UVED Resource

Plant Growth Architecture and Production Dynamics

Preliminary Course: Plant & Crop models

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Contents and Objectives

Models are numerous in agronomy and the related plant and crop sciences.

Presentation

This course introduces plant and crop model approaches.

General considerations about models are first listed, leading to a distinction between descriptive models and causal ones.
The focus here is on causal models.

The principles of various approaches are then shortly introduced, with their pros and cons:

- Process-based models, derived from agronomy, modelling plant production at stand level
- Structural plant models, usually offering 3D representations, defined at individual plant level
- Functional structural plant models, trying to combine plant production and plant structure modelling, also defined at individual plant level

These approaches reflect a wide range of models developed in the communities interested in plant growth models, from agronomy and forestry, up to entertainment.

Course Objectives

The aim of this course is to enable students to:

- Understand the typology of models used in agronomy
- Understand the overall principles of process-based, structural and FSPM models
- Weigh up the pros and cons of the different model approaches
- Choose the right kind of model for a given problem.

Map

Contents

General considerations about models are first considered.
Typologies of plant and crop models are presented.
Among causal models, a distinction is then made between structural approaches and process-based approaches, both computational and mathematical.

The process-based crop model approach is then presented, with an example. The advantages and drawbacks of these models are listed.

The structural plant model approach follows, with an example. The advantages and drawbacks of these models are listed.

Lastly, the functional structural plant model approach is presented, with several examples. The advantages and drawbacks are listed.

Note
Classic empirical forestry models (mainly based on statistics) are not considered here. Further information on this topic can be found in the supplementary resources page.

Course content map

Models and their merits

What is a model?

A model is a simplified representation of a part of reality (i.e. a system representation). Mechanistic models enable us to represent and combine knowledge in a generic way.

Models have many merits:

For research

- testing hypotheses
- cross-disciplinary exchanges and communication
- capitalizing knowledge
- …

For applications

- yield prediction
- greenhouse climate control
- plant selection
- definition of crop management sequences
- economic decision-making
- …

For education

For communication

…

Plant and crop model typology

In climate and fertilization control, forestry, plant and crop production studies, etc., two types of models are widely used: descriptive ones, and explanatory ones.

Descriptive models

These are built using various approaches: black box, regression, statistical, empirical, etc.
They try to build direct relations between input and output. They reflect few or none of the mechanisms that cause the behaviour of the system.

Example.

An experiment carried out on young tomato plants after 40 days of growth at Wageningen University in a climate chamber. In the following table, the respective columns stand for average daily temperature, average nightly temperature and plant height.

T_{day} (°C)	T_{night} (°C)	Plant height (cm)
26	16	52
24	18	50
22	20	34
20	22	35
18	24	28
16	26	23
18	18	18
24	24	54
24	12	39

A statistical model can be defined from these data:

$$Height = 36.3 + 4.48 * (T_{day}-21) + 1.37 * (T_{night}-21)$$

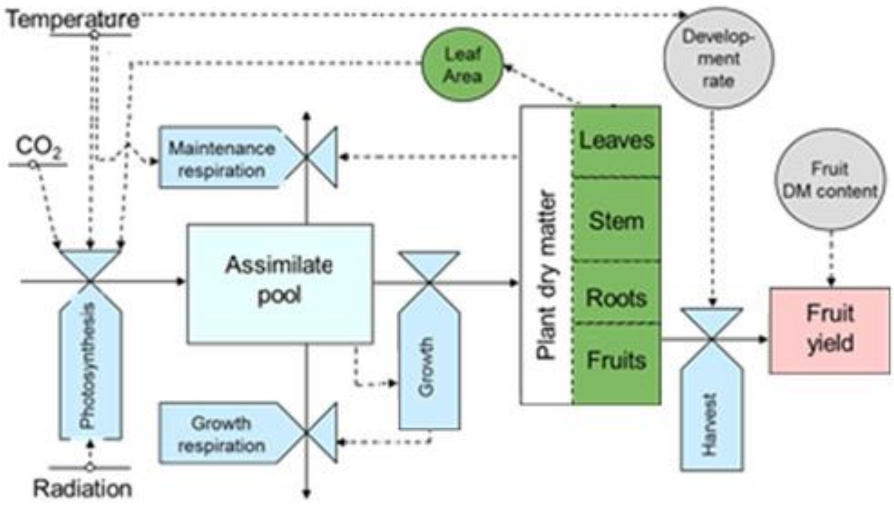
Explanatory (causal) models

These are based on physiological, mechanistic or structural concepts.

They define quantitative descriptions of the underlying mechanisms and processes.

They contain sub-models at least one hierarchical level deeper than the response to be described. At the lowest hierarchical level, sub-models in an explanatory model are descriptive and the model's ability to explain is limited by its number of hierarchical levels.

An example of a mechanistic model.



A mechanistic crop model scheme described according to Foresster diagrams.
The arrows show information pathways while processes are represented in blue containers.
In the light blue rectangle, the biomass pool fed by the leaf area and allocated to the plant organs (in green). (Chart courtesy of E. Heuvelink, WAGENINGEN UNIVERSITY)

Model typology, Pros & Cons

Descriptive and causal models show mutual advantages and drawbacks.

Descriptive model advantages

- Such models are often simple to define and calibrate
- Their behaviour is usually easy to analyse
- In constant contexts, they show high predictive values

Descriptive model drawbacks

- Extrapolations are limited to very low input changes
- They usually cannot integrate new conditions
- They reflect few or none of the mechanisms that cause the behaviour of the system; they are therefore not explaining any result.

Explanatory (causal) model advantages

- They are based on physiological, mechanistic or structural concepts
- They deliver quantitative indicators of the underlying mechanism and process output
- Their genericity allows extrapolation, varying input values
- They are modular, processes can be studied and developed independently
- They provide insights into plant reactions, illustrating *emerging behaviour*

Explanatory (causal) model drawbacks

- Model behaviour analysis is difficult and complex, and reversibility also
- Their developments is complex, very time-consuming, often requiring multiple disciplines (team of researchers)
- Only known effects can be modelled.

Computational and Mathematical Models

In the application of Plant Sciences, explanatory models are usually implemented on computers.

Those implementations may be the implementation of simple mathematical formulae, or be based on the simulation of interactions, simulated from rules or behaviour patterns.
This distinction is important, since model expressions, definition and potential applications are related to it.
In the latter case, we speak about computational models, in the former case we speak about mathematical models.

Computational models

A computational model is a formal model in computational science that requires extensive computational resources to study the behaviour of a complex system by computer simulation.
The system under study is often a complex nonlinear system for which simple, intuitive analytical solutions are not readily available.

Rather than deriving a mathematical analytical solution to the problem, experimentation with the model is done by adjusting the parameters of the system in the computer, and studying the differences in the outcome of the experiments.

The operation theories of the model can be derived/deduced from these computational experiments.

Mathematical models

A mathematical model is a description of a system using mathematical concepts and language.
The process of developing a mathematical model is termed mathematical modelling.

A model may help to explain a system and to study the effects of different components, and to make predictions about behaviour.

Mathematical models can take many forms, including but not limited to dynamic systems, statistical models, differential equations, or game theory models.

These and other types of models can overlap, with a given model involving a variety of abstract structures.

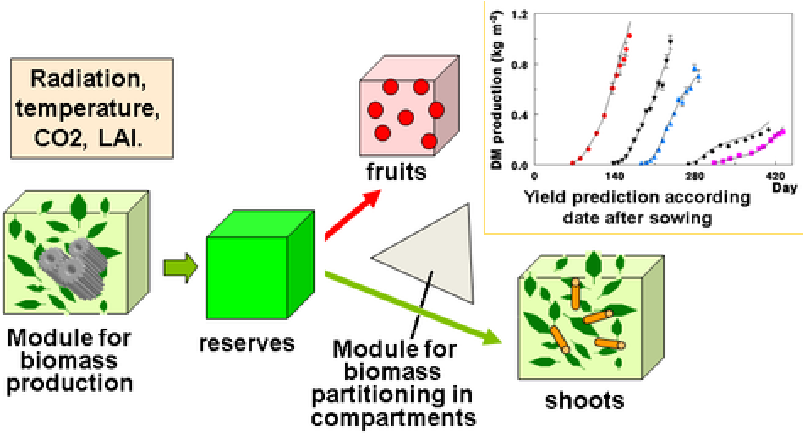
In many cases, the quality of a scientific field depends on how well the mathematical models developed on the theoretical side agree with the results of repeatable experiments.

Plant & Crop Models

Process-based Models

Process-based models or process-based crop models, so-called **PBM**, are designed to predict yields from the simulation of plant functioning according to endogenous plant properties and environmental conditions.
The **harvest index** is a typical output of such models, defined by the weight of the harvested organ divided by the plant weight at the overall crop level.

A process-based model therefore operates on organ compartments.
Such a model is built from several dedicated primitive processes connected together.
It conventionally involves a biomass production model and a biomass partitioning model.

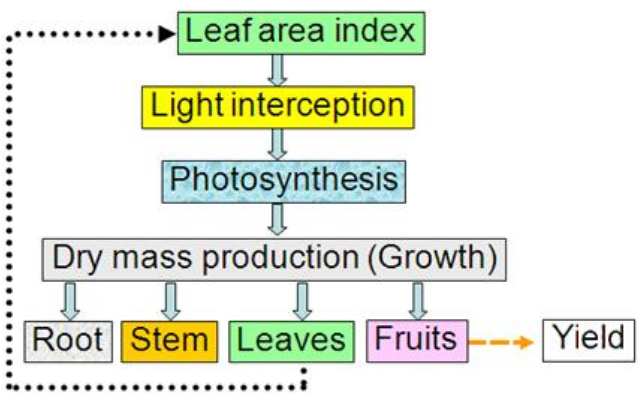


A typical process-based model application. The biomass production model computes the biomass produced by the leaf compartment from the LAI and environmental conditions. The partitioning model then split the biomass between the fruits and the other organ compartments. The model then loops for a new development cycle. In this application, five tomato crops were compared, corresponding to five different germination dates. (Drawing and graph E. Heuvelink, WAGENINGEN UNIV., P. de Reffye, CIRAD)

A Crop Model Example

TOMSIM example
The following diagram presents the TOMSIM crop simulator flow chart, developed by HPC at Wageningen University for a tomato crop (Heuvelink, 1996, 1999).
In this model, the loop involves four main computational steps and the LAI is updated from the leaf biomass compartment pool at each growth cycle (see the preliminary Eco-physiology course for details).

TOMSIM tomato crop simulator workflow.
(Chart E. Heuvelink, WAGENINGEN UNIVERSITY)
Four organ compartments are defined, including the root system.
At each growth cycle, the biomass allocated to leaves allows the LAI update for the next cycle.



Pros and cons of process-based models

Process-based model advantages

- This modular approach makes the development of such a model easy and flexible
- For given environmental conditions, such a model has proved to be efficient on many crops
- Field measurements, calibration and validation are quite easy, since they are limited to few parameters

Process-based model limitations

- The LAI, required as an input, is usually not easy to simulate
- Variations in the harvest index cannot be easily controlled. Specific variations due to the plant structure cannot be distinguished from those due to stress effects (water, light). Conversely, stresses are difficult to relate to harvest indexes
- Stochastic behaviour cannot usually be considered; mean production values can be assessed, but without variances
- Organogenesis is implicit, since organs are considered as compartments. Hence organ differentiation and abortion predictions are difficult
- Problems in linking different modules together (development is often unconnected from growth)
- Girth growth (secondary growth) is often ignored
- The approach suffers from a lack of genericity, often requiring specific developments when trying to switch from one crop (species) to another
- Structure is ignored, hence 3D representation enabling their applications: visualization.

Structural Models

Structural Plant Models also called Geometrical Plant Models are designed to simulate the structure of plants. They have to cope with two major difficulties: firstly, the potential complexity in single plants related to the structural complexity resulting from branching; secondly, the complexity related to the variability found in plants.

Since the early ages of computer sciences, this challenging topic has led to many developments.
To overcome both complexities, computer generated plants may use procedural approaches (automata, particle systems, fractals, combinatorics, etc.) and/or rule-based approaches (grammars). In both cases, computational plant structures are generated with a constructive process related, or usually not, to real plant growth.

Note that numerous computational plant approaches avoid structure computation, using for instance images or so called impostors; they therefore do not deliver 3D structures as output, but simple images or textures.

An interesting review of all these approaches can be found in the book Digital Design of Nature (Deussen and Lintermann 2005).

AMAP approach

The AMAP computational approach is the first procedural construction inspired from botany. It applies mortality, dormancy and branching on the terminal bud of the basic botanical element, the internode.

The structure is then built using an algorithm following the bud development cycles:

```
begin
  for each growth cycle, do
      test bud viability
      test bud dormancy
      if   the bud is alive and not resting, then
         build an internode
         store the new axillary buds (if any)
         if   the internode is the first of a new branch   then
             compute the internode orientation
         end
         compute the internode length and the new bud position
      end
  end
end
```

The algorithm is then recursively called for each new bud generated.

Bibliography

Oliver Deussen, Bernd Lintermann 2005. Digital Design of Nature: Computer Generated Plants and Organics. Editor: Springer may 2005. 307 p. ISBN:978-3540405917

Pros and cons of structural models

Structural model advantages

- Such model builds the plant structure in 3D, offering a fast qualitative data and process check
- With appropriate bases and rules, a structural model can faithfully simulate the structure development of real plants.
- Structural models offer a framework for hosting many applications where plant geometry is required:
  - Mechanical behaviour
  - Pest interactions
  - Comparisons with Lidar, radar, photometric images or acquisitions
  - Simulation of specific crop management sequences, such as pruning
  - Fine radiative simulation
  - etc.
- Structural models specify plant geometry and the underlying structure topology
- Structural models allow stochastic structure representations
- Structural models usually show nice genericity, allowing studies on a wide range of herbs, shrubs, trees

Structural model limitations

- Structural models do not consider functioning, their interest in agronomy is thus very limited:
  - geometrical organ sizes, including internode lengths and diameters, must be fitted from data or empirically defined
  - girth growth (secondary growth) is ignored
  - plant structure plasticity cannot be efficiently studied
  - environmental effects are difficult to integrate
  - early and older development stages cannot usually be simulated from mature stage parameterization
  - ...
- Such models specify the structure, leading to high memory and computing costs on large trees
- The approach is independent from all environmental, climatic and resource conditions
- Extension from a single plant to a crop or stand is difficult and hazardous

Functional Structural Models

Functional-structural plant models (FSPM) simulate the development of plant structure, taking into account plant physiology and environmental factors. They are usually accompanied by visualization of the plant's 3D architecture.
Functional-structural plant models explore and integrate relationships between a plant's structure and processes that underlie its growth and development.

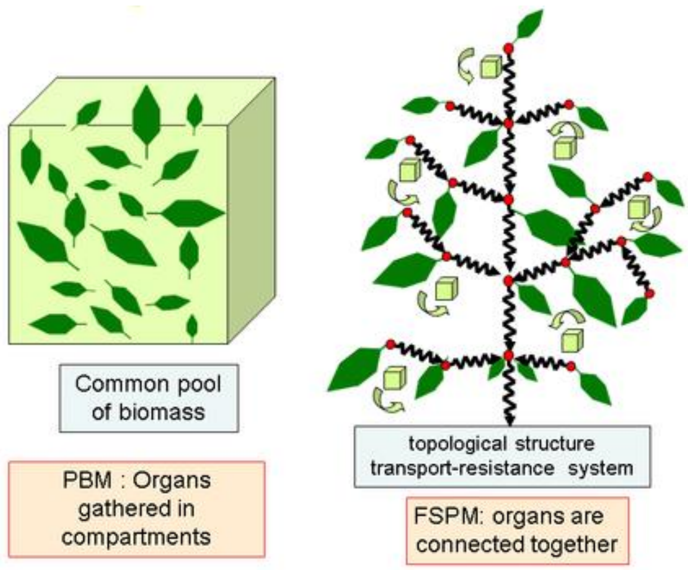
In recent years, the range of topics being addressed by scientists interested in functional-structural plant modelling has expanded greatly. FSPM techniques are now being used to dynamically simulate growth and development occurring on a microscopic scale involving cell division in plant meristems up to the macroscopic scale of whole plants and plant communities. The plant types studied also cover a broad spectrum from algae to trees.

FSPM are highly interdisciplinary and involve scientists with backgrounds in plant physiology, plant anatomy, plant morphology, mathematics, computer science, cellular biology, ecology and agronomy.

Principles
Functional structural plant models (FSPMs) can be defined as models that combine descriptions of metabolic (physiological) processes with a presentation of the 3D structure of a plant. They usually contain the following components (R. Sievänen, 2009)

- Presentation of the plant structure in terms of basic units
- Rules of morphological development
- Models of the metabolic processes that drive plant growth

PBM and FSPM main differences (from the functional viewpoint)
- In PBM, biomass production is shared from a common pool, while in FSPM, biomass is distributed locally, using the plant structure as a transportation system.
- Organs are processed as compartments in PBM, and are individualized in FSPM



Organ source and sink policy in PBM and FSPM.(Drawing P. de Reffye, CIRAD)
The organ compartments are usually limited to organ types in PBM, competing for a common biomass pool. While in FSPM, each organ is individualized, both for sources (locally produced by leaves) and sinks.

The main emphasis in FSPM applications has been on individual plants. It is understandable because, due to the detailed description of the plant structure and, consequently, of the local environment of each organ, FSPMs tend to require a large number of parameters and/or input data. Owing to the large amount of information they contain about the plant to be modelled, they also tend to be computationally heavy.

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Functional Structural Models Examples

LIGNUM

In the LIGNUM model, tree structure is described from three basic units (Tree segment, Branching point and Bud). An STL template library of C++ is used to define a blueprint of a tree that can be instantiated by actual representations of the species' specific components. Four generic algorithms traverse the data structure of the tree and make calculations. L-systems are employed for specifying the morphological development of the trees.

LIGNUM has been employed in several applications. For instance (Sievanen R., 2009) presents a calculation of optimal leaf traits in sugar maple saplings, a system for storing and analysing information on decay in city trees, and simulation of the growth of a tree stand.

L-PEACH

The L-PEACH model is based on the development of peach trees. It demonstrates the usefulness of L-systems in constructing functional-structural models. L-PEACH uses L-systems both to simulate the development of tree structure and to solve differential equations for carbohydrate flow and allocation. New L-system-based algorithms are devised for simulating the behaviour of dynamically changing structures made of hundreds of interacting, time-varying, nonlinear components. L-PEACH incorporates a carbon-allocation model driven by source-sink interactions between tree components. Storage and mobilization of carbohydrates during the annual life cycle of a tree are taken into account. Carbohydrate production in the leaves is simulated based on the availability of water and light. Apices, internodes, leaves and fruit grow according to the resulting local carbohydrate supply. L-PEACH outputs an animated three-dimensional visual representation of the growing tree and user-specified statistics that characterize selected stages of plant development. The model is applied to simulate a tree's response to fruit thinning and changes in water stress. L-PEACH may be used to assist in horticultural decision-making processes after being calibrated to specific trees. (From Allen M.T., 2005)

GreenLab

GreenLab is a generic and mechanistic FSPM. Various botanical architectures can be produced by its organogenesis model. The growth rate is computed from leaf area, and biomass partitioning is governed by the sink strength of growing individual organs present in the plant structure.

A distinguishing feature of the GreenLab model is that plant organogenesis (in terms of the number of organs) and growth (in terms of organ biomass) are formulated using dynamic equations, alongside simulation software.

This facilitates the analytical study of model behaviour, bug-proofing of simulation software, and application of an efficient optimization algorithm for parameter identification and optimal control problems. (From Kang M.G., 2009)

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Allen, M.T., Prusinkiewicz, P., and DeJong, T.M. 2005. Using L-systems for modeling source-sink interactions, architecture and physiology of growing trees: the L-PEACH model. In: New Phytologist, 2005, 166(3), pp. 869-880

Kang, M.G., Cournède, P.H., Mathieu, A., Letort, V., & Qi, R. 2009. A Functional-Structural Plant Model: Theories and its Applications in Agronomy. Cao, W. and White, J. and Wang, E. Crop Modeling and Decision Support, Springer, pp. 148-160, 2009, 978-3-642-01131-3

FSPM Pros & Cons

Functional Structural Plant Model advantages

- The plant simulated structure is a framework able to host functional and specific processes, allowing a wide range of applications
- Girth growth (secondary growth) can be estimated.
- The approach shows genericity
- The plant structure is explicit, hence 3D representation enabling their applications: visualization, interaction with pests, mechanics, pruning simulation, etc.

Functional Structural Plant Model limitations

- Field measurements, calibration and validation are heavy and difficult to carry out
- FSPM show high computing and memory costs in order to simulate the parallel development growth of organs
- FSPM show high computing and memory costs involved in estimating biomass production, especially related to light interception computation, known to be a nonlinear problem (ray tracing)
- FSPM show high computing costs for biomass transport and partitioning in the plant architecture
- Such models usually involve many parameters, preventing inverse method definition and optimisation.
- Stochastic behaviour cannot usually be considered; mean values and variance of production are difficult to assess, requiring sets of numerical experiments
- Model extension from single plant to plant population is not clear and adds a high level of computation complexity

An Example

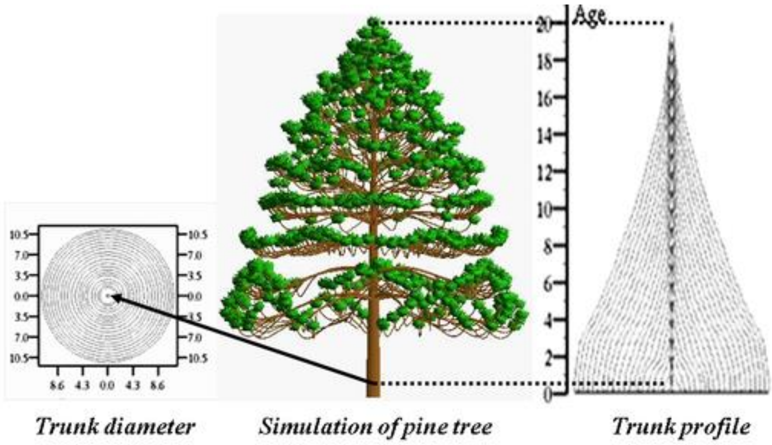
The authors share a long history in plant modelling, from the late seventies to nowadays, developing various plant structural and functional structural models

Computational models

Starting in the late seventies, the first developments by Ph. de Reffye on *Coffea* led to the definition of a **structural or geometrical plant growth model** called AMAP.
This model became popular for various applications including Computer Graphics.

Structural 3D plant simulations (Images P. de Reffye and M. Jaeger, CIRAD)
Left : Benson plotter 4-colour drawing(1984)
Right: Silicon Graphics simulated Cypress (1990).

In the late eighties, the structure was used as a transport pathway support to host functional aspects, such as leaf evapotranspiration and secondary growth, building a **Functional Structural Plant Model (FSPM)**.



An FSPM implementation: the Amap Para Software P. de Reffye, F. Blaise, 1993
Plant structure, leaf evapotranspiration and secondary growth simulation
(Illustrations P. de Reffye and F. Blaise, CIRAD)

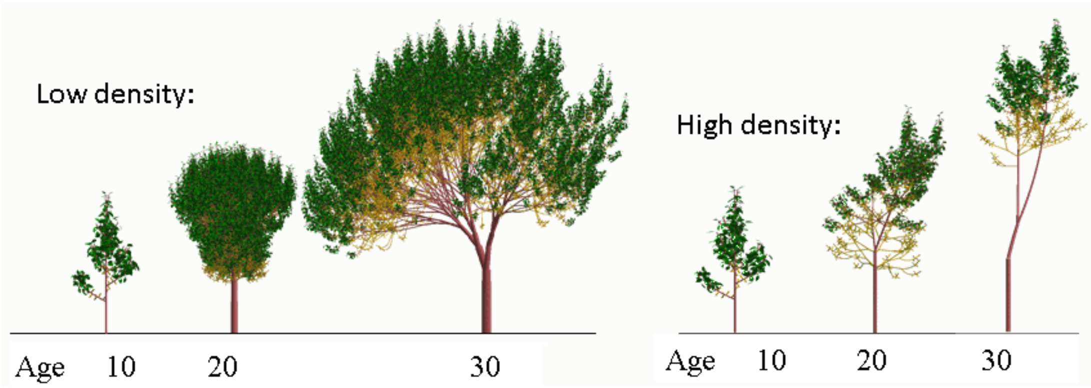
These approaches were computational:
The structure is simulated applying rules of development defined from field observations.

Mathematical models

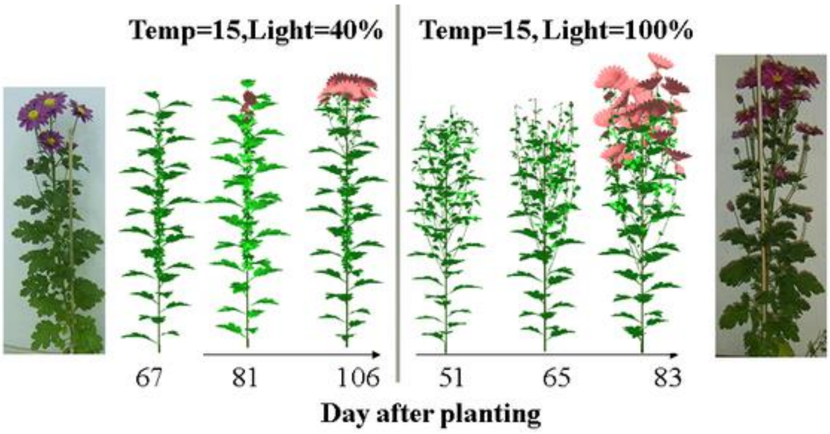
The next model generation, developed in cooperation with China, called GreenLab, is a **mathematical model**.

It differs from computational models in that development and functional processes are described by equations and do not strictly result from simulation.
The model therefore quantifies the structure (the number of organs, their appearance time, etc.) without requiring an exhaustive structural implementation.
This plant model is therefore seen as a classic mathematical dynamic model.
Such an approach makes the model reversible, making parameter identification and optimization more affordable.

In its latest developments, GreenLab can provide functional feedback on the structure under various environmental conditions.



Plant structure plasticity due to density simulated by the GreenLab Model
This example shows three tree growth stages under two different densities.
The underlying concept is the Projection Area, which thresholds branching and axis lengthening in structural development.
(Images Digiplante software, A. Mathieu and P.H. Cournède, Ecole Centrale of Paris, 2007)



Plant structure plasticity due to environmental conditions simulated by the GreenLab Model
This example shows three Chrysanthemum growth stages under two different light and temperature conditions.
(Photos and Illustrations with © GreenScilab software, M.G. Kang, LIAMA-CASIA, 2007)

Supplementary resources

Mathematical models

Recommended on-line resources

GreenLab Overview (English) ../../P2_GLab/Intro/GLintro_intro.html

More detailed GreenLab overviews (pdf files)

Relevant qualitative and quantitative choices for building an efficient dynamic plant growth model (pdf)

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Web sites

Digiplante project (Ecole Centrale Paris) Web site: http://digiplante.mas.ecp.fr/

GreenLab project Web site: http://GreenLab.cirad.fr/

GroGra (structural) http://www.grogra.de/software/groimp

L-studio (structural) http://algorithmicbotany.org/lstudio/whatis.html

PlantMod (functional) http://http://www.imj.com.au/software/plantmod/index.html