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Assessment of the water stress effects on peach fruit quality and size using a fruit tree model, QualiTree

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ABSTRACT

Low water availability has increased the use of regulated deficit irrigation strategies in fruit orchards. However, these water restrictions may have implications on fruit growth and quality. The current paper assesses the suitability of an existing fruit tree model (QualiTree) for describing the effects of water stress on peach fruit growth and quality. The model was parameterised and calibrated for a mid-late maturing peach cultivar ('Catherine'). Mean and variability over time of fruit and vegetative growth were consistent with observed data on trees submitted to full irrigation or to regulated deficit irrigation. The relative root mean square errors of the model for growth ranged between 0.09 and 0.31.

Sugar contents in fruit flesh were fairly well simulated, except for sucrose, which was overestimated. The relative root mean square errors of the model ranged from 0.01 to 0.40 for fructose; from 0.04 to 0.05 for glucose; from 0.21 to 0.41 for sucrose and from 0.09 to 0.28 for sorbitol. Water stress reduced leafy shoot growth up to 23% and fruit final size up to 49% when compared to the well-watered control. However, sugar contents in the flesh increased with water stress, up to 70% in the case of glucose. Simulations showed that a severe water stress during stage III of fruit development decreased fruit sizes by 22%, when compared to the control, whereas it enhanced sugar accumulation in the fruit flesh, up to 70% in the case of glucose and fructose. Therefore, these simulations showed that QualiTree might be useful in the design of innovative horticultural practices.

1. Introduction

Regulated deficit irrigation (RDI) practices are common for peach-tree cultivation in order to save water. This may impose serious water restrictions to the trees. For instance, in Spain, where peach (*Prunus persica* L. Batsch) culture is highly important, restrictions in irrigation water are usually imposed in midsummer, before the harvest of many mid-late maturing cultivars (Lopez et al., 2010); this coincides with the final stage of fruit development (stage III), which is characterised by a high accumulation of fresh and dry weight by the fruit.

Those water restrictions not only may have an effect on fruit size, but also on fruit quality, which is an important issue for fruit production and retailing (Codron et al., 2005). For instance, Berman and DeJong (1996) reported that water stress at stage III limits fruit growth. Hence, marketable fruit size may not be attained. However, other fruit quality criteria could be positively affected, such as soluble solid content in fruit flesh (Crisosto et al., 1994). In this sense, Lopez et al. (2010), studying deficit-irrigated mid-late maturing 'O'Henry' peach, found that RDI significantly increased soluble solid contents. On other species from the *Prunus* genre, such as plum, deficit irrigation has also been reported to increase total soluble solids content in fruits (Intrigliolo and Castel, 2010).

Fruit quality involves a set of traits such as fruit size, overall composition and taste, and proportion of edible tissue (Génard et al., 2009). These traits result from many processes at both the plant and organ levels that show large genotype × environment (management) interactions (Aguirrezábal et al., 2009). Understanding all the interactions between factors affecting fruit quality and the inherent complexity of its build-up is a challenging subject. In this sense, process-based simulation models may be useful tools to discern the complex linked processes controlling fruit size and composition at different levels of organisation (Martre et al., 2011).

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Although several models for simulating fruit-tree functioning have been developed for apple (Costes et al., 2008) and peach (L-PEACH: Allen et al., 2005), accounting for the effect of water stress on carbon partitioning in the latter case (Da Silva et al., 2011), they are not focused on fruit quality. Recently, Lescourret et al. (2011) presented QualiTree, a model that combines physiological and agronomic viewpoints for describing carbon allocation within the tree, vegetative and fruit growth distribution and the development of fruit quality. Because of its parsimony, QualiTree is more convenient than the previous models for quantitative comparison of data for parameterisation and evaluation.

In its present state, QualiTree has not been validated with experimental data on sugar concentrations in fruit flesh. Furthermore, the results reported by Mirás-Avalos et al. (2011) suggest that some parameters within QualiTree are cultivar-dependent. Therefore, the aim of the present work was to validate QualiTree sugar sub-model for a mid-maturing peach tree cultivar (the previous studies were done on early and late maturing cultivars, Mirás-Avalos et al., 2011, 2012) and to use the predictive capabilities of the model for evaluating the effects of water restrictions on fruit and vegetative growth, and also on sugar concentrations in the fruit flesh.

First, QualiTree was parameterised for a mid-maturing peach cultivar (cv. 'Catherine') and validated with observed data from different situations concerning irrigation conditions. The variables considered were the fruit and the leafy shoot dry masses, and the concentrations of four sugars (sucrose, glucose, fructose, and sorbitol) in the fruit. Then, we designed several simulation scenarios to observe the response of the model. Some of these scenarios were theoretical for testing the behaviour of the model and some others were constructed using field observations involving deficit irrigation practices as a basis.

2. Materials and methods

2.1. QualiTree, model overview

QualiTree (Lescourret et al., 2011) is a generic fruit tree model that describes the tree as a set of objects: fruiting units (FU) composed of fruits, leafy shoots and stem wood in a tree architecture, and other compartments viewed globally: old wood (trunk and branches), coarse roots, and fine roots. QualiTree runs, on a daily timestep, from bloom or after bloom until the end of the fruit growing season, starting from an initial state of the tree.

In order to represent the growth in dry mass of all the tree objects, QualiTree uses a carbon-supply approach, allocation rules (priority sequence between processes – e.g., maintenance, then growth – or organs – e.g., leafy shoot growth, then fruit growth; use of reserve as buffers; passive carbon storage), and equations of carbon assimilation (based on leaf area for photosynthesis) and growth requirements (demands). These equations are taken mainly from the FU carbon model of Lescourret et al. (1998).

Briefly, to restore carbon balance within the tree, two main principles are applied. First, the coordination theory (Reynolds and Chen, 1996; Chen and Reynolds, 1997) is used to propose that the imbalance (Im) between leafy shoots and fine roots defined as the ratio of dry structural masses of young shoots and fine roots to the shoot:root ratio at equilibrium (model parameter, SReq) changes the demands of leafy shoots and fine roots. Second, carbon exchanges occur between the tree objects, with proportionality to the supply of the donor, the demands of the recipient and a decreasing effect of geometric distance between donor and recipient objects according to a negative power law. The core of these carbon balance principles lies on three main equations. First, the demands of the stem wood, old wood and coarse root compartments are based on the following equation of potential growth in dry mass (DM, g) according to degree-days (dd):

$$\frac{\Delta DM_x}{\Delta dd} = RGR_x^{ini} DM_x e^{-\theta_\lambda dd} \qquad (1)$$

where subscript x is sw for stem wood, ow for old wood and cr for coarse roots, $RGR_x{}^{ini}$, the initial relative growth rate, and θ_λ are parameters (dd^{-1}).

Second, the demands of fruit or leafy shoots of the FU and of fine roots are based on the following equation of potential growth:

$$\frac{\Delta DM_x}{\Delta dd} = RGR_x^{ini} Im^a g(dd) DM_x \left(1 - \frac{DM_x}{Im^a DM_x^{\max}}\right) \qquad (2)$$

where subscript x is f for fruit, ls for leafy shoots and fr for fine roots, $RGR_x{}^{ini}$ (dd^{-1}) is the initial relative growth rate (model parameter), Im (dimensionless) is the imbalance between leafy shoots and fine root masses defined previously, exponent a is 0 for fruit, -1 for leafy shoots and 1 for roots, and $g(dd)$ is defined as:

$$\begin{aligned} &g(dd) = 1 \text{ if } dd < dd_{\min} \\ &g(dd) = \frac{dd_{\max} - dd}{dd_{\min} - dd} \text{ if } dd \text{ is between } dd_{\min} \text{ and } dd_{\max} \\ &g(dd) = 0 \text{ if } dd > dd_{\max} \end{aligned} \qquad (3)$$

with $dd_{\min}$ and $dd_{\max}$ as organ-specific parameters (dd).

$DM_f{}^{\max}$ (g) is the maximum dry mass of a fruit. $DM_{ls}{}^{\max}$ is the product of the leafy shoot number of the FU and the maximum mass of an average individual leafy shoot $DM_{ils}{}^{\max}$. Respect to the set of fine roots, $DM_{fr}{}^{\max}$ is calculated assuming that its ratio to the maximum mass of leafy shoots on the tree is equal to the shoot:root ratio at equilibrium, SReq:

$$DM_{fr}^{\max} = \frac{N_{ls} DM_{ils}^{\max}}{\text{SReq}} \qquad (4)$$

where N_{ls} is the number of leafy shoots on the tree.

Third, the equation depicting the carbon flow F_{ij} between two object i and j of the tree is:

$$F_{ij} = \frac{ACP_i Demand_j}{\sum_{j=1}^{n} Demand_j} dist_{ij}^{-k} \qquad (5)$$

where ACP_i is the available carbon pool of i (gC), i.e., the carbon pool remaining after satisfaction of maintenance respiration (and of leaf growth if i is an FU) from an initial pool made of photosynthates (if i is an FU) and of mobilised reserves, $Demand_j$ (gC) is the carbon demand of j, $dist_{ij}$ (mm) the geometric distance between i and j, n is the total number of objects exchanging carbon and k is a positive parameter (dimensionless). Parameter k expresses the effect of distance on carbon exchange: when k is close to zero, the distance has no effect and carbon is distributed proportionally to carbon demands, whereas high values for k lead to severe effects of distance.

Several fruit quality traits (fruit size, the proportion of the total mass consisting of fruit flesh, dry matter content of the flesh, concentrations of various sugars, and a sweetness index) are also represented by QualiTree.