PEACH: PEACH CROP YIELD AND TREE GROWTH SIMULATION MODEL FOR RESEARCH AND EDUCATION

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1. Purpose of the *PEACH* model

The initial purpose of the model was to develop an integrated understanding of the annual carbon budget of peach fruit growth and crop production and to simulate the potential effects of environmental factors (temperature, light, etc.), physiological processes (leaf photosynthetic rate, respiration rate, organ developmental rates) and management practices (pruning system, fruit thinning, etc.) on peach fruit size and yield. As an environmental physiologist with the responsibility of trying to develop techniques for improving the production and management efficiency of growing fruit crops, I needed to develop an integrated, quantitative understanding of fruit crop production. Crop simulation modelling appeared to be one approach to developing that understanding. There have been very few previous attempts to develop quantitative, physiologically-based simulation models of tree fruit production because most of the early crop models depended on empirically-derived, sequential harvest data of whole plants and this approach was not feasible for large, long-lived tree crops. In 1985 the project was begun by simply trying to quantify the seasonal carbon costs for growth and respiration for fruit of early and late maturing peach cultivars (DeJong *et al.*, 1987). This lead to the development of a relative growth rate model for describing the developmental growth potential of individual growth of peach fruit (DeJong and Goudriaan, 1989) and eventually to an integrated simulation model for the whole tree using a carbon supply and demand approach for accumulating and partitioning carbon on a daily basis throughout the growing season (Grossman and DeJong, 1994; DeJong and Grossman, 1994). The approach we used for simulating carbon partitioning was developed independently but is similar to the approach used by Marcelis (1994) for cucumbers.

2. Application of area of the model

After the initial development of the model it appeared to have educational value for demonstrating some of the interactions between environmental conditions, tree physiology and orchard management to students and growers. Consequently the program was rewritten into a more user-friendly "windows" environment. Since that time it has been used in undergraduate pomology classes to demonstrate the consequences of fruit thinning time and severity on crop yield and fruit size. It has also been used to demonstrate the relationship of leaf photosynthetic capacity to crop yield in peach, and the effect of cultivar harvest date on yield potential (Berman *et al.*, 1998). At the same time the model was used to re-examine and refine some of our existing concepts about how carbon is partitioned in plants. This lead to a number of additional field studies to test these hypotheses (Saenz *et al.*, 1997; DeJong and Grossman, 1996; Grossman and DeJong, 1994, 1995a, 1995b, 1995c; Berman and DeJong, 1997a, 1997b)

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3. Structure of the model

3.1. Design assumptions

PEACH is a state-variable in which fruit, leaf current-year stem, branch, trunk, and root weight are the state variables, and minimum and maximum air and soil temperatures, degree-days, and solar radiation are the driving variables. The rate variables that characterise carbohydrate supply and demand are derived from previous studies on photosynthesis, respiration, and growth potential in peach trees (DeJong and Goudriaan, 1989b; DeJong *et al.*, 1990; Grossman and DeJong, 1994a, 1994b, 1995a, 1995b). The model assumes that the trees are optimally irrigated and fertilised. Further information on the model is published in Grossman and DeJong (1994b).

3.2. Carbohydrate supply

The photosynthetic carbon assimilation submodel was modified from an annual crop growth model, SUCROS '86 (Simple and Universal Crop Growth Simulator, van Keulen *et al.*, 1982; van Kraalingen and Spitters, 1986), which explicitly simulates total daily canopy photosynthesis using Gaussian integration of the instantaneous rate of leaf photosynthesis over canopy depth and diurnal light conditions (Goudriaan, 1986; Kropff *et al.*, 1987). The assimilation module of SUCROS '86 was modified to account for the discontinuous canopy within a peach orchard using empirical data on the seasonal pattern of daily light interception within peach orchards to adjust the effective leaf area index throughout the day (DeJong and Goudriaan, 1989b). The light-saturated instantaneous photosynthetic rate (DeJong and Doyle, 1985; DeJong *et al.*, 1989) is adjusted for the effect of air temperature (Grossman, unpublished data), leaf age (DeJong and Doyle, 1984) and light exposure with canopy depth (DeJong and Doyle 1985). Leaf area index is calculated from simulated leaf weight using an experimentally determined average specific leaf area.

3.3. Carbohydrate demand

3.3.1. Maintenance respiration

Leaf maintenance respiration rates were estimated from previously determined leaf specific respiration by the mature tissue method (Amthor, 1989; Grossman and DeJong, 1994a). Stem, branch and trunk maintenance respiration rates at 20°C were estimated using the regression method:

$$RS = RM + (G * RGR)$$

where RS is the specific respiration rate (g carbohydrate g^{-1} second), RM is the maintenance respiration rate (g carbohydrate g^{-1} second^{-1}), G is the growth respiration coefficient (g carbohydrate g^{-1}), and RGR is the relative growth rate (g g^{-1} second^{-1}) (Amthor, 1989). The growth respiration coefficient, G, for peach fruits was used in the calculation (0.211 g carbohydrate g^{-1}, DeJong and Goudriaan, 1989a). Current year stems, branches and trunk specific respiration rates, RSs, and relative growth rates, RGRs, were obtained experimentally as previously described (Grossman and DeJong 1995a, 1995b). The

maintenance respiration rate for roots was set to the rate determined from branches of similar size.

The model calculates temperature and maintenance respiration hourly because maintenance is sensitive to temperature, approximately doubling when the temperature increases from 20 to 30°C (Amthor, 1989; Grossman and DeJong,1994a). Hourly temperatures are calculated from air and soil minimum and maximum temperatures assuming a sinusoidal temperature pattern during the day and an exponential temperature decline during the night (van Kraalingen and Rappoldt, 1987). The daily carbohydrate cost of maintenance respiration is determined as the sum of the products of the hourly respiration rates and the dry weights for each organ type.

3.3.2. Growth

The model determines daily potential net sink strength for each organ type from experimentally determined seasonal patterns of organ growth potential (Grossman and DeJong, 1995a, 1995b). The daily conditional net sink strength, reflecting the effect of temperature on growth, is determined from the potential net sink strength and the number of degree-days accumulated on each day. The carbohydrate cost of daily growth is calculated as the sum of the carbohydrate equivalent weight of the dry weight added by growth (sink strength) and the respiratory cost of that growth:

$$CG = (CEDM * DM) + (G * DM)$$

where CG (g carbohydrate day^{-1}) is the carbohydrate cost of the dry matter added, CEDM (g carbohydrate g^{-1}) is the carbohydrate equivalent weight of the dry matter, DM (g day^{-1}) is the weight of the dry matter added, and G (g carbohydrate g^{-1}) is the growth respiration coefficient. The carbohydrate equivalent weights of leaves, current-year stems, trunk and roots were determined by pyrolysis at the Microanalytical Laboratory, Department of Chemistry, University of California, Berkeley, CA.

3.3.3. Partitioning

PEACH simulates carbohydrate partitioning on a daily basis. The model supplies carbohydrate for maintenance respiration requirements before supplying carbohydrate for growth (Crapo and Ketellapper, 1981). The carbohydrate requirements for growth are satisfied based on the conditional net sink strengths of the growing organs and their proximity to the source. Similar approaches to partitioning have been taken in modelling the growth of potatoes (Ng and Loomis, 1984), grapevines (Wermelinger *et al.*, 1991), and kiwifruit (Buwalda, 1991). All carbohydrate partitioning is characterised in terms of dry weight gain, representing the weight of structural growth and carbohydrate storage reserves.

Sink strength is calculated by grouping organs of the same type together although it is recognised that transport occurs to individual growing organs. The fruits, leaves, stems, and branches are modelled as being closest to the source, followed by the trunk, and finally the roots. Daily carbohydrate availability after maintenance respiration, and the carbohydrate cost of daily potential fruit, leaf, stem, and branch growth are calculated. Growth occurs at the potential rate if sufficient carbohydrate is available. If this is not possible, the fraction of potential growth that can be supported is calculated as the ratio of carbohydrate availability after maintenance respiration to carbohydrate requirement for potential growth. This fraction

is multiplied by the daily potential growth of each organ type to determine organ growth. Trunk growth is determined by calculating the ratio of carbohydrate available after fruit, leaf, stem, and branch growth to the carbohydrate cost of daily trunk growth potential.

The daily carbon budget is balanced by assigning remaining carbohydrate to root growth. No attempt is made to account for loss of carbohydrate from the roots by fine root turnover, exudation, and increased respiration during active transport of nutrients. For this reason, although the model calculates root growth, the values should more reasonably be attributed to root function, including metabolic processes and structural and storage biomass gain.

Until the "storage day," fruits, leaves, stems, and branches are allowed to grow at their conditional growth rates unrestricted by carbohydrate availability. If the carbohydrate available from current photosynthesis is not sufficient to support this growth, it is provided by stored carbohydrate and deducted from the dry weight of the trunk and roots (Ryugo and Davis, 1959; Johnson and Lakso, 1986). During the rest of the season, the carbohydrate demand is met by daily carbon assimilation.

3.3.4. Organ growth potential

The organ growth potential is the genetically determined growth attained when an organ is grown under optimal environmental conditions in the presence of a nonlimiting supply of carbon and other resources (Warren Wilson, 1967, 1972; Wareing and Patrick, 1975; Ho, 1984, 1988). Under these conditions, organ growth is limited only by endogenous characteristics of the organ, and is termed sink-limited growth (Warren Wilson, 1967, 1972; Wareing and Patrick, 1975). In contrast, growth that is limited by resource supply is termed source-limited growth. The organ growth potential determines the potential net sink strength, the maximum rate at which an organ can accumulate dry matter per unit time(Warren Wilson, 1967, 1972; Wareing and Patrick, 1975; DeJong and Goudriaan, 1989a; DeJong and Grossman, 1992).

3.3.5. Potential net sink strength

The potential net sink strength is the maximum rate at which an organ can accumulate dry matter per unit time (Warren Wilson, 1967, 1972; Wareing and Patrick, 1975; DeJong and Goudriaan, 1989a; DeJong and Grossman, 1992). The potential net sink strength is the product of sink size and potential sink activity expressed as the relative growth rate:

$$\text{potential net sink strength} = \text{sink size} \times \text{potential sink activity}$$

3.3.6. Potential gross sink strength

The potential gross sink strength is the sum of the potential net sink strength and the respiratory losses of the growing organ:

$$\text{potential gross sink strength} = \text{potential net sink strength} + \text{growth respiration} + \text{maintenance respiration}$$

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4. Model parameterisation

The trees used in the development and testing of the model were a mid-August maturing peach cultivar *(Prunus persica* (L.) Batsch cv. Cal Red) planted in 1984 at the University of California Kearney Agricultural Center in Parlier, California. Calibration data on fruit and vegetative growth potentials were obtained on trees that had been heavily thinned and defruited at bloom, respectively (Grossman and DeJong, 1995a, 1995b)

Minimum and maximum air and soil temperatures, and solar radiation was obtained from the California Irrigation Management Information System (CIMIS) weather station located at the Kearney Agricultural Center. Degree-days were calculated using the single sine horizontal cut-off method, with critical temperatures of 7 and 35°C (Zalom *et al.*, 1983; DeJong and Goudriaan, 1989a).

5. History of the model code

The modelling effort began using CSMP when the fruit growth "demand" submodel was being developed in conjunction with parts of the Wageningen SUCROS model that were revised for simulating carbon assimilation in tree crops. When the comprehensive model was developed, it was first written in FORTRAN, and subsequently in VISUAL BASIC for the "Windows" environment. The current system requirements are: Windows 3.1 or greater, DOS 5.0 or greater, processor with 4 megabytes of RAM (preferably a 486 DX with 8 megabytes of RAM), 10 Megabytes of free hard disk space and a VGA (or better) monitor. (The program, with source code, is available for a small fee, by contacting tmdejong@ucdavis.edu)

6. Sensitivity and uncertainty analysis and evaluation of the model

Because of the complexity of the model and the system that is being modelled there has been no systematic attempt to analyse the sensitivity or uncertainly of the model. During the initial development of the model, the model's ability to predict various reproductive and vegetative rowth parameters was tested and it was found to be relatively successful (Grossman and DeJong, 1994). Subsequently, the model has been used to predict the effect of environment on growth, respiration and yield of peach trees growing in different locations or with different maximum leaf photosynthetic capacities (DeJong *et al.*, 1996). Since it is impossible to actually do these experiments in the field, it is impossible to empirically test the modelled results. However, in every case the results subjectively appeared to be reasonable. Recently the model was used to predict the differences in potential yield of seven clingstone peach cultivars and the results corresponded to practical experience in the field (Berman *et al.*, 1998). At this stage in the development of the model, I have become convinced that, for a model for this type, the precision of the model for quantitative prediction is not as important as the accuracy of the concepts incorporated in the model. Since the empirical precision and variability of the input variables are always major limitations to obtaining precise results the model will probably never be useful for precise quantitative predictions. However, the model has already proved its value in forcing the development of a unified concept of tree growth and carbon partitioning and providing a mechanism to qualitatively test the influence of various physiological, environmental and management factors on tree performance.

7. Future plans

The model, as it is currently written, is also clearly deficient in its handling of growth and storage functions in the root. It currently only partitions carbon for growth and storage to the root after the above-ground needs of the tree are met. Experiments are being currently conducting to better understand the control of carbon partitioning to the root. The model will be modified to more accurately accommodate root growth when a mechanism for doing so is identified.

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