

Modelling Product Quality in Horticulture: an Overview

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Abstract

Although modelling product quality is of special importance in the horticultural production and supply chain, including product quality in crop modelling is still in its infancy. In this paper several examples of modelling product quality are presented and discussed. More often than not models on postharvest behaviour of products are not explicitly linked to pre-harvest conditions, although these conditions are known to be of great importance. Besides the average value for a quality attribute, the distribution in a batch (biological variation) of that quality attribute contains important information. Recently an approach has been developed to model this information and hence make it useful. In ornamental horticulture, one of the dominant quality attributes is plant shape. Architectural modelling exists already for many years (e.g. L-systems) and is especially applied for trees. Recently, GREENLAB has been developed, an architectural model structure focusing on organogenesis and biomass production and partitioning of resources to the different plant parts. Until now, growth conditions like e.g. climate conditions and crop management are not included in these architectural models. It is a great challenge to link architectural models to physiological models. Integration of both modelling approaches will provide a very powerful tool and will bring modelling of ornamental quality a major step forward.

INTRODUCTION

In agriculture in general, the focus in crop modelling has traditionally been on biomass production. Recently, more emphasis has been put on modelling product quality. Product quality can be defined as the degree to which a product meets the expectations of the user (Meiselman and MacFie, 1996). However, to make product quality suitable for modelling, we look at only one or a few aspects (hopefully the most important ones) determining quality. Sensory (e.g. color, size, taste, external damage) and non-sensory (e.g. vitamin-C content, residue, NO₃⁻-content) aspects can be distinguished. Furthermore, quality aspects can be internal (non-visible; e.g. vase life, shelf life, safety) or external (visible; e.g. size, colour, degree of damage). From these few examples it is already clear that product quality is a very diverse and large field with many species-specific evaluations. This hampers modelling product quality. A philosophical approach to quality targeting specifically the modelling issue has been developed (Sloof et al., 1996; Wilkinson and Tijskens, 2001). Because the market demands accurate predictions of yield and quality, crop models will increasingly need modules for product quality.

Two major groups of models can be distinguished (Challa, 1985). A first group are regression models, which are also called black-box, empirical or statistical models. These models make a direct relation between input and output, without taking into account physiological knowledge. A second group are the mechanistic or explanatory models. In these models at least two hierarchical levels are distinguished (Penning de Vries et al., 1989).

Only a limited number of models for horticultural product quality exist, and most

of these models focus on external quality in ornamentals (plant height, flower size) or color, firmness and taste in vegetables and fruits. Only very few models link internal quality to growth conditions. Searching for vase life in the CAB-database 1995-2003 for example, resulted in 808 hits, whereas vase life and model resulted in only 8 hits. All 8 hits were exclusively on modelling postharvest behaviour. Some examples of product quality models in horticulture are listed in Table 1.

MODELLING QUALITY ASPECTS IN WHICH ASSIMILATES PLAY AN IMPORTANT ROLE

There are several quality aspects in which assimilates play a dominant role, e.g. fruit size, mass, firmness and tissue tension. Modelling these aspects is achieved quite easily by extending photosynthesis-driven biomass production models, provided the relation between the assimilates and the quality aspects is sufficiently known. In these models, the partitioning of assimilates between organs is preferably modelled based on relative sink strengths. The fraction of the daily available assimilates partitioned to a certain organ is calculated as the sink strength of that organ divided by the total sink strength of all organs on the plant. The sink strength can be defined as the potential demand or potential capacity of an organ for assimilate accumulation. This potential demand or capacity can be quantified by the potential growth rate of the organ (Fig. 1), i.e. the growth rate under conditions of non-limiting assimilate supply (Marcelis et al., 1998). An example is the prediction of average fruit mass using the model TOMSIM (Heuvelink, 1999), for different greenhouse temperatures (Fig. 2) or truss pruning treatments (Fig. 3). Marcelis and Gijzen (1998) showed that with such a modelling approach fruit size distribution in cucumber could be predicted in good agreement with observed distribution at commercial growers.

Number of inflorescences in Kalanchoe pot plants could be predicted using a positive linear relationship between produced biomass (assimilate availability) and number of inflorescences (Eveleens-Clark et al., 2004). A similar relationship was observed between produced biomass and flower number per stem in cut chrysanthemum (Fig. 4). Validation results of the combination of a photosynthesis-driven model and this linear relationship for predicting flower number are presented by Heuvelink et al. (2001) and Carvalho et al. (2003). In contrast, individual flower size and flower mass in cut chrysanthemum were found to be constant under a wide range of conditions (Carvalho and Heuvelink, 2004). Hence, instead of flower size, number of flowers per stem increased with assimilate availability.

Verkerke et al. (1998), working on predicting taste of tomato fruits, showed that a regression model with only five easily measured parameters like sugar content and juiciness can give accurate predictions of sensory panel evaluations. Such a model is very valuable (but in comparable situations only) as it makes large-scale assessments possible in a shorter time and at lower costs. However, until now, models that explain how the measured fruit attributes are affected by cultivation techniques and greenhouse climate are missing. When this type of models become available, it will be possible to direct the growth conditions to a higher quality and a higher acceptability while maintaining the usual targets of crop growing. Flavour of tomato fruits is known to be determined primarily by the concentration of sugars and acids. Hence, one could expect that flavour and aroma could be predicted along similar lines as described above, rather straight forward from a photosynthesis-driven model extended with developmental aspects. However, so far such models are not available. Certainly, dry matter partitioned into the fruit parts is not the same as sugar content. Water balance in the fruits plays an important role as well. In fact more fundamental modelling of dry matter content is needed. Knowledge on 'growth as increase in dry matter' and 'growth as increase in volume-water content' needs to be integrated. Here lies a field of research, highly important for horticultural yield and quality modelling, still to be explored.

LINKING PRE- AND POSTHARVEST

Based on theoretical considerations of how quality might grow during plant development (Tijskens and Van Kooten, 2002; Tijskens et al., 2003), it was shown that for understanding the sometimes erratic behaviour during postharvest stage and handling, it is crucial to think in terms of plant and fruit development stage rather than in simple calendar time counting from the moment of harvest (Fig. 5 and Fig. 6).

Let us assume that firmness (F) during growth is generated out of the daily production of sugars as a general substrate, by an autocatalytic action of some enzyme (E). Autocatalytic means that during the production of firmness, the amount of enzyme increases proportionally. At the same time the generated firmness degrades, both during growth as well as during storage, under action of the same enzyme. This mechanism, active during growth, can be represented as:



with kg and kdg reaction rate constants for formation and degradation of firmness, respectively. During postharvest storage, photosynthesis is in general no longer active, and firmness will decay according to the reaction of Eqn. 2. Now, assume that the produce is harvested at different times, or stages of maturity, starting at e.g. 20 days up to 44 days after fruit set every fourth day. Depending on the maturity at harvest, a different level of firmness will be present in the produce, as well as different amounts of enzyme (Fig. 5). Converting this picture into a postharvest framework, counting time from the moment of harvest, the behaviour of firmness now is so confusing (Fig. 6), we hardly can make out what is happening in the product. Not only the starting point of firmness at time zero greatly differs between the successive harvest dates, but also the apparent rate of the decrease strongly depends on the maturity at harvest (through the available enzyme). Without further information on the exact growing and harvest conditions, it is almost impossible to find out why the behaviour of the product is so different for different batches of product.

In a study on cut tomato slices, Lana et al. (2004a, 2004b) reported that the mechanism of colour and firmness change was not affected by the time of harvest, provided that the biological development stage was taken into account. The behaviour of firmness decrease in tomato slices harvested at different stages of maturity could be described and analysed together according to an exponential behaviour:

$$F_0 = (F_{g,0} - F_{fix}) \cdot e^{-(k_g \cdot t_g + k \cdot t)} + F_{fix} \quad \text{Eqn. 3}$$

where F= firmness at time t after harvest (in Newton), F_{fix} = invariable part of firmness (in Newton), $F_{g,0}$ = the firmness (in Newton) of tomato at stage I when both t_g and $t = 0$, k= reaction rate constant, k_g = reaction rate constant at growth temperature, t= time (in days), counting from the moment of harvest, t_g = time of growth (days) arbitrarily counting from reaching stage I. The parameter t_g represents the time at the plant necessary to reach the next stage of maturity, and is a direct measure of the biological age of the product. An example of a pooled analysis is given in Fig. 7.

To fully integrate preharvest information into postharvest quality models, not only the action of important enzymes is needed, but at the same time more intrinsic knowledge on how these enzyme systems are formed and maintained. In other words, not only the dynamics of enzyme actions have to be elucidated, but also the dynamics of formation and denaturation of these enzymes in relation to the conditions applied during crop growth (Tijskens and Van Kooten, 2002; Tijskens et al., 2003).

LINKING ARCHITECTURAL AND PHYSIOLOGICAL MODELS

Photosynthesis-driven models usually contain a simple description of the plant in

a few broad compartments (roots, stems, leaves, flowers, fruits). These models aim at predicting the dry matter production as the result of the functioning of the plant (photosynthesis, respiration, biomass partitioning) regulated by environmental factors. They usually give accurate predictions of biomass production and yield, but important aspects of ornamental quality (plant architecture) are missing. Alternatively, plant architectural models have been developed. These morphological models aim at generating 3-D virtual plants that are faithful to botany. This approach contains two complementary parts: (1) the elaboration of mathematical models based on morphological knowledge and experimental measurements and, (2) the computer simulation and graphical representation of plant development based on these mathematical models. A well-known example is L-systems grammar (Prusinkiewicz et al., 1990), which provides the possibility to formalize the description of plant architecture. L-studio (<http://www.cpsc.ucalgary.ca/Research/bmv/lstudio/>) is a software package that uses L-systems grammar in combination with a graphical interface to create a 3D virtual plant. De Visser et al. (2004) used an L-systems algorithm to simulate a number of flower mutants of *Arabidopsis*. These authors also discuss the potentials of such a 3D model to simulate simple gene expressions in ornamental species controlled by environmental conditions.

Another example is the GREENLAB plant model, which is derived from earlier plant models AMAPsim and AMAPhydro (De Reffye & Houllier, 1997). However, GREENLAB is more than a pure morphological model as it simulates interactions between plant structure and function. It uses dual scale automaton (Zhao et al., 2001; Yan et al., 2004) to simulate plant organogenesis from germination to maturity on the basis of organogenetic growth cycles that have constant thermal time. Microstates, macrostates and the transition relationships among them are defined to represent phytomers, growth units and metamorphic rules individually (Fig. 8). This organogenesis model is flexible in generating complex plant structures and can provide type, number and status of different organs in each growth cycle. Generally in morphological models the topological structure of a plant is made of an idealized elementary unit that is repeated numerous times, and plants are described according to a given genetic program of the plant. Pure morphological models do not allow for predictions of effects of different environmental conditions and horticultural crop management (e.g. pruning).

Physiological and architectural plant models have originally been developed for different purposes and therefore have little in common, thus making combined applications difficult (Yan et al., 2004). A recent trend are efforts to combine photosynthesis-driven and architectural models, i.e. linking structure and functioning of the plants. Mech and Prusinkiewicz (1996) introduced the formalism of open L-systems, allowing exchange of information with the environment. Hence, it becomes possible to make the development of the structure responsive to external and local conditions (Prusinkiewicz, 1999). One could also think of e.g. calculating assimilate production and organ sink strength (growth potential) using a photosynthesis-driven model, and feed this information into an L-system. The L-system then allocates growth to specific buds, shoots and leaves in accordance with their relative growth potentials (Hanan and Hearn, 2003). The L-system also calculates the numbers and size of organs present in the next cycle (e.g. the next day) and this information is fed into the photosynthesis-driven model. Complete integration of these modelling approaches should combine the strong points of both, resulting in a powerful tool which will bring modelling of ornamental quality a major step forward.

GREENLAB is one of the few plant models that links physiological plant activity with plant architecture. Recently, many papers on the development, simulation results and application of GREENLAB have been published, including colorful pictures of 3-D virtual plants (Hu and Jaeger, 2003). In GREENLAB plant fresh biomass production is computed from transpiration, assuming transpiration efficiency to be constant and atmospheric demand to be the driving force, under non-limiting water supply (Yan et al., 2004). The fresh biomass is then distributed among expanding organs according to their relative demand (as mentioned above). Demand for organ growth is estimated from

allometric relationships (e.g., leaf surface to weight ratios) and kinetics of potential growth rate for each organ type. These are obtained through parameter optimization against empirical, morphological data sets by running the model in inverted mode. The model reproduced accurately the dynamics of plant growth, architecture and geometry of various annual and woody plants, enabling 3D visualisation (Fig. 9). Although calibrated by optimization to reconstruct observed, prototypic plants, the model is able to simulate some of the plant's phenotypic plasticity resulting from competition among sinks for resources. GREENLAB is able to simulate the variability of leaf size on the plant as a result of water stress in different phases of plant development and compensatory growth following pruning (Yan et al., 2004). This, as well as the dynamic simulation of complex morphogenetic processes using the principle of sub-structures, constitutes important innovations in plant architectural modelling.

The future challenges confronting this approach (Yan et al., 2004) will be (1) the need to substitute some of the lumped functions (black boxes) with mechanistic processes, such as energy interception and conversion, and water status dynamics and their physiological feedbacks on plant growth; (2) the formulation of feedbacks of physiological status on architecture, in addition to plant geometry; and (3) the demonstration that the resulting system is useful not only for the re-creation of observed structures (representation, explanation) but also for the accurate prediction of phenotypes in hypothetical environments (extrapolation).

CONCLUDING REMARKS

Compared to the simulation of biomass production, modelling product quality in horticulture is still in its infancy. However, a lot of progress has been made in the last decade. Development of quality models is hampered by the large diversity in product attributes and species-specific evaluations. There is a need to find general processes in this field, comparable to the photosynthesis process for biomass prediction. Although crop production and postharvest physiology operate almost as separate scientific fields, it is essential to make the link between pre- and postharvest. The first steps towards such a link have been made with very promising results. Integration of photosynthesis-driven models and architectural models is another promising field. Especially for modelling visual quality of ornamental crops, plant architecture is essential. Much work on modelling the interaction between plant architecture and environment is still needed. Dry matter content is an important parameter for both yield and quality prediction for horticultural produce. The vast fields of knowledge on dry matter production and distribution and on water relationships in plants need to be integrated. This integrated knowledge will bring forward the understanding and prediction of quality aspects like flavour, shelf life and vase life.

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Tables

Table 1. Examples of product quality models in horticulture.

Quality aspect	Specification	References
Internal quality		
Product contents	Nitrate in lettuce	Seginer et al., 1998 Zhang et al., 2004
Flavour	Glucoraphanin in broccoli Flavour in tomato	Kläring et al., 2001 Verkerke et al., 1998
Postharvest life		
Shelf life	Shelf life in cucumber Shelf life in strawberry	Schouten et al., 2002a Schouten et al., 2002c
Vase life	Vase life in roses	Reid et al., 1996
External quality		
Plant architecture	L-systems L-systems + genotype GREENLAB	Prusinkiewicz, 1998 De Visser et al., 2004 De Reffye and Houllier, 1997
Plant height	DIF (difference between day and night temperature)	Erwin et al., 1989 Carvalho et al., 2002 Schouten et al., 2002b
Number of flowers	Number and size of internodes Chrysanthemum	Carvalho and Heuvelink, 2004 Carvalho and Heuvelink, 2004
Shape	PTR= Photothermal ratio	Liu & Heins, 2002
Organ size	Cucumber Tomato Carrots and red beet	Marcelis and Gijzen, 1998 De Koning, 1994 Benjamin et al., 1999

Figures

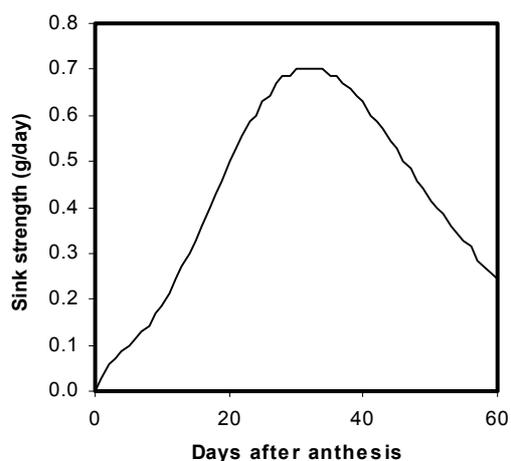


Fig. 1. Sink strength of a beefsteak tomato fruit as a function of days after anthesis.

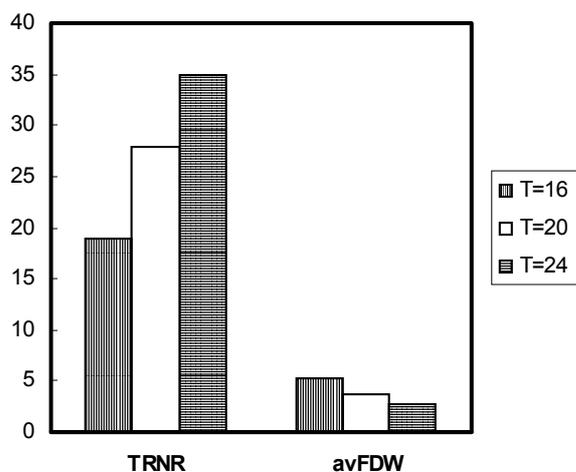


Fig. 2. Simulated (TOMSIM) number of trusses per plant (TRNR) and average fruit dry weight (avFDW; g fruit⁻¹) for a tomato crop grown at 16°C, 20°C or 24°C.

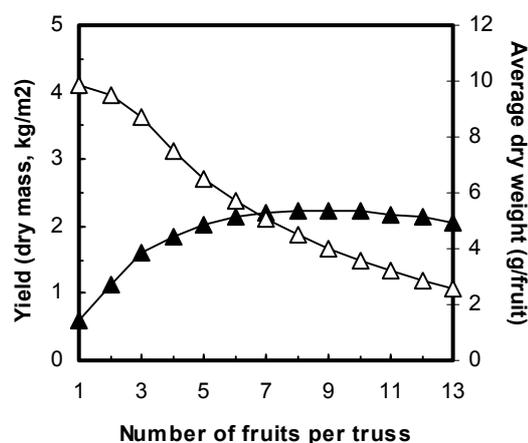


Fig. 3. Simulated (TOMSIM) effects of the number of fruits per truss at standard growth conditions (Heuvelink and Bakker, 2003) on total harvested ripe fruit dry weight -▲- and average dry weight per fruit harvested -Δ-).

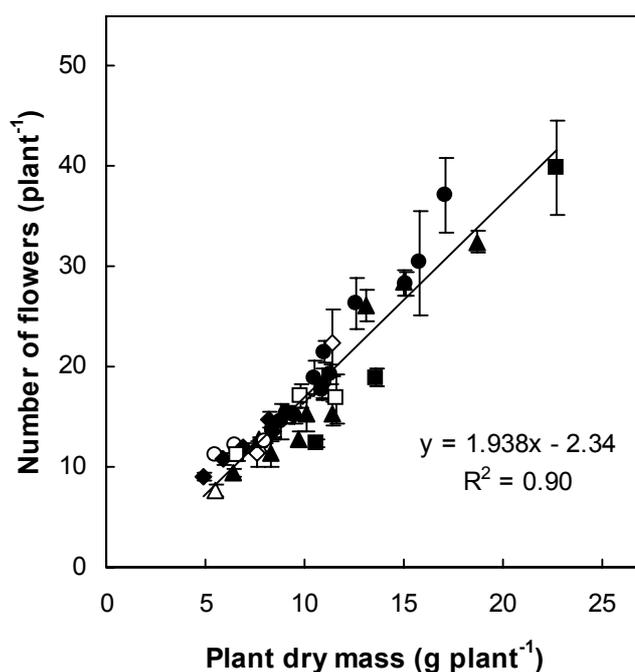


Fig. 4. Relationship between total number of flowers pr plant, including buds, and total dry mass per plant at harvest of Chrysanthemum 'Reagan Improved'. Different symbols represent different experiments and solid line represents linear regression. Vertical bars indicate standard error of means when larger than symbols. Source: Carvalho and Heuvelink, 2003.

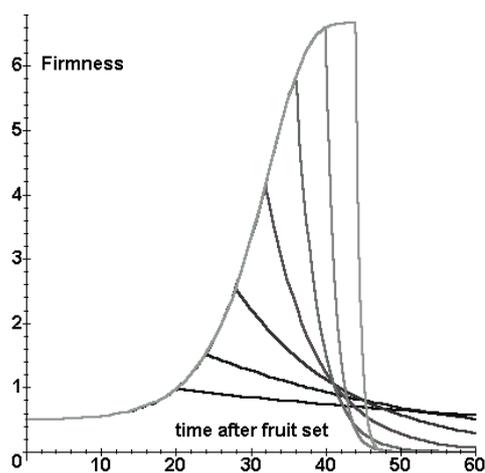


Fig. 5. Development of firmness during growth and decay after harvest at different stages of maturity (darkest line = 20 days, lightest line = 44 days).

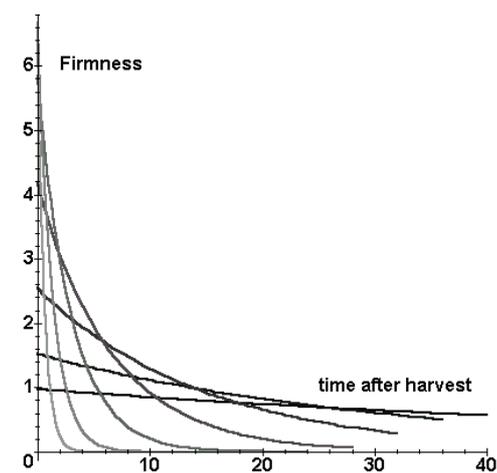


Fig. 6. The same behaviour of firmness as in Fig. 5 during postharvest storage, counting time from the moment of respective harvests.

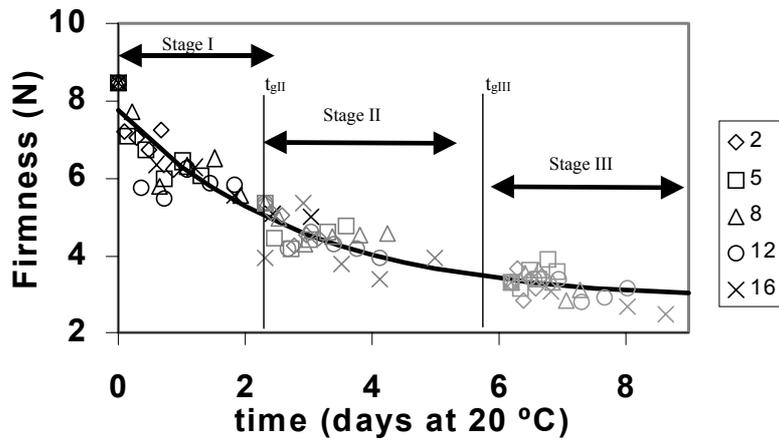


Fig. 7. Decrease in tomato pericarp firmness in time for tomato fruits harvested in three stages of development. Colour stages I, II and III correspond to the following grades of the CBT (Centraal Bureau van de Tuinbouwveilingen) scale: I = grade 3 (equivalent to breaker stage), II = grade 5 and 6 (equivalent to pink stage) and III = grade 9 (equivalent to red stage). Different symbols represent different postharvest temperatures (2°C, 5°C, 8°C, 12°C or 16°C). Source: Lana et al., 2004a.

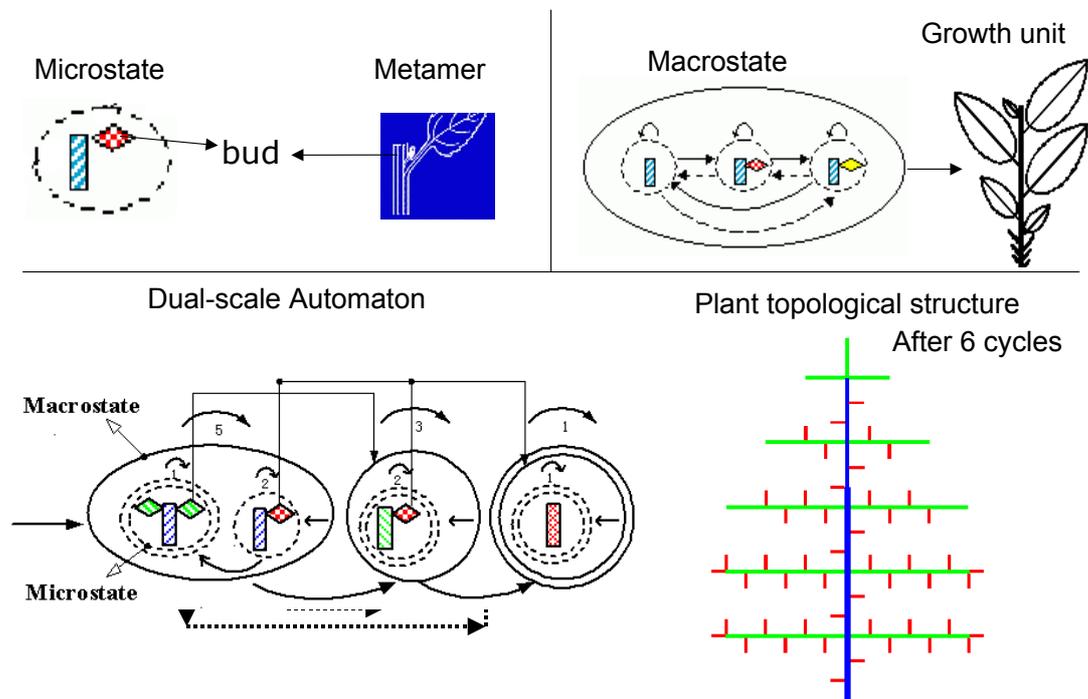
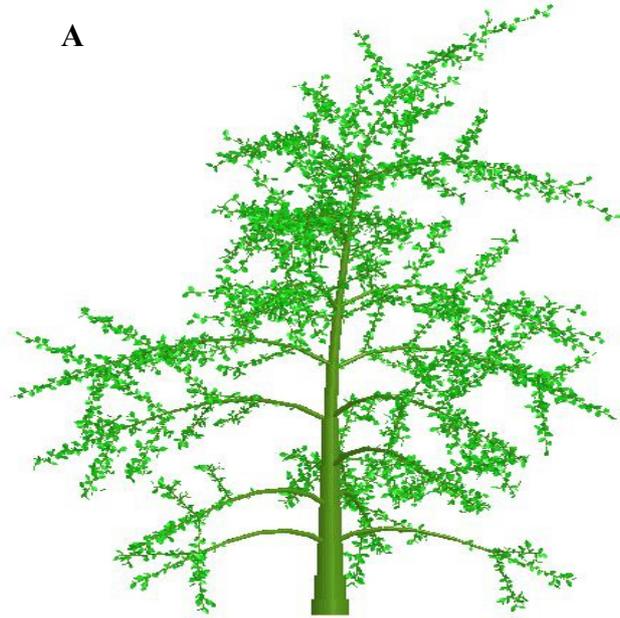


Fig. 8. GREENLAB dual-scale automaton for organogenesis. Source: De Reffye and Hu, 2003.

A



B



Fig. 9. Simulation (GREENLAB) of (A) a *Ginkgo biloba* tree of 15 years old and (B) a demo plant showing that GREENLAB takes into account that organ expansion depends on organ position inside the plant architecture.