MODIFYING 'PEACH' TO MODEL THE VEGETATIVE AND REPRODUCTIVE GROWTH OF ALMONDS

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Abstract

A carbon budget computer simulation model for almonds has been developed by modifying the existing PEACH model (DeJong et al., 1996). 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 the organ growth potentials. Although peaches and almonds are closely related, they have some architectural and physiological differences due both to genetic and management-induced (e.g. pruning and training systems, thinning, etc.) causes. These differences required modification of the parameters of some of the equations used in the main parts of the model, the carbon *supply* and *demand* modules, although the main structure of the PEACH model was not changed. Carbon assimilation (supply) is simulated as a function of solar radiation, minimum and maximum temperatures, degree-days, tree light interception, and leaf photosynthetic rates. Respiration and growth are simulated to determine the various organ carbon demands; carbon partitioning is simulated based on sink strength (organ growth potential) and source-proximity of tree organs as well as on carbohydrate availability. The model provides a framework for integrating environmental and physiological factors controlling carbohydrate supply and demand for growth of almonds at the orchard level and indicates 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 in the last years 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.

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The central concept behind PEACH is the hypothesis that trees are collections of semi-autonomous but interacting organs whose carbon partitioning is driven by competition based on their growth potential, their source 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 limitation of water or nitrogen in which the fruit load was manipulated to minimise competition for carbohydrates (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 trying to make the model adaptation.

The scope 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 as a test of the feasibility of adapting the PEACH model to different fruit tree species.

2. Materials and methods

2.1. Modifications to the PEACH model

2.1.1. Model parameterisation

The almond trees used to parameterise 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%), alternately with 'Monterrey' (25%) and 'Price' (25%) pollinizer rows.

Four eight-year-old trees were excavated at the end of the growing season in October 22 of 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 in 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 was estimated by considering the final number of fruits per tree at harvest as well as data on fruit set 22.06 % measured for that season (1996). For the simulations, the number of fruits was assumed to decline according to a power curve $y = at^k$ from the full bloom date to May 1, where y = number of fruits per degree day, a = initial number of fruits (at bloom), t = accumulated degree days, and K constant = -0.2378.

2.1.2. 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, but work is ongoing to develop more realistic daily and seasonal patters of almond leaf photosynthesis.

Regarding the carbon demand module, all the organ growth potential curves were replaced by those obtained for 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 similar 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. Fruit growth in trees with normal fruit load was also monitored in Shafter, CA during the 1996 season for model verification/validation. No changes were made to the organ maintenance respiration functions 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 and respiration are currently being collected, so these data can be re-evaluated in the future.

2.2. 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 for the model simulations (Fig. 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 cut-off method, with critical temperatures of 7 and 35 °C (Zalom et al., 1983; DeJong and Goudriaan 1989).

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 a bigger tree size than peaches; also, almonds exhibit a proportionally more dense aboveground structure (trunk, scaffolds, and primary and secondary branches) than peaches, which reflects the less intensive pruning in almonds. Genetic differences surely also 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 modifications done to the PEACH model in this first trial were based on these differences.

Degree-days rather than calendar days were used to obtain the equations of Table 1. Degree-day accumulation and the other driving environmental variables used as basic inputs in the model simulations are shown in Fig. 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 radiation and temperature. These variations were reflected in fewer degree-days accumulated per day and ultimately in the simulated carbon assimilation shown in Fig. 2.

3.2. Model simulations

Simulation of the seasonal pattern of daily carbon assimilation is shown in Fig. 2. The maximum rates of daily assimilation were similar to those reported for peach and other C_3 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 C_3 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 gained 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 the harvest (August 13th); the rest of the assimilation was used in maintenance respiration, which is represented by the difference between both curves in Fig. 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 (Fig. 1 and 3). The cost of growth was probably underestimated since, in comparison with peach, almond fruit growth exhibits an important 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 for fruits growing in trees with normal fruit load at Shafter, CA in 1996 (Fig. 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 (Fig. 4). We are currently collecting the growth data for other organs to verify/validate the model simulations shown in Fig. 2 and 3. However, these results indicate that the modifications done so far allow the model to reasonably simulate fruit growth.

The model provides a framework for integrating environmental and physiological factors controlling carbohydrate supply and demand for reproductive and vegetative growth of almonds at an orchard level and provides a method to evaluate future potential avenues of research related to growth and productivity of almonds.

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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 per dd)
Fruit number at bloom		24516	
Final fruit number		5410	
Individual fruit			$=\exp(-5.07 + 0.036dd - (7.16 \times 10^{-5})dd^2 + (4.75 \times 10^{-8})dd^3 - (dd>500)(4.75 \times 10^{-8})(dd-500)^3 + (dd>1450)(8.5 \times 10^{-11})(dd-1450)^3)$
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	154443	154443	$=\exp(154443 + (2.53 \times 10^{-5})dd)$
Branches[Y]	86313	86313	$=\exp(86313 + (5.50 \times 10^{-5})dd)$
Root	54438	54438	

[Z] Includes stump and main scaffolds

[Y] Woody parts other than trunk, stems and roots
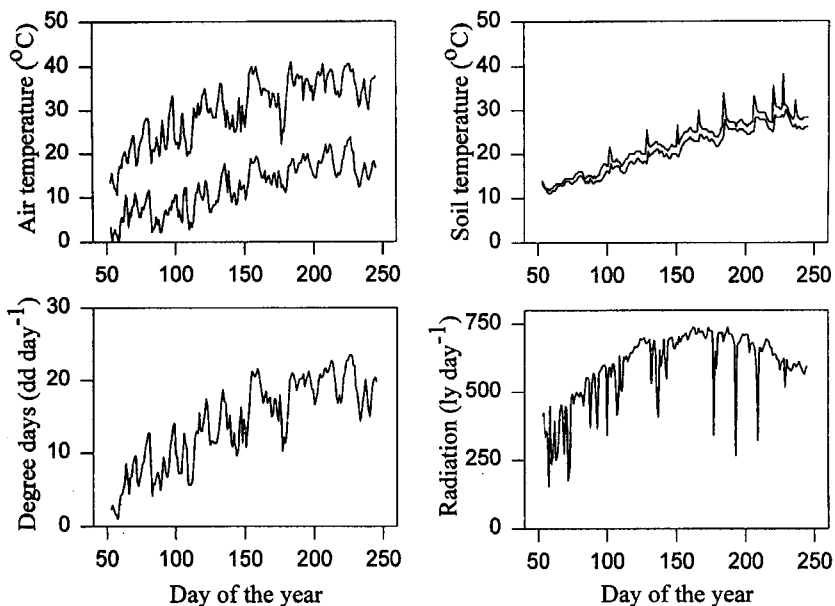
[X] dd = degree days

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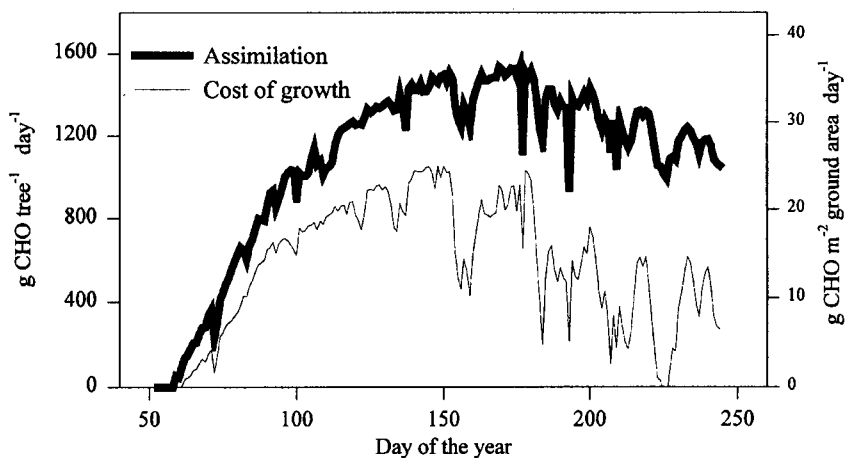

Figure 2 - Simulated seasonal patterns of daily carbon assimilation and daily cost of growth for almond trees at Shafter, CA.
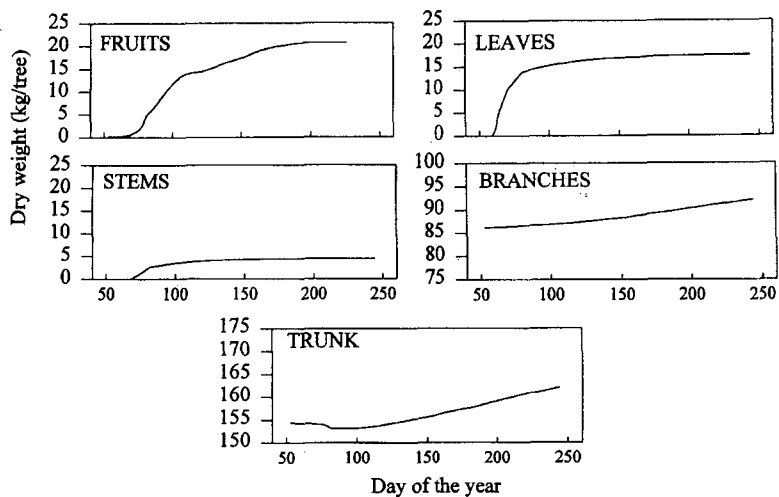
Figure 3 - Simulated seasonal patterns of organ dry weight accumulation per tree for almond trees in Shafter, CA during the 1996 season.
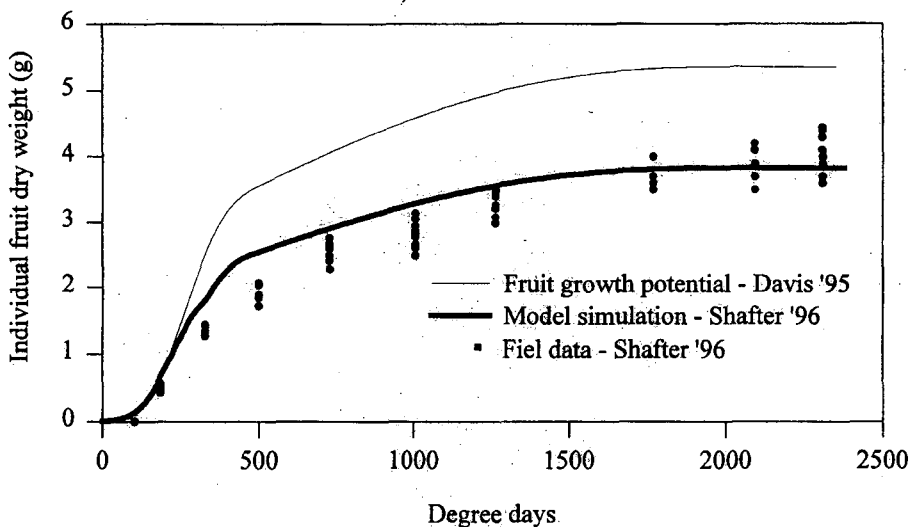

Figure 4 - Fruit growth potential obtained from almond trees growing with a very low fruit load at Davis, CA in 1995, and model-simulated and actual field growth data of individual almond fruits growing in trees with a normal fruit load at Shafter, CA in 1996.

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