UVED Resource

Plant Growth Architecture and Production Dynamics

GreenLab Course: Principles

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Contents and Objectives

Presentation

Aside the classic process-based crop models and individual structural plant models, GreenLab displays an original positioning.

GreenLab is a mathematical dynamic model aiming to model and simulate plant structure establishment and production.

It differs from computational models by the fact that both development and functional processes are described by equations.
The model therefore quantifies structure (the number of organs, etc..) without requiring exhaustive structural implementation.

It also differs from classic functional structural plant models by the fact that organ production is quantified by compartments, competing for a common biomass pool.
It also differs from biomass production based on the Beer Lambert Law, conventionally used in PBM.

In a growth cycle, the model sequences organogenesis, biomass production and its partitioning in a dynamic loop.

Around the world, researchers have developed various implementations of this model, allowing deterministic or stochastic simulations, with more or less detailed implementation of structural aspects or functional aspects.
Specific developments are also based on model inversion (parameter identification and estimation) and on applications.

Course Objectives

The aim of this course is to enable students to:

- Understand the positioning of the GreenLab model between PBM and FSPM, along with its Pros and Cons
- Assimilate Greenlab's assumptions and principals
- Acquire an overview of Greenlab implementations

Map

This section introduces the principles of the GreenLab functional structural plant model, highlighting the following aspects:

The model is derived from various disciplines.

GreenLab is an extended process-based model and a simplified structural model (structure is not explicitly required).

The growth cycle schedules organogenesis, biomass production, and the organ expansion processes.

The model has several implementations.

Course content map

About modelling

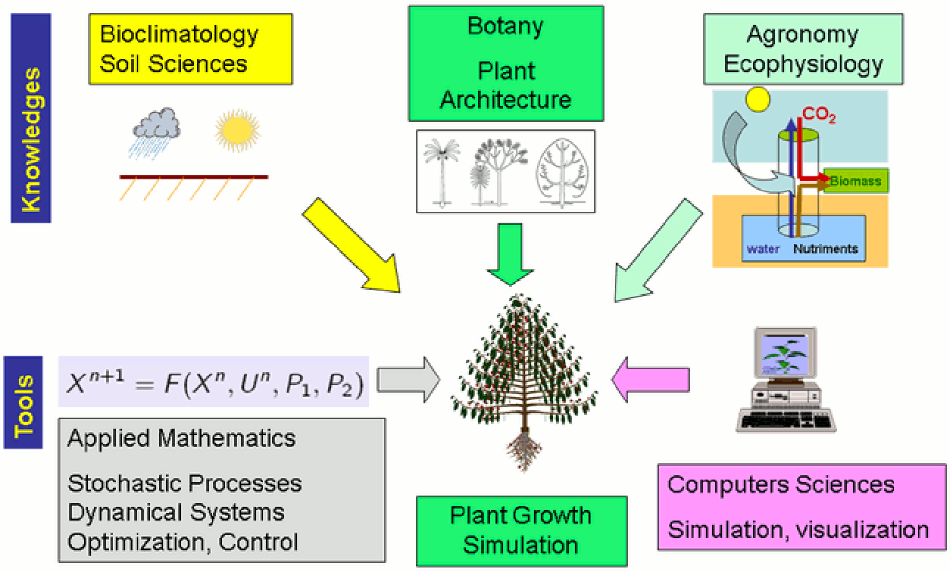
Scientific disciplines

Plant growth and development modelling is a challenging research topic relying on the knowledge of several disciplines:

- Botany: plant morphology and more precisely plant **Architecture** considered on the scale of the individual plant.
- Physiology: the plant seen as a dynamic system exchanging fluxes, usually seen at crop level, related to Agronomy
- Bioclimatology: as providing the environmental resources for plant development

Formalisms, Models, and Tools combining knowledge from these disciplines have to be developed in order to succeed in defining the generic modelling and simulation of plant growth and development.

Applied mathematics and computer sciences are thus involved in this task.

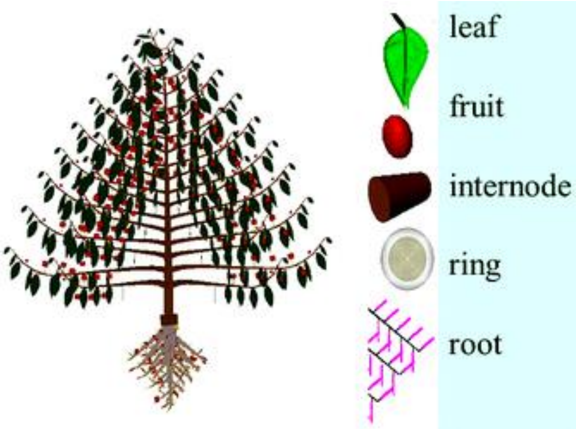


Disciplines involved in Plant growth modelling: knowledge (Botany, Eco-physiology, Bioclimatology) and tools (Applied Mathematics and Computer Sciences) (Drawing P. de Reffye, CIRAD)

REMPLACER :
Knowledges par Knowledge / Nutriments par Nutrients / Dynamical Systems par Dynamic Systems / Computers Sciences par Computer Sciences

Organs

In the GreenLab model, the plant components involved in the plant architecture are the leaves, fruits (flowers), internodes, rings and roots.
They are called Organs.



Organs: plant components (Drawing P. de Reffye, CIRAD)
Leaves, fruits, internodes, wood rings and roots are the tree components used in the GreenLab approach

Organs are made of fresh matter, mainly composed of water and sugars (80% H20 + 15% CHO).

Organ geometry (size, length, diameter, area, etc.) derives from allometric rules, density and the amount of biomass allocated during their growth.

Factors affecting plant growth and modelling

Plant growth results from both endogenous processes and environmental factors.

The endogenous process drives plant structure establishment

Plant structure establishment is the final result of endogenous processes. Differentiation and production of the various organs can be expressed from rules applied to successive metamers.

Such rules can be simulated with an automaton. Models simulating such organ differentiation are called **structural or geometric**. They aim to generate the plant structure at various ages, up to detailed geometry allowing 3D representations. The rules are based on botanical architectural notions. Ideally, for a given species, an efficient model defines rules for each axis typology (each physiological age), suitable for a wide range of plant ages and environmental conditions.

Environmental factors also impact on plant growth.

Resources, and more precisely the supply of water and light, affect organ biomass accumulation and thus organ size.

Models relative to these aspects are called functional models. Such is the case of process-based models or crop models.

- Light produces photosynthates via green leaf functioning. Empirically, the effect of incident light is well known. Depending on light intensity, a linear effect can be seen gradually reaching saturation. Light also has a strong influence on plant plasticity. It can modify plant development by affecting the rules of meristem production. This can be a difficult point for modelling, requiring functional to structural feedback.

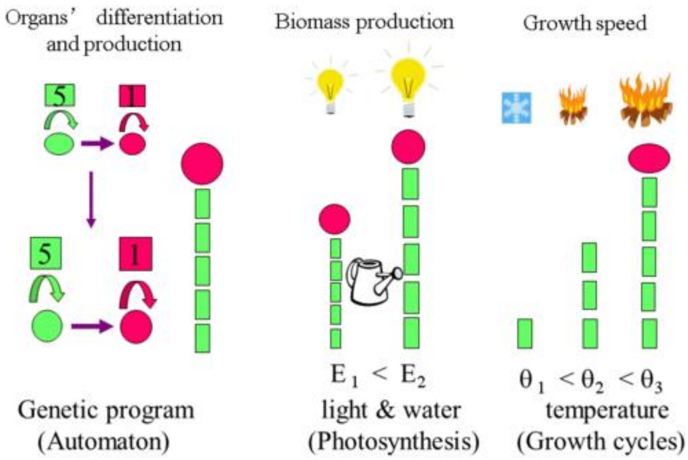
- Water is taken up by roots from the root environment and evaporates by transpiration at leaf level. As both transpiration and photosynthesis are strongly influenced by light intensity, a close relation is often seen between crop transpiration and biomass production. Plant transpiration depends primarily on radiation and leaf area. It can be limited by water shortages in the root environment (stomata will close). The cumulated effect of water transpiration over the long term is often linearly related to plant biomass production.

Modelling biomass production (photosynthesis) is a key point, and mutually benefits from the empirical light effect law and the linear water transpiration / biomass production relation.
However, biomass attribution to a given organ results from competition between organs. During growth, available biomass will be allotted to a given organ depending on its sink strength.

- Temperature also affects growth.
In most of plants, the structure development steps are governed by the thermal energy received. Temperature controls the rate of shoot development and the duration of organ expansion. Within a given temperature range (i.e., when the development rate is linearly related to temperature), there is a linear relationship between the number of phytomers formed on a shoot and the sum of daily effective temperatures received by the plant.

To sum up, temperature affects the rate of structure development, and light and water affect biomass growth.

Hence, in advanced models, development cycles are scheduled by thermal time, rather than calendar time.



Factors affecting plant growth and modelling (Drawing and animation P. de Reffye, CIRAD)
REPLACER Organs' par Organ / Growth speed par Growth rate
Left, an endogenous factor. In the illustrated example, the structure is built from five consecutive metamers at the same stage of differentiation. The terminal bud then reaches a flowering stage; growth is thus determinate.
Middle and right: Environmental factors illustrating growth dynamics.
Two levels of resources and three levels of temperatures are shown.

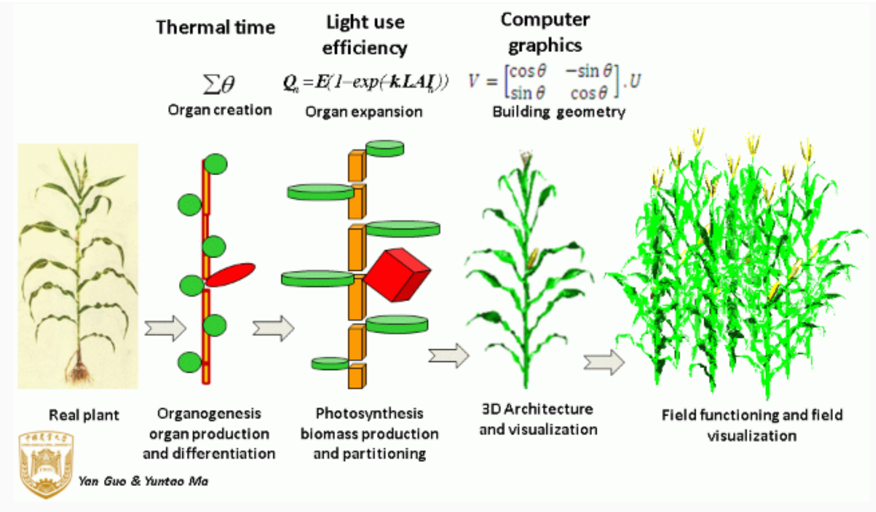
From real plant measurements to simulated stands

Modelling / simulation workflow

In most functional structural plant models, the modelling flow chart generates the plant and crop simulation results from several steps.

- Measurements at single plant level
- Building of the plant structure: organogenesis
- Definition of plant functioning: biomass production
- Building, if required, the 3D plant structure
- Building applications at crop level

The following animation illustrates studies the work flow in studies hold on maize crops at Chinese University of Agriculture.



Modelling / simulation flow chart for maize stands (© Y. Guo,Y.T. Ma, CAU, Beijing)

1. Maize plants are individually measured (organ position, weight, etc.)

2. A structural model is built (defining the plant topology; here it is likely to be constant in the stand)

3. A functional model is defined and calibrated

4. Geometric details are added, as well as material properties for faithful 3D representations

5. The model is extended and used at stand level

In the GreenLab model approach, this flowchart is strictly respected.

In software implementations, this flowchart can be applied for each growth cycle or for a given final age.

In the examples and illustrations of this course, we use an implementation based on the following:

1. The structure (or rather structural parts) are fully computed first
2. Production is then computed for all growth stages, defining organ dimensions from the biomass produced by the leaves intercepting light
3. A 3D structure is constructed if requested (but not required)
4. Applications at stand level are issued, for instance by statistical studies based on stochastic simulations

Field observations consist of:

- Organ distributions (according to botanical architectural typology); these help to define structural rules, laws of development, viability and branching.
- Organ geometry analysis, in order to define allometries for each organ type
- Organ weight/area in order to fit functional parameters
- Stand information (such as density, for applications)
- Climatic data (for applications, if not constant)
- Specific geometric and optical information (for 3D reconstruction and rendering)

GreenLab positioning

The GreenLab model approach seeks to benefit from the advantages of both process-based and structural models.

Main assumptions

Inspired from Process-Based Models

- Environmental conditions define the biomass production level
- Biomass production mainly depends on LAI and LUE, transposed from crop to individual plant level.
- The produced biomass is shared among organs in a common pool.
- Biomass production and partitioning are independent processes.
- Biomass partitioning is performed between individual organs in competition for the common pool.
- Organ sinks are proportional.

Inspired from Structural Models

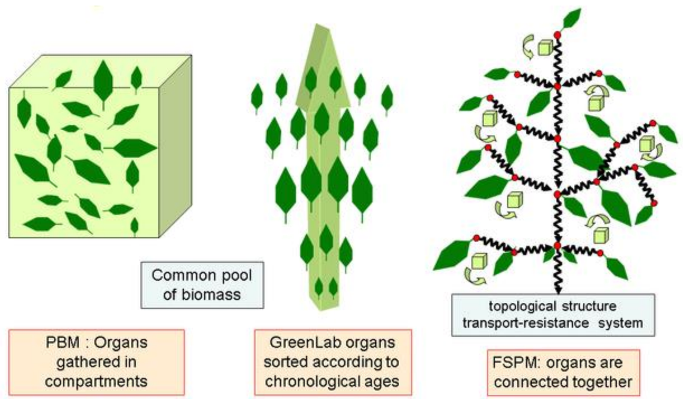
- Organ differentiation is taken into account, using a classification indexed by both the Physiological age and the chronological age.
- Organogenesis is explicit and quantified.
- Plant structure and its topology can be explicit, allowing 3D representations
- Stochastic behaviour can be considered
- Girth growth (secondary growth) can be considered
- The approach shows a generic framework.

PbM, FSPM and GreenLab

GreenLab model positioning

In PBM and Greenlab, biomass production is shared from a common pool, while in FSPM, biomass is locally distributed, using the plant structure as a transportation system.

In structural models and Greenlab, organs are distributed according to temporal compartments and structural typology: the physiological age. However their precise topological and geometric positions are not required in the GreenLab model.



Organ Source and Sink policy in PBM, GreenLab and FSPM (Drawing P. de Reffye, CIRAD)

Left: the organ compartments are usually limited to the organ types in PBM.

Middle: Organs are organized in physiological and chronological ages in GreenLab, implicitly related to architectural concepts.

Right: while in FSPM, each organ is individualized, both for sources (leaves) and sinks.

Growth cycles

GreenLab model growth and development cycles

A discrete Model

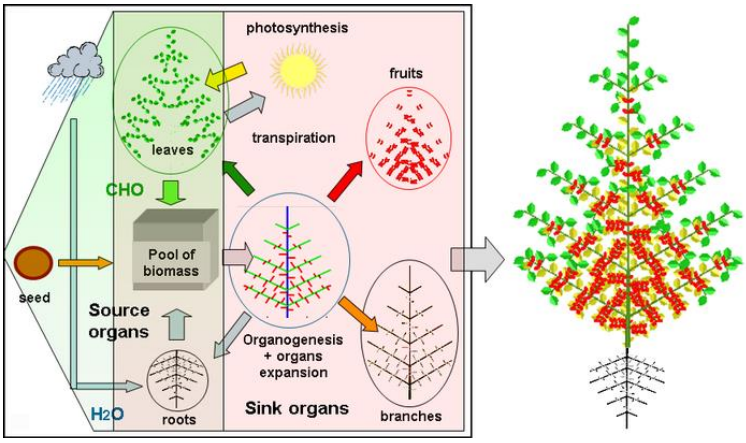
The GreenLab model evaluates plant structure and production at regular thermal time periods. The unit time cycle, defined from an average daily temperature sum ratio, is called a **growth cycle (CG: cycle of growt)**.

The growth cycle value is usually low compared to a shoot development cycle (under ideal temperature conditions, typical values range from a couple of days for a seasonable plant to several weeks for temperate trees). Hence:

- Thermal time implicitly controls the plant development rate (organogenesis).
- Thermal time implicitly controls the duration of organ functioning and expansion.
- However, organ growth does not depend on the temperature, but only on the available biomass to be shared with the other organs.

Growth and development cycle: principles

- For each growth cycle, the model defines organogenesis evolution on a representative of each metamer organ cohort (since all organs in a given cohort share the same chronological and physiological properties).
- Biomass production is computed from organ sources and sizes (usually the functional leaf areas).
- If organogenesis occurs, the different organ cohorts are updated, according to micro and macro state evolutions.
- Biomass demand is then evaluated, for each organ cluster, according to its sink value.
- The remaining pool of biomass is then divided among the available functioning organ clusters, as a proportion if the demand exceeds the pool.
- Organ sizes are computed from their chronological age, their expansion state, and allometry rules
- The remaining biomass, if any, is kept in the biomass pool.



The GreenLab dynamic model cycle (Drawing P. de Reffye, CIRAD)
For each growth cycle:

1. *Plant production is computed and stored in the common biomass pool*
2. *Organogenesis is computed with potentially new organ cohorts*
3. *Plant demand is evaluated and the required biomass split among the organs in proportion to their sink and to biomass availability*

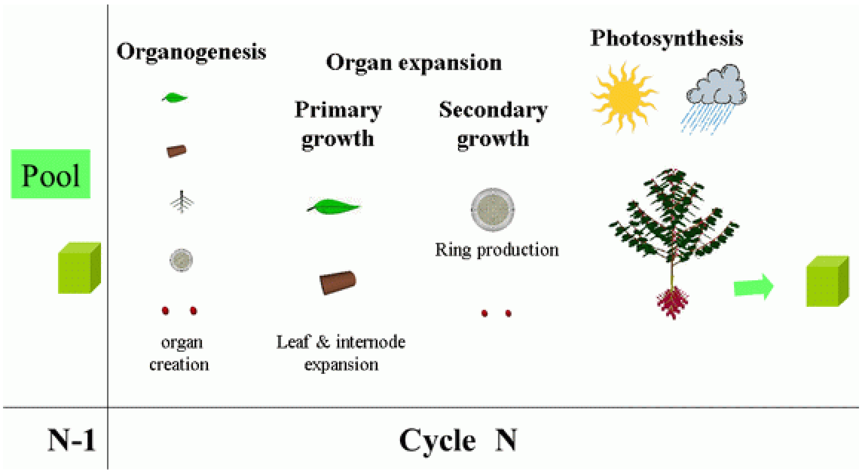
The growth cycle. The computational view

The growth and development cycle

For each growth cycle, the model evaluates in sequence the following processes:

- Organogenesis. Representatives of new metamer organ cohorts can be created, according to micro and macro state evolutions.
- Plant Demand is computed, from all cohorts still in expansion.
- For each organ cohort, biomass allocation is evaluated, according to its sink value, the total demand and the available biomass.
- Organ sizes are computed using allometry rules
- Biomass production is computed from organ sources and sizes (usually the area of all functional leaves).
- The biomass produced is added to the remaining biomass if any, and stored in the biomass pool for the next growth cycle.

Processes involved in the growth cycle



This figure illustrates the process involved in a growth cycle (Drawing P. de Reffye, CIRAD)
Note that expansion is not synchronized with organogenesis.
Organ expansion can be delayed, typically in fruits.
It also operates on the organs created in previous cycles, until reaching the term of their development.

GreenLab implementations

Various GreenLab implementations under different environments are available.
They also differ in their specifications, allowing stochastic simulation or not, fitting or not, retroaction on structure or not.

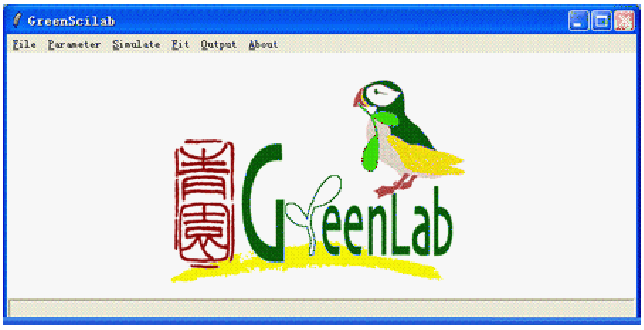
The following table summarises the implementations and their specifications

Name	Environment	Stochastic	Retroaction	Diffusion	Language	Main developer	Usage	Url
GreenScilab	Windows Os	-	-	Freeware	Scilab	Chinese Academy of Sciences - CASIA	Education	GreenScilab
Xplo with GreenLab Plug-in	All Os	-	-	Freeware	Java	CIRAD - Amap (Amapstudio)	Research	Xplo
dgpSDK libraries	Windows and Linux Os	X	X	Free to partners	C++	Ecole Centrale Paris	Research	digiplante's software
GLOUPS	Windows and Linux Os	X	X	Free to partners	Mathlab	CIRAD- Amap Unit	Research	GLOUPS
QingYuan	Windows Os	X	X	Contractual	Qt / C++	Chinese Academy of Sciences - CASIA	Research	QingYuan

Some GreenLab implementations and their specifications

GreenScilab

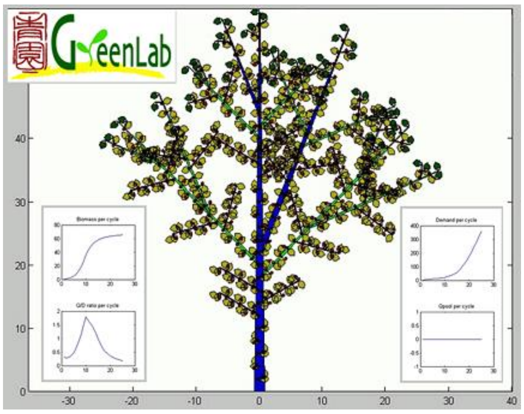
GreenScilab is a toolbox developed by Mengzhen Kang and Qi Riu (CASIA) in the Scilab environment to run the GreenLab model.
GreenScilab can simulate many crop plants, such as tomato, cucumber, chrysanthemum and maize, and these crops have been calibrated with experimental data.
See GreenScilab inline page for download and tutorial.



GreenScilab interface (Liama, CASIA)

Gloups

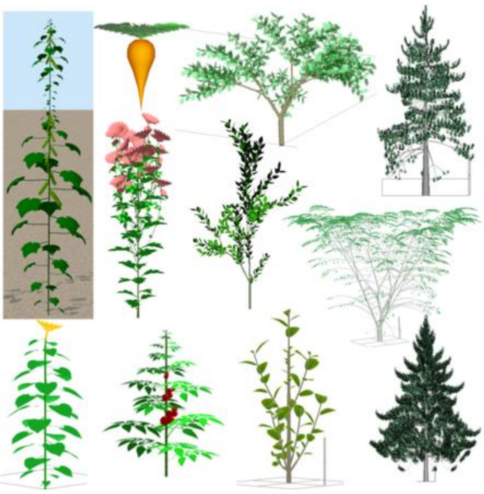
Gloups (GreenLab Universal Plant Simulator) is a toolbox developed by Philippe de Reffye (CIRAD Amap) in the Matlab environment to run the GreenLab model.
Gloups is a research prototype. It is the most advanced GreenLab implementation, allowing both simulation and fitting. See Gloups inline page for more information.



Gloups interface (Snap shot M. Jaeger, CIRAD)

Qinyuan

Qingyuan, written by Hua Jing (CASIA) under the Qt environment, in C++, offers an advanced GreenLab implementation with high performance.
It can simulate trees, such as albizia, ginkgo, pine and orange tree....
See http://www.cybernature.com.cn/cPlant/software.html for further information.



Some QingYuan simulations (Hua Jing, Liama, CASIA)

PyGMAlion and **dgpSDK**

Developed by Ecole Centrale Paris, in C++, these environments are dedicated to researchers.

PyGMAlion (Plant Growth Modelling Analysis and identification) is a C++ framework embedding modelling, simulation, parameter estimation, and discrete system sensibility analysis tools.
dgpSDK is a library set implementing the GreenLab model with basic applications.
See http://digiplante.mas.ecp.fr/software for further information.

Supplementary resources

Recommended on-line resources

Architectural Botany course (English)
../../P1_Prelim/Bota/Bota_intro.html

Eco-physiology for crop modelling course (English)
../../P1_Prelim/EPhysio/Physio_intro.html

Introduction to Models (English)
../../P1_Prelim/Model/Model_intro.html

GreenLab Full Course (English)
../GL_intro.html

More detailed GreenLab overviews (pdf files)

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

Plant growth models (pdf)

Bibliography

Recommended reading

Hallé, F., Oldemann, R.A.A. 1970. Essai sur l'architecture et la dynamique de croissance des arbres tropicaux. Paris: Masson.

Barthélémy, D., Caraglio, Y. 2007. Plant Architecture: A Dynamic, Multilevel and Comprehensive Approach to Plant Form, Structure and Ontogeny. Annals of Botany, 99 (3) : pp. 375-407 19 (access to paper and pdf)

De Reffye P., Hu BG, 2003. Relevant qualitative and quantitative choices for building an efficient dynamic plant growth model: GreenLab case. In Hu BG, Jaeger M (Eds), Plant growth modelling and applications (PMA03), Proceedings of the 2003' International Symposium on Plant Growth Modeling, Simulation, Visualization and Their ApplicationsTsinghua University Press, Springer; pp. 87-107. (pdf)

(Cournède)De Reffye P., Heuvelink E, Barthélémy D, Cournède PH. 2008. Plant growth models. In: Jorgensen S, Fath B (Eds.), Ecological Models, Vol. 4 of Encyclopedia of Ecology (5 volumes), Elsevier (Oxford), pp. 2824-2837. (pdf)

Web sites

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

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

Une histoire de la modélisation des plantes (French)