

MODELING THE VEGETATIVE AND REPRODUCTIVE GROWTH OF ALMONDS

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Additional Index Words: Almond simulation model, carbon budget, carbon assimilation, carbon demand, organ growth potential, carbon partitioning.

Abstract

A carbon budget computer simulation model for almonds has been developed by modifying the existing PEACH model (DeJong et al., 1996. *Acta Horticulturae*, 416). The model simulates, on a daily basis, the seasonal carbon supply and demand for reproductive and vegetative growth. The concept behind the model is that the tree grows as a collection of semiautonomous interacting organs competing for carbohydrates, whose partitioning is dependent on organ growth potentials. Although peaches and almonds are closely related, they have some architectural and physiological differences due both to genetic differences and differing management practices (e.g. pruning and training systems, thinning, etc.). These differences required modification of some equations used in the model, however the main structure of the PEACH model was not changed. Carbon assimilation (supply) was simulated as a function of solar radiation, air temperature, accumulated degree-days, tree light interception, and leaf photosynthetic rates. Respiration and growth were simulated to determine the various organ carbon demands. Carbon partitioning was simulated based on sink strength (organ growth potential), source-sink proximity, and carbohydrate availability. The model provided a framework for integrating the environmental and physiological factors controlling carbohydrate supply and growth. Output could be scaled to the orchard level and indicated potential avenues of research related to growth and productivity. Results of the first model simulations are presented.

1. Introduction

Carbon budget computer simulation models have been used to relate plant growth to environmental conditions for several years (Thornley, 1990). Unfortunately, very few of these models have been developed for fruit tree crops, particularly on a whole tree basis (DeJong and Grossman, 1992, 1994). PEACH was developed recently as an attempt in this direction (Grossman and DeJong, 1994). PEACH simulates, on a daily basis, the annual carbon supply and demand for reproductive and vegetative growth of peach trees. It is a state

variable simulation model in which fruit, leaf, stem, branch, trunk and root weight are the state variables, and minimum and maximum air and soil temperatures, degree days, solar radiation and canopy light interception are the driving variables.

The central organizing concept in PEACH is the hypothesis that trees are collections of semi-autonomous but interacting organs and that carbon partitioning is driven by competition among organs. The competition is regulated by organ growth potential, source-sink proximity and carbohydrate availability (DeJong and Grossman, 1992; Grossman and DeJong, 1994). The way the model simulates carbon supply and demand as well as carbon partitioning can be reviewed in detail in previous publications (Grossman, 1993; Grossman and DeJong, 1994; DeJong et al, 1996). The assimilated carbon represents the "supply" part of the model; this carbon pool is available for growth and respiration, which represent the "demand" part. Carbon assimilation is simulated as a function of the seasonal patterns of canopy light interception, photosynthesis, and daily maximum and minimum air temperatures. Organ growth simulation is based on experimentally determined maximum achievable growth in trees growing with no water or nitrogen limitations and in which the fruit load was manipulated (potential growth rates).

Carbon partitioning is simulated first by satisfying the maintenance respiration needs; then, carbon is allocated to organ growth based on sink strength (potential growth rates), source-proximity (fruits, leaves, stems and branches first, then trunk, and roots last), and carbon availability (for details see Grossman, 1993 and Grossman and DeJong, 1994). During the first 200 degree-days, fruits, leaves stems and branches are left to grow at their potential growth rates, and their cost is subtracted from the trunk and root reserves. The code of the model is written in Visual Basic.

Field validation has shown that PEACH simulates the vegetative and reproductive growth of peach trees growing under different fruit loads and environmental conditions reasonably well (Grossman and DeJong, 1994; DeJong et al, 1996). Current research is being done in order to adapt PEACH to other fruit tree species. One might presume that PEACH should be easily adapted to species such as almonds, which are closely related to peaches. However, some architectural, anatomical and physiological differences can be observed between these species, requiring modification of the two main parts of the model, the supply and demand modules. We gave special attention to those characteristics in which these species differ when adapting the model to almond.

The aim of this study was to develop the first version of an ALMOND carbon budget model and run the first simulations of the carbon supply and demand for reproductive and vegetative growth of almond trees. At the same time, this study serves to test the feasibility of adapting the PEACH model to different fruit tree species.

2. Materials and Methods

2.2 Modifications to the PEACH model

2.2.1 Model parameterization

The almond trees used to parameterize the model were 'Nonpareil' grafted on 'Nemaguard' rootstocks growing in a high yielding orchard at the Paramount Farming Company, Shafter, CA (35°N 117°E). The trees are planted 6.5 x 6.5 m in a North-South orientation. The orchard included 'Nonpareil' rows (50%), alternating with 'Monterey' (25%) and 'Price' (25%) pollinizer rows.

Four eight-year-old trees were excavated at the end of the growing season on October 22, 1996 to determine the initial values of biomass corresponding to the various tree organs including fruits, leaves, stems, branches, trunk and roots (baseline data). The nut yield was determined after shaking the trees on August 13, 1996; the leaves that fell because of the shaking were accounted for as well as those that the trees dropped prior to the excavation. The initial number of fruits per tree (which is actually the flowers per tree) was estimated by considering the final number of fruits per tree (counted at harvest) and the percent fruit set (22.06 %, measured at bloom). For the simulations, the number of fruits was assumed to decline according to a power curve, $y = atk$, from the bloom date until May 1st.

2.2.2. Carbon supply and demand modifications

The main change to the carbon supply module was the modification of the surface response curve describing the daily and seasonal tree light interception. New curves were obtained by monitoring tree light interception of Nonpareil almonds over the growing season of 1996. In the initial simulations, no changes were made to the leaf photosynthesis parameters.

Regarding the carbon demand module, all the organ growth potential curves were replaced by those measured in almonds. Fruit growth potential was obtained by monitoring fruit growth in 10 'Nonpareil' trees with a very low fruit load (<500 fruits per tree) growing at Davis, CA. during the season of 1995. Leaf canopy and trunk growth potentials were assessed by manually manipulating/adjusting the fruit load of 10 trees, which were heavily thinned at bloom in Shafter, CA in 1997, and measuring growth over the growing season; the main branches were assumed to grow similarly to the trunk. The stem weight obtained from the excavated trees was assumed as the highest value of the growth curve; stem growth was monitored during the 1997 season. With the intent of model verification/validation, fruit growth in trees with normal fruit load was also monitored in Shafter, CA during the 1996 season. No changes were made to the organ maintenance respiration equations except to that of the branches. Since the almond branches are more massive than those of peach, the peach trunk respiration parameters were used for almond branches. Carbon

partitioning was simulated as in the PEACH model (Grossman and DeJong, 1994). More data about organ growth are currently being collected, so these data can be re-evaluated in the future.

2.3. Environmental data

Minimum and maximum air and soil temperature and solar radiation data were obtained from the California Irrigation Management Information System (CIMIS) weather station located in Shafter, CA for the year 1996, and used in the model simulations (Figure 1). Data from Davis (1995) and Shafter (1997) were also used to obtain some of the calibration equations as described in last paragraph. The calculation of degree-days was done by the single sine, horizontal cutoff method, with critical temperatures of 7 and 35 oC (Zalom ET al, 1983; DeJong and Goudriaan 1989).

Table 1. Various tree organ biomass, initial values of state variables, and organ growth potential calibration equations used in the model simulations.

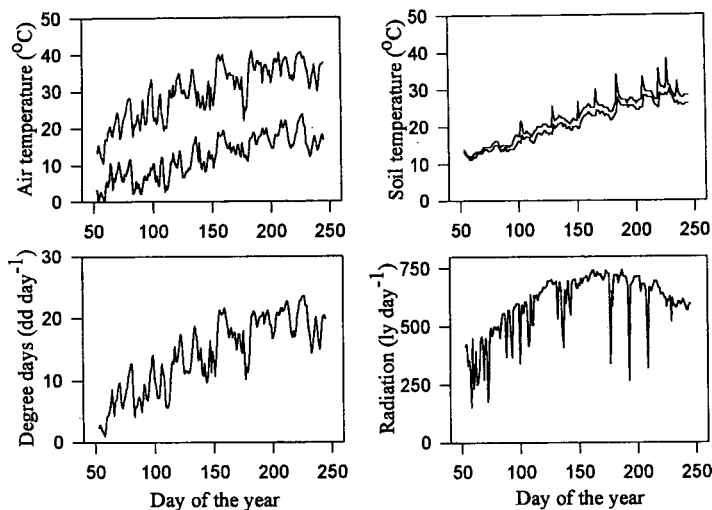
Variable	Organ biomass dry weight (g/tree)	Initial values	Calibration equation ^X (g of organ dry weight)
Fruit number at bloom		24516	
Final fruit number		5410	
Individual fruit			$=\exp(-5.07 + 0.036dd - (7.16 \times 10^{-5})dd^2 + (4.75 \times 10^{-8})dd^3 - (dd > 500)(4.75 \times 10^{-8})(dd-500)^3 + (dd > 1450)(8.5 \times 10^{-11}))$
Total Fruit	24077		
Leaves	17618		$\exp(95.85 - (1039.48/dd))^{0.5}$
Stems	4300		$+\exp(70.81 - (26982.7/dd^{1.5}))^{0.5}$
Trunk ^Z	154443	154443	$=\exp(154443 + (2.53 \times 10^{-5})dd)$
Branches ^Y	86313	86313	$=\exp(86313 + (5.5 \times 10^{-5})dd)$
Root	54438	54438	

^Z Includes stump and main scaffolds

^Y Woody parts other than trunk, stems and roots

^X dd = degree days

Figure 1. Seasonal patterns of minimum and maximum air and soil temperatures, degree-day accumulation and solar radiation at Shafter, CA, 1996.



3. Results and Discussion

3.1 Input variables

Table 1 shows the values of the parameters used in the model simulations. The results of the excavation as well as the calibration equations describing the organ growth potentials are also given. Compared to the values of the parameters used in the original PEACH model (Grossman and DeJong, 1994), almonds have bigger tree size than peaches; also, almonds exhibit a proportionally denser aboveground structure (trunk, scaffolds, and primary and secondary branches) than peaches, which reflects the less intensive pruning in almonds. Genetic differences also surely account for these differences. Stems, on the other hand, are proportionally more dense and bigger in peaches than in almonds and the water sprouts represent a greater fraction of stem dry weight in almonds than in peaches. Other aspects in which both species differ markedly are related to fruits; the number of fruits per tree is much greater in almonds whereas the fruit size is much larger in peaches. The fruit growth patterns are also distinct in both species, particularly during the last stage of development, in which the growth of the fleshy mesocarp accounts for most of the accumulated dry matter in peaches whereas the dry matter accumulates mostly in the kernel in the case of the non fleshy almond fruits. The growth pattern of almond fruits as well as that of the other organs is described by the calibration equations of Table 1. The main modifications done to the PEACH model in this first trial were based on these main differences.

Figure 2. Simulated seasonal patterns of daily carbon assimilation and daily cost of growth for almond trees at Shafter, CA.

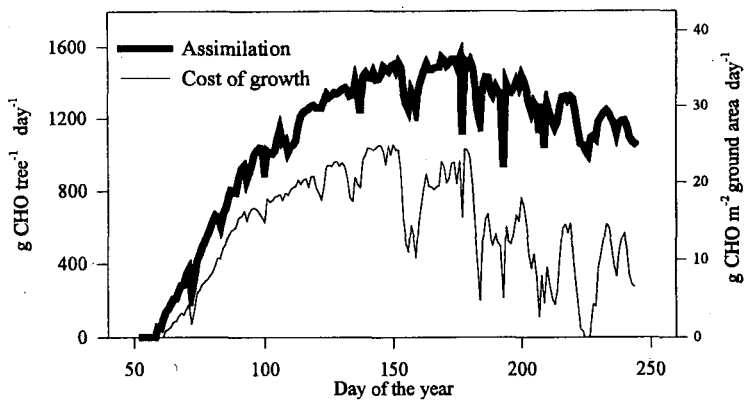
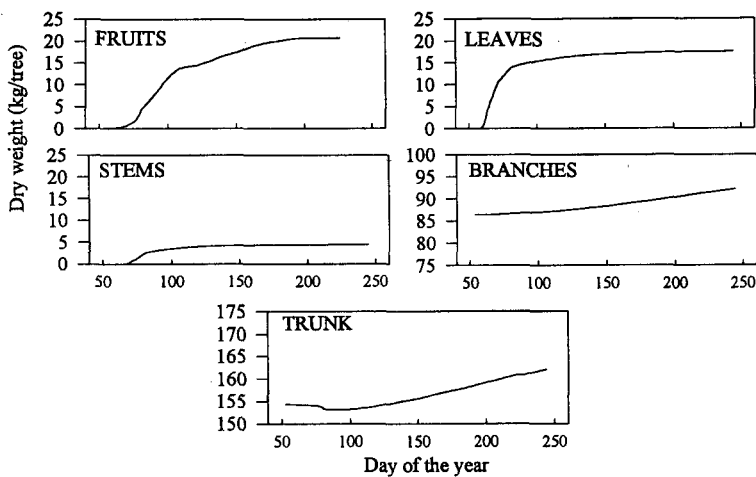


Figure 3. Simulated seasonal patterns of organ dry weight accumulation per tree for almond trees in Shafter, CA during the 1996 season.



Degree-days rather than calendar days were used to obtain the equations of Table 1. Degree-day accumulation as well as the other driving environmental variables used as basic inputs in the model simulations are shown in Figure 1. As the season progressed, a higher accumulation of degree-days occurred due to a parallel temperature increment; some cloudy days were present during the season and caused variation in the radiation and temperature. These variations were reflected in fewer degree days accumulated per day and ultimately in reduced simulated carbon assimilation shown in Figure 2.

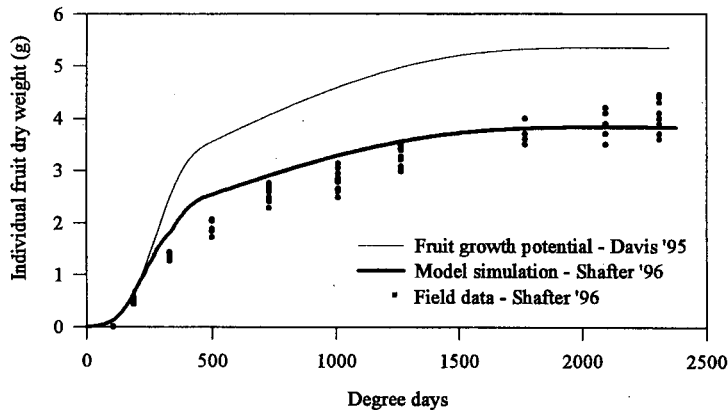
3.2. Model simulations

Simulation of the seasonal pattern of daily carbon assimilation is shown in Figure 2. The maximum rates of daily assimilation were similar to that reported for peach and other C3 crops (Grossman and DeJong, 1994; Ng and Loomis, 1984). These results indicate that the model modifications done to the tree light interception resulted in reasonable estimations of carbon assimilation for a C3 crop.

At the beginning of the season, most of the assimilated carbon was used for growth; however, as the season progressed, the fraction of the carbon going to growth decreased (Figures 2 and 3). The total organ growth represented a carbohydrate cost of 52.6 % of the carbon assimilated until harvest (August 13th); the rest of the assimilation was used in maintenance respiration, which is represented by the difference between both curves in Figure 2. The carbon allocated to maintenance respiration, as opposed to growth, was more prominent at the end of the simulated season because of the higher temperatures and the progressive accumulation of dry matter (Figures 1 and 3). The cost of growth was probably underestimated since, in comparison with peach, almond fruit growth exhibits an large accumulation of dry matter in the kernel rather than in the mesocarp during the last phase of growth. At this time, lipids, which are more expensive to produce, accumulate in the kernel (Hawker and Buttrose, 1980). Adjustments to fruit growth due to the lipid conversion were not done in this preliminary version of the model.

In the case of fruit growth, the model was tested with field data of fruits growing in trees with normal fruit load at Shafter, CA in 1996 (figure 4). The model predictions corresponded reasonably well to the observed values, with some apparent overestimation in the 300-1000 degree-day period. Final individual fruit weight on normal cropped trees at Shafter (1996) was 24% less than on thinned trees at Davis (1995) and the model simulated this difference quite well (Figure 4).

Figure 4. Fruit growth potential obtained from almond trees growing with a very low fruit load at Davis, CA in 1995, and model-simulated and actual field growth data of individual almond fruits growing in trees with a normal fruit load at Shafter, CA in 1996.



We are currently collecting the growth data for other organs to verify/validate the model simulations shown in Figures 2 and 3. However, these results indicate that the modifications done so far allow the model to reasonably simulate fruit growth in almond.

The model provides a framework for integrating environmental and physiological factors that control carbohydrate supply and demand for reproductive and vegetative growth in almond. Results can be scaled to the orchard level and provide a method to evaluate future research areas related to growth and productivity.

Acknowledgments

This research was partially supported by Paramount Farming Company.

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