Using L-PEACH for Dynamic Simulation of Source-Sink Behavior of Peach Trees: Effects of Date of Thinning on Fruit Growth

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Abstract

The goal of the L-PEACH, a functional-structural plant model, is to simulate tree architectural growth and carbohydrate source-sink relationships and transport in peach trees. Although the original model provided a basic prototype for how to integrate tree architectural growth and carbon economy, the simulation of crop yield responses to commercial practices was not previously addressed. The goal of this project was to test the ability of a new version of L-PEACH to simulate the effects of date of fruit thinning on fruit growth. To accomplish this objective interactions among fruit set, natural fruit abscission, date of fruit thinning, location of fruit in the tree architecture and source sink relationships were modelled. We simulated tree architectural development and dry mass growth of a peach tree until the beginning of the fourth growing season. This simulation output was saved and then additional simulations were restarted from the same point using different fruit thinning practices. The tree was either not thinned or thinned on four different dates; full bloom and 30, 60 and 90 days after bloom. Fruit thinning was established by using an automatic fruit thinning program in which the spacing between fruits was defined as four metamers (~11 cm) on individual shoots. There was a substantial benefit from reducing time between bloom and fruit thinning on seasonal patterns of mean individual fruit dry mass and final fruit mass distributions. This was because peach fruits were unable to recover potential growth lost early in the season. Therefore, as has been demonstrated in commercial orchards, L-PEACH simulations substantiated that to optimize fruit size and yield, fruit thinning should be carried out early in the season.

INTRODUCTION

PEACH, a mechanistically based computer model (Grossman and DeJong, 1994b), was developed to gain a better understanding of the environmental physiology of peach trees. This model was based on concepts of carbon supply and demand for growth, storage and maintenance of various organs derived from field experimental data (Grossman and DeJong, 1994a, 1995a, b; DeJong and Grossman, 1995). The PEACH model made it possible to simulate seasonal tree carbon assimilation and partitioning on a daily basis. However, PEACH largely ignored interactions between tree architecture and carbon allocation; each organ type was treated collectively as a single compartment and consequently all organs of a given type grew at the same rate.

L-PEACH is a graphics based model based on the source-sink concepts of PEACH and integrates physiological and architectural aspects of tree growth (Allen et al., 2005). This functional-structural peach tree model provided a prototype for how plant architectural growth and carbon economy can be integrated into a single model. L-systems (Lindenmayer, 1968) with subsequent extensions (Prusinkiewicz and Lindemayer, 1990; Mech and Prusinkiewicz, 1996; Karwowski and Prusinkiewicz, 2003) were used to address the problem of integrating architectural growth with tree physiology. The carbon source-sink interactions and carbohydrate transport within the tree were modeled using an analogy to electric circuits (Federl and Prusinkiewicz, 2004; Prusinkiewicz et al., 2007).

Although the basic approach for simultaneously modelling tree architectural growth and carbohydrate source-sink relationships and transport in peach trees appeared to be functioning well in previous versions of L-PEACH (Allen et al., 2005, 2007), simulation of source-sink interactions on early fruit development were not fully addressed. Originally, a specified percentage of the flowers buds set a fruit in the next season. This fruit set process occurred right after bloom date and consequently the final crop load was established early in the season. However, it is well known that under optimum weather conditions the majority of flowers on a peach tree can set fruit (Costa and Vizzotto, 2000). Thus, this process can produce a large fruit carbohydrate demand early in the season that was not considered in the original L-PEACH version. The objective of this study was to enhance the L-PEACH model to realistically simulate interactions among fruit set, natural fruit abscission, date and extent of fruit thinning, location of fruit in the tree architecture and source-sink relationships in order to permit user-prescribed experiments related to all of these factors. To test the potential of the new L-PEACH version we simulated fruit thinning at different times during the fourth growing season of a mid-late maturing peach cultivar. Since previous research has documented that peach fruits are unable to recover potential growth lost early in the season (Grossman and DeJong, 1995b), we hypothesized that the simulated final fruit mass would be greater on early than on late thinned trees.

THE MODEL

The general model structure and simulation algorithm is that reported by Allen et al. (2005, 2007). Original and subsequent development in the model design involved in the present research is described below.

Input Data

In each daily step, daily incident global solar radiation and daily max-min temperatures were used as environmental drivers to compute daily photosynthesis by individual leaves, organ maintenance respiration and organ development rates, respectively (Allen et al., 2007). Weather data was obtained from the CIMIS (California Irrigation Management Information System) data for the Davis station. The tree model was interfaced with a model of light environment as described by Grossman and DeJong (1994b).

Tree Architecture

L-PEACH architecture was simulated by means of integrating hidden semi-Markov chains, a statistical model that has been used to reproduce plant architecture (Smith et al., 2008). Moreover, Smith et al. (2008) improved the tree pruning responses that were defined in the previous version of the model (Allen et al., 2007) by introducing several new simulation "rules" that governed growth responses to pruning branches of various sizes and locations. Consequently, the three-dimensional graphic simulations produced by the model are more similar to the architecture of peach trees observed in commercial orchards than those produced by earlier versions.

Fruit Set, Fruit Abscission and Fruit Thinning

In the current version of L-PEACH initial crop load is established right after bloom when a user-specified percentage of flower buds set fruit shortly after the bloom date. Since the tree can produce more fruits than it can support, natural fruit abscission and fruit thinning programs have been developed to determine the final crop load.

Fruit abscission has been programmed to be a function of the realized individual fruit growth (that is subject to availability of carbohydrates to an individual fruit) compared to the potential fruit growth over a specific length of time during the initial fruit growth period. Options have been included for both manual and automated thinning. For manual fruit thinning, the user can select the fruits to be removed using the L-studio interactive editor (Prusinkiewicz, 2004). The automated fruit thinning attempts to simulate commercial fruit thinning practices and is based in the proximity of fruits to one another. A pass from the base to distal end of the fruiting shoots is done to locate the fruit on a shoot and if two peaches are separated by less than a specified number of metamers (one metamer ~2.7 cm) the more distal fruit of the two is removed.

Fruit set and fruit abscission may vary according to weather and local growing conditions. Fruit thinning requirements may also vary according to commercial objectives. To cover these types of scenarios a series of user-defined parameters can be adjusted for running multiple fruit growth/crop load simulations. These parameters include full bloom date, percentage of flowers that set fruit, sensitivity of fruit abscission to carbon supply during the drop period, length of the fruit abscission period, fruit thinning date, and fruit thinning done manually or with the intensity expressed as a minimum number of metamers between fruits. We anticipate that future early reproductive development features of the L-PEACH model could include environmentally and physiologically induced differences in bloom and fruit set dates.

Running Simulations with L-PEACH

To facilitate simulations with L-PEACH we developed two additional practical features. The first is a parameter window that includes both the physiological and management parameters that can be specified by the user. This window allows users to parameterize their own simulations without getting involved in the L-PEACH programming code. The second practical feature allows model outputs to be saved at the end of several years of simulation and then the model can be repeatedly restarted from the same point. This allows simulated management experiments such as fruit thinning to be repeated on the same initial tree in silico.

Analysis of Simulations and Quantitative Data

Three-dimensional depictions of the simulated tree are defined graphically using the L-studio interactive function editor (Prusinkiewicz, 2004). Quantitative data generated during a simulation is automatically transferred to an external MATLAB program (v. 7.0, release 14. MathWorks, Natick, Massachusetts, USA) to graphically display data.

SIMULATION OF THE EFFECTS OF FRUIT THINNING TIMING ON FRUIT CARBOHYDRATE ASSIMILATION

We simulated tree architectural development and dry mass growth of a peach tree until the beginning of the fourth growing season. During the simulation full bloom occurred on the 72th day of the year. All the flowers set fruit one week after the bloom date. Natural fruit abscission was programmed from the fruit set date until 60 days after full bloom. Harvest occurred at the end of August, representing a mid-late maturing cultivar. The dormancy period started about mid-November. The tree was trained to a perpendicular V system by means of pruning cuts in winter (Fig. 1).

This model output was saved and was then simulations were restarted from the same point using different fruit thinning practices. The tree was not thinned or thinned on four different dates; at bloom and 30, 60 and 90 days after bloom. Fruit thinning was established by using the automatic fruit thinning program in which the spacing between fruits was defined as four metamers (~11 cm) on individual shoots.

On each daily step, the total number of fruits per tree, individual fruit dry mass and total fruit dry mass per tree was analyzed. At harvest, fruits were divided into ten dry mass classes, which were defined as follows: class 1 (<4.2 g), class 2 (4.2–8.4 g), class 3 (8.4–12.6 g), class 4 (12.6–16.8 g), class 5 (16.8–21.0 g), class 6 (21.0–25.2 g), class 7 (25.2–29.4 g), class 8 (29.4–33.6 g), class 9 (33.6–37.8 g), class 10 (>37.8 g).

Model Predictions

During the fourth growing season, the total number of fruits per tree after bloom date was 1175. Fruit load at harvest in unthinned trees was what remained after natural fruit abscission (887 fruits tree^{-1}). Fruit load at harvest in thinned trees was 220 fruits tree^{-1} and was established at bloom or 30, 60 or 90 days after bloom, according to the fruit thinning dates.

Total fruit dry mass per tree was greater on unthinned trees than on thinned trees (Fig. 2) but unthinned trees had the lowest individual mean fruit dry mass values (Fig. 3). Within thinned trees, total and mean individual fruit dry mass tended to be greater on earlier than on later-thinned trees with the exception that total and mean individual fruit dry mass on trees thinned at bloom- and 30 days after bloom were similar (Fig. 2 and 3).

At harvest, although fruit dry mass on unthinned trees ranged between classes 2 and 6, about 65% of the fruits were in class 4 (Fig. 4). Generally, fruit dry mass in thinned trees ranged between classes 4 and 9 and only thinned trees at bloom had a small fraction of fruits in class 10 (Fig. 4). In thinned trees, the fraction of fruits in the classes 5, 6 and 7 decreased with decreases in the number of days between bloom and fruit thinning date (Fig. 4). The opposite behavior was observed in the classes 8 and 9; generally, the fraction of fruits in those classes increased with decreases in the number of days between bloom and fruit thinning date (Fig. 4). Consequently, the variability in the fraction of fruits between classes in earlier thinned trees (thinned at bloom and 30 days after bloom) was lower than that observed in later thinned trees (60 and 90 days after bloom) (Fig. 4).

Model Predictions Discussion

Modelled seasonal patterns of mean individual fruit dry mass in response to different fruit thinning strategies (Fig. 3) were similar to those obtained in field experiments (Grossman and DeJong, 1995b). However, Grossman and DeJong (1995b) reported higher average final fruit mass values than observed in our model predictions. This difference may be explained by the lower total number of fruits per tree and the training system used in the field experiment, i.e., fruit loads in thinned trees in the field experiment were about 60 fruits per central leader tree whereas fruit loads in our model simulation were 220 fruits per perpendicular V tree. Although further research to simulate crop load effects on fruit growth under specific circumstances is necessary, the potential of L-PEACH to simulate crop load effects on fruit dry mass growth was clear. Total fruit dry mass per tree decreased with a reduction in the number of fruits per tree (Fig. 2), but final fruit mass was negatively correlated with increases in fruit load (Fig. 3) (Naor et al., 1997).

The substantial benefit achieved from reducing time between bloom and fruit thinning on average fruit dry mass (Fig. 3) was accompanied by beneficial effects on final fruit mass distributions (Fig. 4). Since the fraction of fruits in the highest classes increased with decreases in the number of days between bloom and fruit thinning date (Fig. 4), and there is a clear marketing trend toward packing larger-sized fruit (Lopez et al., 2007), the profitability of earlier thinned trees would be expected to be greater than that of later thinned trees.

Previous field experiments (Grossman and DeJong, 1995b) indicate that peach fruits are unable to recover potential growth lost early in the season. The model simulates this behavior because peach fruit growth for any interval of time is a function of fruit mass at the beginning of that interval, the potential growth rate and the resources available to support growth (Grossman and DeJong, 1995a). L-PEACH simulations also clarified the practical implications of this fruit growth behavior and, as has been demonstrated in commercial orchards (DeJong et al., 1992), substantiated the idea that fruit thinning should be carried out early in the season to optimize fruit size and yield.

CONCLUSIONS

The basic approach for simultaneously modelling tree architectural growth and carbohydrate source-sink relationships and transport in plants appeared to be functioning well in L-PEACH. In the present study, we also demonstrated how L-PEACH was able to simulate crop yield responses to commercial practices such as fruit thinning and should be useful for making fruit growers understand how to optimize fruit thinning operations. More work remains in quantitatively validating the model but it is already a powerful research tool for integrating, simulating and understanding interactions between carbon source-sink relationships and architectural growth in peach trees.

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Figures

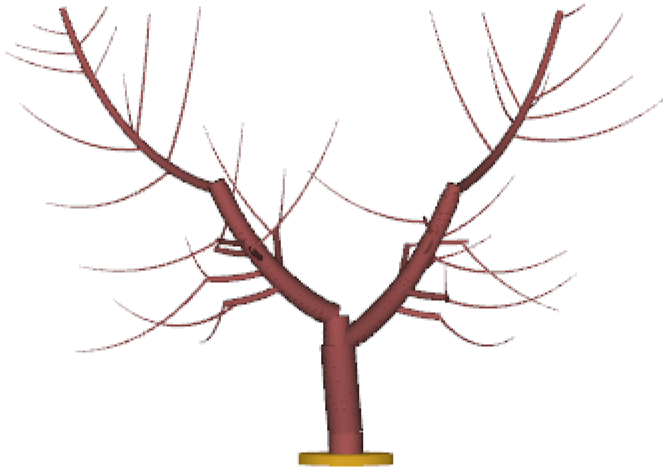

Fig. 1. Model output showing three-dimensional depiction of a peach tree at the beginning of the fourth growing season after winter pruning practices. The tree was trained to a perpendicular V system by means of pruning cuts in winter. The tree height was about 2.5 m.

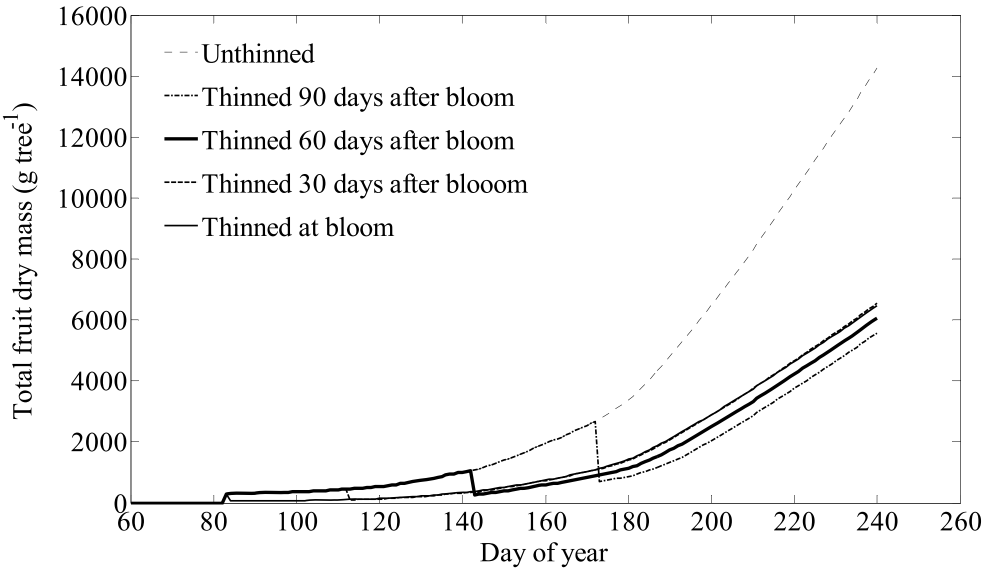

Fig. 2. Seasonal patterns of total fruit dry mass in response to different fruit thinning strategies. Fruit growth simulations were obtained during the fourth growing season of a mid-late maturing peach cultivar.

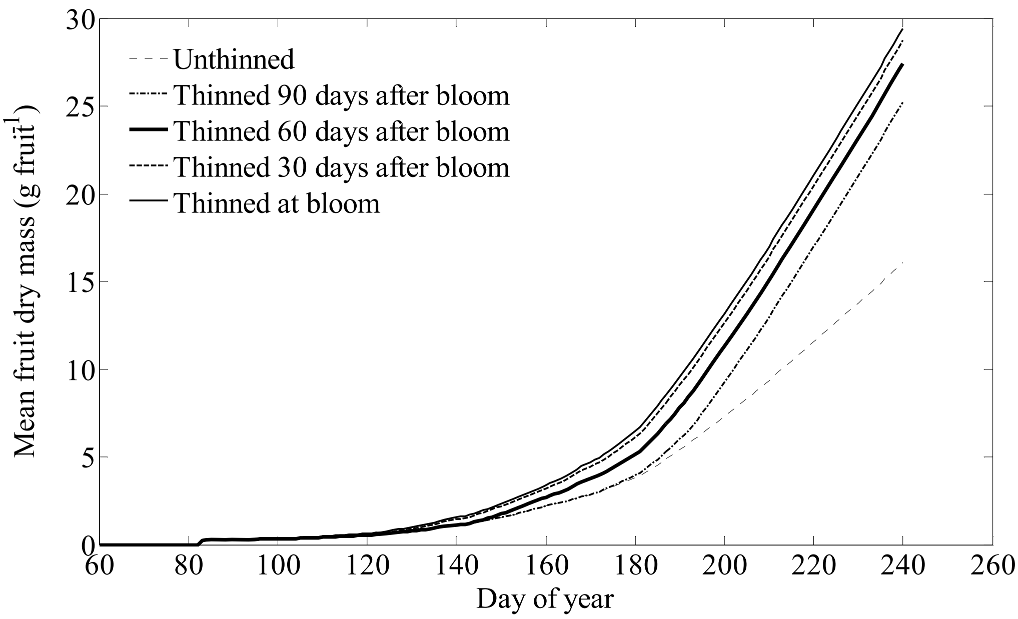

Fig. 3. Seasonal patterns of mean individual fruit dry mass in response to different fruit thinning strategies. Fruit growth simulations were obtained during the fourth growing season of a mid-late maturing peach cultivar.

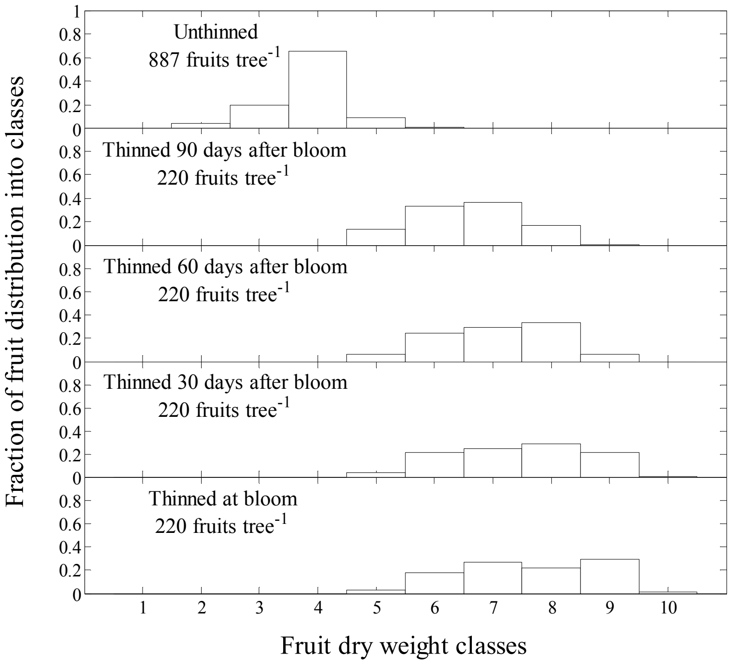

Fig. 4. Fraction of fruit distributed into different fruit dry mass classes for simulated peach trees under five different fruit thinning strategies during the fourth growing season. Fruit mass classes were defined as follows: class 1 (<4.2 g), class 2 (4.2–8.4 g), class 3 (8.4–12.6 g), class 4 (12.6–16.8 g), class 5 (16.8–21.0 g), class 6 (21.0–25.2 g), class 7 (25.2–29.4 g), class 8 (29.4–33.6 g), class 9 (33.6–37.8 g), class 10 (>37.8 g).