total tagged spur population bore fruit in any given year and therefore while individual fruiting spurs exhibited a high level of non-bearing after fruiting the previous year, the spurs that did produce fruit in any year generally did not constitute enough of the total spur population to exhibit alternate bearing at the whole population level. Our results suggest that annual bearing fluctuations in almond are probably mainly due to year-to-year variations of parameters affecting fruit set, and that high rates of fruit set in a given year may involve a larger-than-normal percentage of a spur population in fruit bearing. This would limit the size of the spur population available for flowering in the subsequent year and could cause alternate year bearing. However, from historical records, this would appear to be the exception rather than a normal circumstance. Therefore, almond should not be considered a strictly alternate-bearing species.

- 4) Fourth, this study provided statistical models for the structure of shoots of three almond cultivars that can be used in the L-almond model.

Systematic Analysis of Branching Patterns of Three Almond Cultivars with Different Tree Architectures.
Negron, C., L. Contador, B. D. Lampinen, S. G. Metcalf, Y. Guedon, E. Costes and T. M. DeJong. 2013.
J. Amer. Soc. Hort. Sci. 138:407-415.

Abstract: Different almond (*Prunus dulcis*) cultivars have been characterized by their contrasting shoot branching patterns; however, the differences between patterns have been difficult to quantify. This study aimed to model the branching patterns of 2-year-old proleptic shoots on three almond cultivars (Nonpareil, Aldrich, and Winters) representing different tree architectures. The effects of branching pattern on flowering were also studied. The branching patterns of shoots of different length categories were assessed by a single hidden semi-Markov model for each cultivar. The models identified zones of homogeneous branching composition along shoots and were used to extract the occurrence and number of nodes of the zones according to shoot length categories. The numbers of flower buds were also determined for each shoot length category in each cultivar. The models of branching patterns of 'Nonpareil' and 'Aldrich' were similar and differed from the 'Winters' model. 'Winters' shoots produced more zones, but some of the zones had similar characteristics as previous zones and thus appeared to be repeated. This cultivar also had more spurs and syleptic shoots than the other cultivars. The occurrence and node number of the central zones decreased along with reduction in shoot length in all the cultivars. 'Aldrich' tended to have more flower buds than comparable-length shoots of the other two cultivars. This study provides a quantitative description of the shoot branching patterns of three important cultivars and explains how branching changes in relation to shoot length, whereas production of flower buds varies despite similar branching patterns.

- 5) This study clarified the effects of water stress on shoot growth and will be useful in understanding long term water stress effects on almond tree growth and productivity.

Differences in proleptic and epicormic shoot structures in relation to water deficit and growth rate in almond trees (Prunus dulcis).

Negron, C, L. Contador, B. D. Lampinen, S. G. Metcalf, Y. Guedon, E. Costes and T. M. DeJong. 2014.

Annals of Botany 113:545-554.

Background and Aims Shoot characteristics differ depending on the meristem tissue that they originate from and environmental conditions during their development. This study focused on the effects of plant water status on axillary meristem fate and flowering patterns along proleptic and epicormic shoots, as well as on shoot growth rates on 'Nonpareil' almond trees (*Prunus dulcis*). The aims were (1) to characterize the structural differences between proleptic and epicormic shoots, (2) to determine whether water deficits modify shoot structures differently depending on shoot type, and (3) to determine whether shoot structures are related to shoot growth rates.

Methods A hidden semi-Markov model of the axillary meristem fate and number of flower buds per node was built for two shoot types growing on trees exposed to three plant water status treatments. The models segmented observed shoots into successive homogeneous zones, which were compared between treatments. Shoot growth rates were calculated from shoot extension measurements made during the growing season.

Key Results. Proleptic shoots had seven successive homogeneous zones while epicormic shoots had five zones. Shoot structures were associated with changes in

growth rate over the season. Water deficit (1) affected the occurrence and lengths of the first zones of proleptic shoots, but only the occurrence of the third zone was reduced in epicormic shoots; (2) had a minor effect on zone flowering patterns and did not modify shoot or zone composition of axillary meristem fates; and (3) reduced growth rates, although patterns over the season were similar among treatments.

Conclusions. Two meristem types, with different latency durations, produced shoots with different growth rates and distinct structures. Differences between shoot type structure responses to water deficit appeared to reflect their ontogenetic characteristics and/or resource availability for their development. Tree water deficit appeared to stimulate a more rapid progression through ontogenetic states.

- 6) Sixth, in this study documented the influence of pruning severity on subsequent year shoot growth, structure and potential productivity.

How different pruning severities alter shoot structure: A modelling approach in young 'Nonpareil' almond trees.

Claudia Negrón, Loreto Contador, Bruce D. Lampinen, Samuel G. Metcalf, Yann Guédon, Evelyne Costes and Theodore M. DeJong
Functional Plant Biology (in press)

Abstract: Axillary meristem fate patterns along shoots, also referred to as shoot structure; appear to be fairly consistent among trees within a genotype growing under similar conditions. Less is known about shoot structural plasticity following external manipulations, such as pruning. This study on almond [*Prunus dulcis* (Mill.)] shoots aimed to answer: how pruning severity affects the structure of 1-year-old shoots that grew after pruning (regrowth shoots), the 2-year-old portion of shoots that remained from the previous year's growth after pruning (pruned shoots) and whether regrowth shoots reiterate the original structure of the 1-year-old shoots prior to pruning. Three pruning severities were imposed and the structures along the different shoots were assessed by building hidden semi-Markov models of axillary meristem fates. The structures of regrowth and pruned shoots depended on pruning severity, but maintained some of the original shoot characteristics. Regrowth shoots developed more complex structures with severe pruning, but had simpler structures than original shoots indicating progressive simplification with tree age. Pruned shoot structures were affected by the severity of pruning, by the structure when the shoots were one year old, and probably by local competition among buds. Changes in structure due to pruning can be modeled and be predictable.

- 7) Seventh, although not directly supported by this project this study investigated relationships between bud-break based chill requirements and yield-based chill requirements of three California nut crops and indicates that almond yields are relatively insensitive to the minimal chill years experienced in California to date.

Nut crop yield records show bud-break based chilling requirements may not reflect yield decline chill thresholds.

Katherine S. Pope, Volker Dose, David Da Silva, Patrick H. Brown and Theodore M.

Abstract: Warming winters due to climate change may critically affect temperate tree species. Insufficiently cold winters are thought to result in fewer viable flower buds, and the subsequent development of fewer fruits or nuts, decreasing the yield of an orchard or fecundity of a species. The best existing approximation for a threshold of sufficient cold accumulation, the “chilling requirement” of a species or variety, has been quantified by manipulating or modeling the conditions that result in dormant buds breaking. However, the physiological processes that affect bud-break are not the same as those that determine yield. This study sought to test whether bud-break based chilling thresholds can reasonably approximate the thresholds that affect yield, particularly regarding the potential impacts of climate change on temperate tree crop yields. County-wide yield records for almond (*Prunus dulcis*), pistachio (*Pistacia vera*) and walnut (*Juglans regia*) in the Central Valley of California were compared with 50 years of weather records. Bayesian nonparametric function estimation was used to model yield potentials at varying amounts of chill accumulation. In almonds, average yields occurred when chill accumulation was close to the bud-break based chilling requirement. However in the other two crops, pistachios and walnuts, the best previous estimate of the bud-break based chilling requirements were 19-32% higher than the chilling accumulations associated with average or above average yields. This research indicates that physiological processes beyond requirements for bud-break should to be considered when estimating chill accumulation thresholds of yield decline and potential impacts of climate change.

- 8) This paper presents a new approach to modeling bud-break in almond that incorporates the interaction between winter chill and heat accumulation into one model and should be useful for future analysis and modeling of annual cycles of almond tree growth.

A biologically based approach to modeling spring phenology in temperate deciduous trees

*K. S. Pope, D. Da Silva, P.H. Brown and T.M. DeJong
Agricultural and Forest Meteorology (in press)*

Abstract: Prediction of the timing of spring phenological events such as bloom and leaf-out has important uses in agricultural and ecological management and modeling. However, after decades of model comparison there remains no consensus model to predict the date of spring phenological events in perennial temperate trees across species and locations. This lack of consensus may be due to over-fitting resulting from high model complexity, use of parameters that have not been adequately validated, or omission of parameters that are sound biological indicators of dormancy breaking. The aim of this study was to construct spring phenology candidate models with biologically-based parameters and starting values to test hypotheses regarding chill accumulation duration and the impact of pre-bloom conditions. Bloom data for three cultivars of *Prunus dulcis* (almond) from three decades in California were analyzed. Across all three cultivars, models which accumulated chill until approximately 75% of the heat

requirement had been met, and did not integrate pre-bloom conditions, were substantially supported by the data. This suggests cold temperatures affect dormancy breaking well after the chilling requirement has been met and bud break timing is not substantially impacted by environmental conditions just prior to bud break. Fitting spring phenology using biologically based starting values estimated from bud break records may allow for the development of improved predictive models and improved approximations of critical phenological thresholds.

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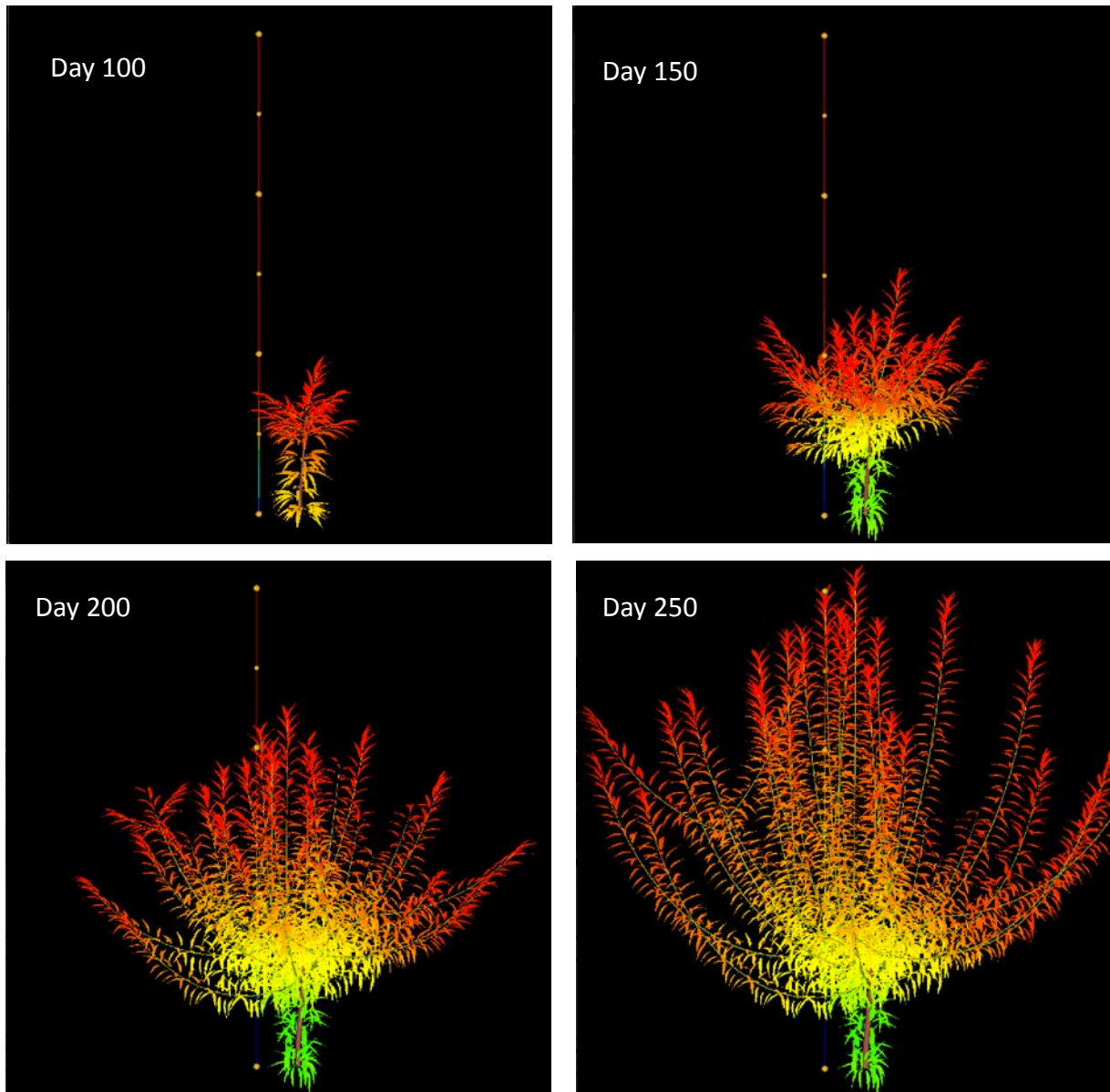


Figure 1. Depiction of L-Almond computer simulated shadow propagation within the canopies of almond trees during their first year of growth in the orchard. Green and yellow colors near the base of the tree indicate most intense shade.