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

Project No.: **12-PREC1-DeJong**

Project Leader:
T.M. DeJong
Plant Sciences Department
UC Davis
One Shields Avenue
Davis, CA 95616
530.572.1843
tmdejong@ucdavis.edu

Project Cooperators and Personnel:
B. Lampinen, C. Negron, E. Marvinney, S. Metcalf, and D. Da Silva, Plant Sciences Department, UC Davis

Objectives:

This project has two major objectives. The first is to collect research data on almond (and related species) tree growth, biomass productivity, dry matter partitioning, and carbon assimilation, utilization and distribution. 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 second objective.

The second and longer-term objective of this project is to develop a comprehensive functional-structural tree model (L-Almond) 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.

Interpretive Summary:

Objective one. 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 at this time. 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. We have been working with a professional orchard removal company to obtain data on the weight of chippings obtained during the removal of orchards. Last year we reported that data from 61 removed orchards, representing 2,034 acres, indicated that orchard 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.

Because of this variation in tree size and density among orchards it is necessary to develop a way to estimate the standing biomass in an individual orchard in a relatively simple manner. To develop a method to estimate standing biomass in existing orchards we been surveying specific orchards prior to removal to determine the average tree trunk cross sectional area (TCSA) per acre. We are now testing the mathematical relationship between TCSA/acre and the amount of biomass per acre removed in the clearing process. The results have been promising but much more data needs to be collected to validate our model relationship.

Objective two. 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 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 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; Da Silva et al. 2011), and that model is now being converted to develop an L-Almond model.

The first step for conversion of the L-Peach model 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 of three cultivars with contrasting growth habits (Nonpareil, Aldrich, and Winters) and studies of shoot architectural responses to water stress and pruning on Nonpareil have been completed.

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. New Nonpareil statistical shoot models have been inserted in the L-Almond model and we have begun running simulations of several sequential years of tree growth using the model. However we have discovered that the structure of our simulated almond trees are becoming so complex after four years of simulated growth that our computers are having difficulty in coping with the complexity of the tree. We are currently attempting to find computer software solutions to this problem.

This past year we have also upgraded the simulation of annual carbohydrate storage in woody tissues so that the tree growth and development can be simulated over multiple years, and the critical period of carbohydrate limitation between bloom and when there is sufficient new leaf area to support both vegetative and fruit growth in the spring can be realistically simulated. Development of an integrated dynamic simulation model of almond tree growth and productivity is a challenging project but will result in the most sophisticated environmental physiology-based model of a fruit or nut tree ever developed.

A corollary effort associated with this project has been the development of an almond phenology model to predict the time of bloom of Nonpareil almond based on weather records for a given fall and winter period. This project has been largely funded by other sources of funding but the objective is to be able to use multiple years of weather data to not only drive growth and carbon budgets during the growing season of individual years but to predict date of bloom and resumption of growth between several successive seasons. A new phenology model has been developed and is currently being validated.

Materials and Methods:

Assembling Data on Whole Tree Biomass. Several biomass companies have been contacted to obtain standing biomass data at the time of orchard removal, however only one has been interested in regularly working with us. In order to deal with the variability among orchards of different ages, vigor, and densities, we are developing a relatively simple orchard surveying method that should 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 have been testing a linear sampling method to quickly determine the mean TCSA/acre of specific orchards slated for removal prior to their actual removal. The pre-removal survey involves measuring the trunk diameter of every tree in 3-7 rows (depending on the orchard size and uniformity) of the orchard (perpendicular to the pollinizer row orientation) and noting the tree spacing. From these data the trunk cross-sectional area per acre is estimated. The trunk cross-sectional area is then regressed against the biomass removed per acre.

Development of an L-Almond Model. The second objective (developing a model of almond tree growth by converting the L-Peach model) 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, CA. Detailed analysis of shoot structural changes in Nonpareil almond in response to water stress and pruning were also conducted. Details of the procedures used in these studies are contained in previous reports. All of this research has now been completed and manuscripts reporting this work have been submitted to scientific journals.

The shoot structural models have been incorporated into the new L-Almond computer simulation model and we are in the process of validating the outputs of the model with empirical data. However, we have run into difficulties in running the model beyond four years because of computational capacities and are currently consulting with computer scientists to address this issue.

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) in order to develop an almond phenology model to predict bloom date based on fall and winter weather conditions. Data from these trials have been used to test several previously reported models and develop a new model. We are currently in the process of collecting bloom data from additional years to validate the new model before details of this model are released.

Results and Discussion:

Empirical estimation of standing biomass in almond orchards. We have been working with a professional orchard removal company to obtain data on the weight of chippings obtained during the removal of an orchard. Last year we reported that data from 61 removed orchards representing 2034 acres indicated that orchard 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.

In light of this large variation in orchard standing biomass, we began to investigate methods to survey orchards to estimate standing biomass based on combining measured mean trunk diameter data and biomass data from orchard removal. This involves cooperative work between an orchard removal company (GF Ag Services LLC. Ripon) and UC researchers (DeJong and Lampinen labs, UC Davis).

This past year more than 40 orchard removal sites were surveyed prior to tree removal to collect tree trunk diameter data on several rows of trees across the orchard and to estimate the mean tree trunk cross sectional area (TCSA) per acre and the total TCSA per site. We now have TCSA and biomass data on twenty-three of the sites surveyed but data from several of the sites still needs to be verified by revisiting sites to ensure that all trees that we surveyed were removed. As anticipated, our preliminary data (from about half of the surveyed sites) indicates that there is a good correlation between estimated TCSA per acre and the amount of biomass removed per acre (**Figure 1, 2**). During the next few months we will verify data from more sites and work with the tree removal company to add more sites to the data set. We also plan to work with Joel Kimmelshue of LandIQ (formerly NewFields), LLC, to determine if we can further refine the relationships by using Google Earth images to account for missing trees and verify reported orchard acreage removed.

Development of an 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 at UC Davis (Grossman and DeJong 1994, Esparza et al 1999, Esparza et al 2001). Statistical shoot models for describing the architecture and bud fates of Nonpareil almond shoots were developed and inserted into the L-Almond model in the place of statistical models describing peach shoots.

Currently, simulations beyond four years are difficult because the model keeps track of every plant part at the node level, and when the tree gets large the simulations get bogged down because of physical limitations in computer hardware. We are currently working on how to deal with this problem. We are also working to validate simulation results.

The L-Almond model is now capable of making reasonable simulations of architectural tree growth and cumulative biomass during the first four years after planting (**Figure 3**). Initial runs of the model pointed out that additional work was necessary on the over-wintering storage and spring mobilization of carbohydrate in the stems and roots. A new approach to modeling carbohydrate storage spring mobilization has been incorporated into the model and the simulations now appear more realistic than before.

Interestingly, this modeling effort has identified an underappreciated, critical period during fruit growth and development that may be a major determinate of final yield (**Figure 4**). This is the period of fruit drop after pollination but before shell hardening. While this fruit drop has been a concern to growers for many years, the cause of this fruit drop has not been clear. The L-Almond model indicates that this fruit drop is likely caused by a lack of carbohydrates available to support fruit growth during a critical period when vegetative and reproductive growth transitions from dependency on stored carbohydrates to current photosynthates. Note that for the year of the weather records used in this simulation there was a cloudy period that corresponded to the time when the primary period of fruit, shoot, and root growth accelerated. The actual decrease in carbohydrate storage probably occurs slightly earlier than is depicted on this graph (**Figure 4**) because it is known that mobilization of stored carbohydrates precedes resumption of growth. We are currently attempting to address this aspect in the model. Additional field research should be conducted to investigate this phenomena and the model can be used to pinpoint critical timing for field sample collection.

Acknowledgements:

We want to formally recognize the collaboration of GF Ag Services LLC. Ripon, CA in providing biomass removal data and sharing the locations of almond orchards slated for removal so that we can conduct field surveys prior to removal. This has been essential for conducting this project.

References:

Allen, M.T., Prusinkiewicz, P., DeJong, T.M. (2005) Using L-systems for modeling source-sink interactions, architecture and physiology of growing trees: the L-PEACH model. *New Phytologist* 166, 869-880.

Allen, M.T., Prusinkiewicz, P., Favreau, R.R., DeJong, TM. (2007) L-Peach, an L-system-based model for simulating architecture, carbohydrate source-sink interactions and physiological responses of growing trees. In ‘Functional-structural plant modeling in crop production’ (Eds. J Vos, LFM. de Visser, PC. Struick, JB Evers).

Da Silva, D., Favreau, R., Auzmendi I., DeJong T. 2011. Linking water stress effects on carbon partitioning by introducing a xylem circuit into L-PEACH. Annals of Botany 108:1135-1145.

Esparza, G., DeJong, TM., and Grossman, Y.L. (1999) Modifying PEACH to model the vegetative and reproductive growth of almonds. *Acta Hort.* 499, 91-98.

Esparza G., DeJong T.M., Weinbaum S.A. (2001) Effects of irrigation deprivation during the harvest period on nonstructural carbohydrate and nitrogen contents of dormant, mature almond trees. *Tree Physiology* 21, 1081-1086,

Esparza G., DeJong T.M., Weinbaum S.A., I. Klein. (2001) Effects of irrigation deprivation during the harvest period on yield determinants in mature almond trees. *Tree Physiology* 21, 1071-1079,

Guédon, Y., Barthélémy, D., Caraglio, Y., Costes, E. (2001) Pattern analysis in branching and axillary flowering sequences. *Journal of Theoretical Biology.* 212, 481-520.

Grossman, YL, and DeJong, TM. (1994) PEACH: A simulation model of reproductive and vegetative growth of peach trees. *Tree Physiology* 14, 329-345.

Lopez, G., Favreau, R.R., Smith, C., Costes, E., Prusinkiewicz, P., DeJong, T.M. (2008) Integrating simulation of architectural development and source-sink behaviour of peach trees by incorporating Markov chain and physiological organ function sub-models into L-PEACH. *Functional Plant Biology* 35, 761-771.

Figures:

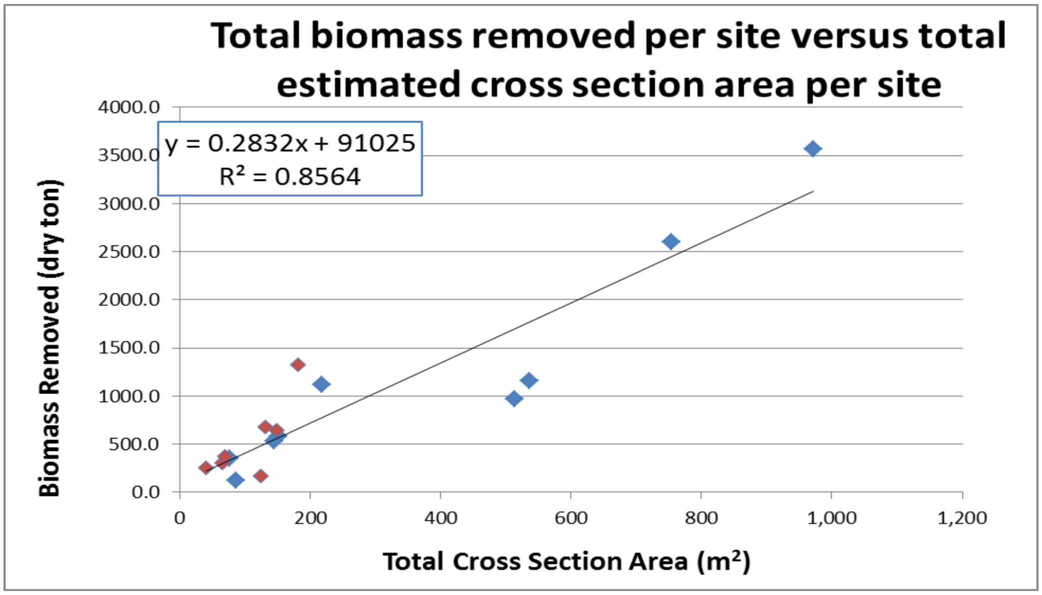

Figure 1. The relationship between dry orchard biomass removed per orchard site and estimated almond tree trunk cross-sectional area per site from almond orchards removed in the Central Valley of California.

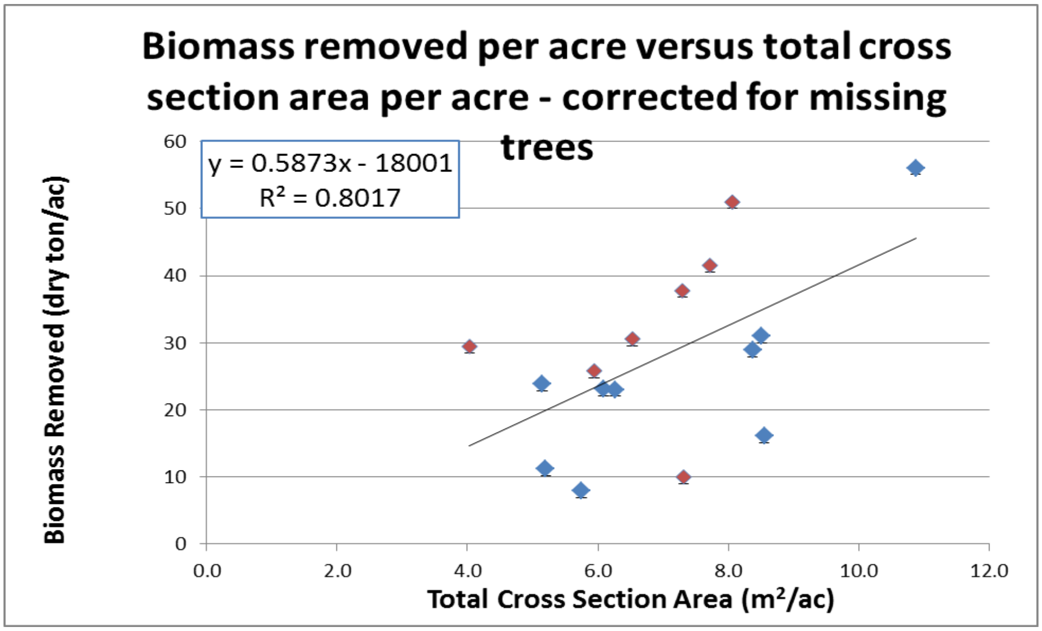

Figure 2. The relationship between dry orchard biomass removed per orchard acre and estimated almond tree trunk cross-sectional area per acre from almond orchards removed in the Central Valley of California; corrected for missing trees.

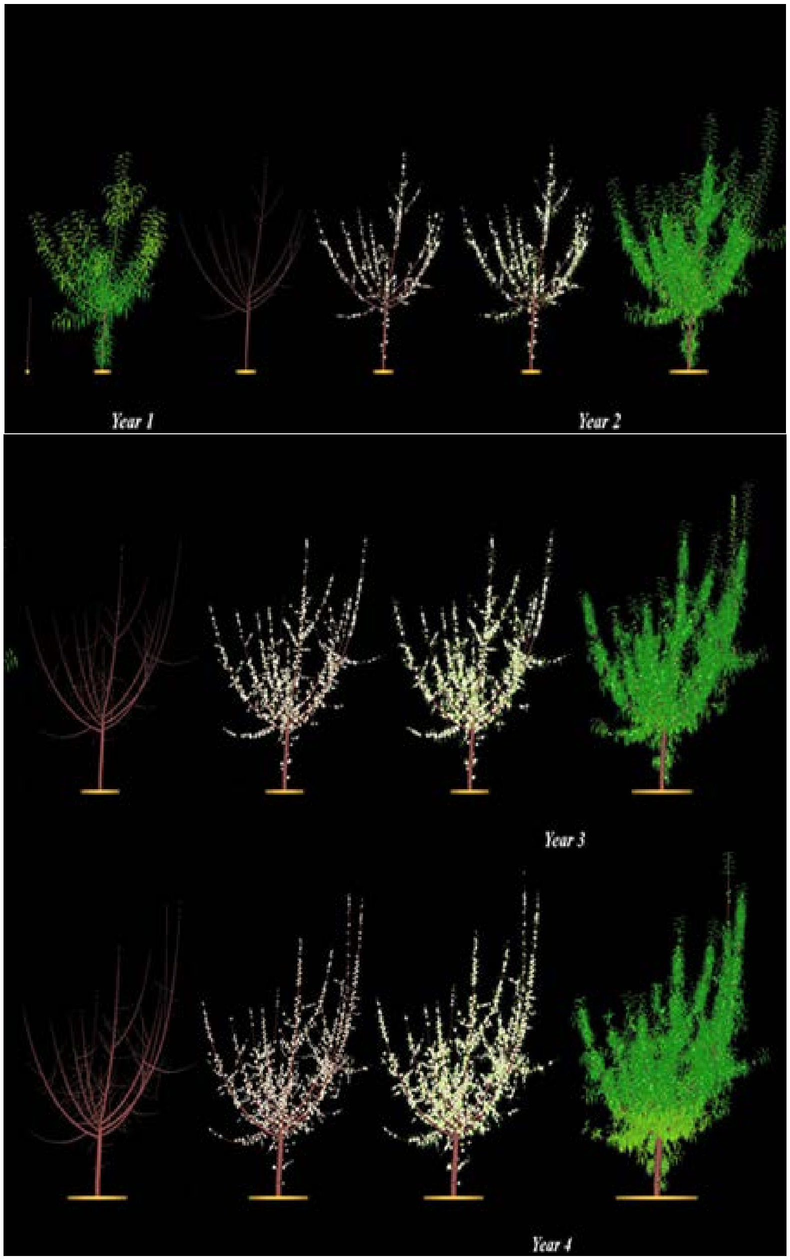

Figure 3. Simulated virtual almond trees produced by the L-Almond model. These renditions are preliminary images depicting four years of growth of young almond trees. Year 1 are trees growing in the nursery. The trees were pruned in the computer during the simulated dormant season between each year but minimal pruning was done between years 3 and 4. The architecture of the trees was developed according to bud fate models developed for Nonpareil almond. Additional research is now required to test the outputs of the model and improve the accuracy of the physiological functioning according to data available from field experiments.

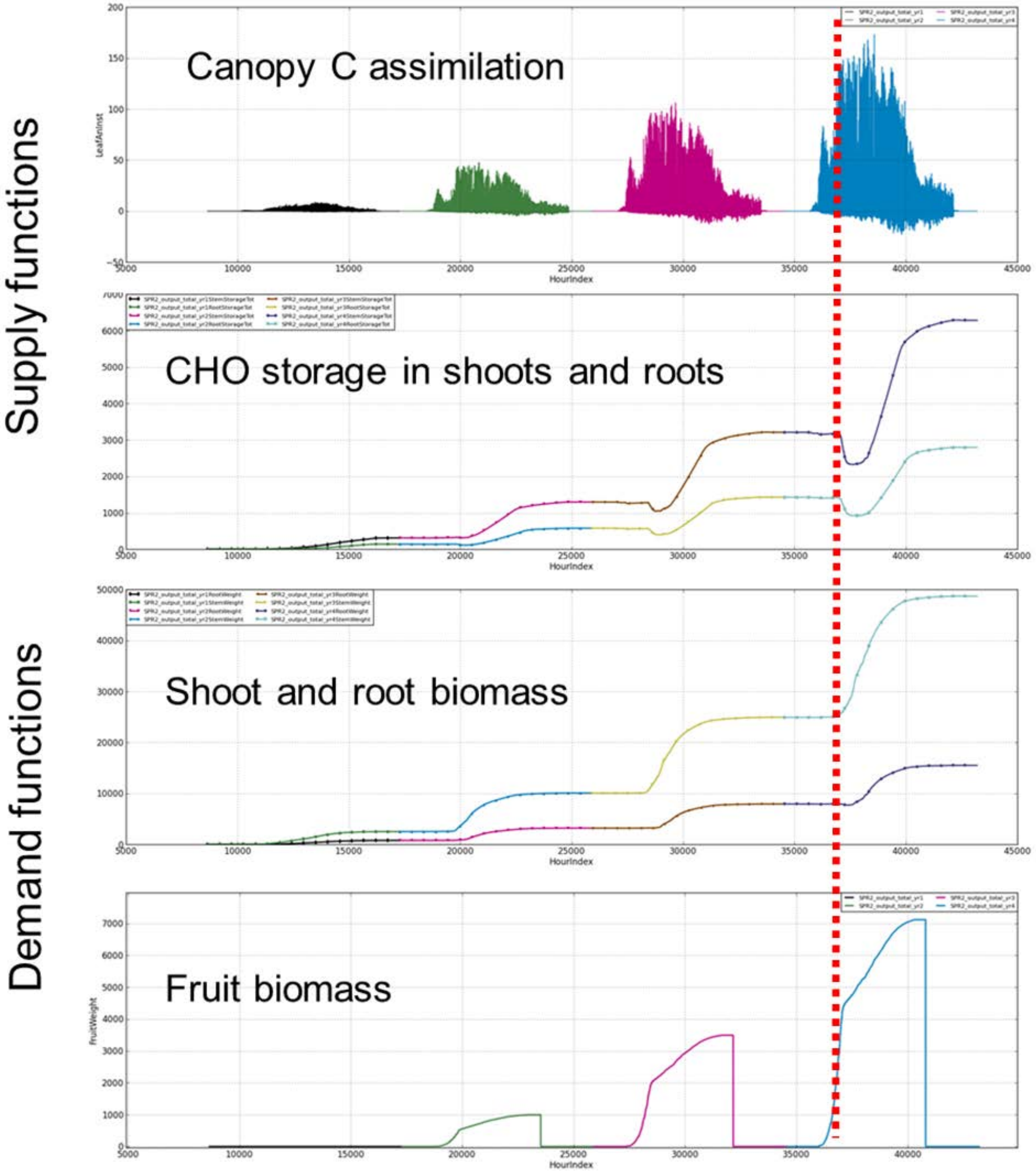

Figure 4. Simulated patterns of tree carbohydrate supply and demand functions over four years. Vertical bar indicates critical period of potential assimilate limitation that may be responsible for early fruit drop in the field.