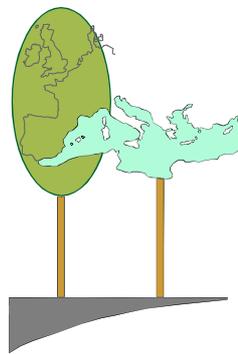


# **ModMED**

## **Modelling Mediterranean Ecosystem Dynamics**



## **FINAL REPORT**

EU - DG XII - ENV4 CT97 0680

## LIST OF PARTICIPANTS

### *Contractors*

- 1) Dipartimento di Arboricoltura, Botanica e Patologia Vegetale, Università di Napoli *Federico II*, Italy  
Prof. Stefano Mazzoleni (project coordinator) – email: [mazzolen@unina.it](mailto:mazzolen@unina.it)
- 2) Institute of Ecology and Resource Management, University of Edinburgh, UK  
Dr. Colin Legg.
- 3) Department of Ecology and Systematics, University of Athens, Greece  
Prof. Margarita Arianoutsou.
- 4) Dipartimento di Coltivazione e Difesa delle Specie Legnose, Università di Pisa, Italy  
Prof. Riccardo Gucci.

### *Associate contractors*

- 5) Remote Sensing Department, University of Trier, Germany  
Prof. Joachim Hill.
- 6) Estação Florestal Nacional, Portugal  
Prof. Francisco Manuel Cardoso de Castro Rego.
- 7) Dipartimento di Scienze Animali, Vegetali e dell'Ambiente, Università del Molise, Italy  
Prof. Donato Chiatante.
- 8) Istituto sulla propagazione delle specie legnose, Italy  
Dr. Massimiliano Tattini.

### *Sub-contractors*

- 9) Istituto di Biologia, II Università di Napoli, Italy  
Prof. Antonietta Fioretto.
- 10) GE.PRO.TER. soc.coop. a.r.l., Italy  
Dr. Antonio Di Gennaro.
- 11) Institute of Sub-Tropical Plants and Olive Tree, Greece  
Mr. C.D. Economakis.
- 12) Centre de Recerca Ecologica i Aplicacions Forestals (CREAF), Spain  
Prof. Carlos Gracia.
- 13) World in box Finland OY  
Mr. Duncan Heathfield.

### *External participants*

(supported by OMFB Hungarian Foundation - INCO funds)

- 13) Department of Plant Taxonomy and Ecology, Leotvos University of Budapest, Hungary  
Dr. Peter Csontos.

# **COMMUNITY LEVEL MODELS**

# n-Species model

Colin Legg and Alistair Hamilton

## Rationale

The purpose of the n-species model is to model quantitatively the changes in plant species presence and attributes in Mediterranean ecosystems. Plant species are modelled at the species level and the model contains no concept or representation of individual plants, so there is no spatial representation within the model. The model is designed to be used either as a stand-alone model to allow exploration of model behaviour and sensitivity, or as a single pixel within a gridded landscape using Landlord.

## Design

There are two main levels within the model (Figure 1). The outer level models the properties of the whole patch and processes at the community scale. These include hydrology, fire and the behaviour of grazing animals. The inner model comprises the properties of individual species and the processes of growth and establishment. For ease of understanding, model components are grouped together into submodels.

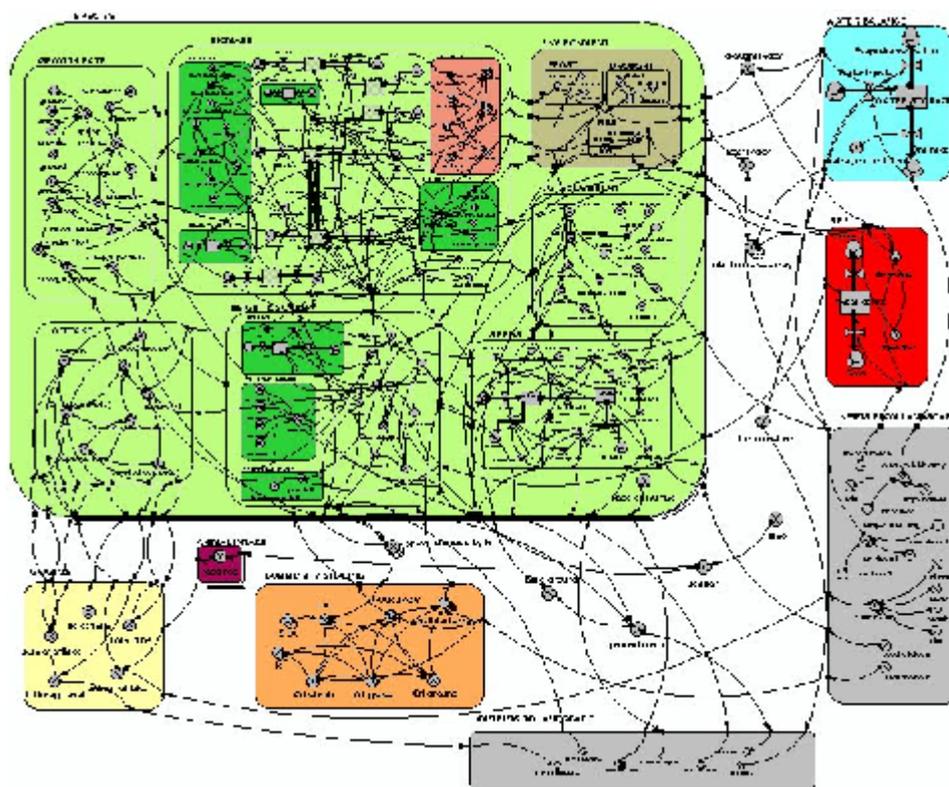


Figure 1. n-Species model showing the multiple-instances of the species-level submodel (large box) and the community-level components around the outside. The full model is available on the ModMED CD.

## Species components

At the species level a single model is designed with multiple instances representing different species; species-specific behaviour is achieved by different parameterisation of each instance. The species model includes submodels reflecting the growth processes of green material, woody material and reserves; the effects of environmental conditions on growth processes; losses due to fire, drought and grazing animals; seed production, storage in the seed bank and establishment.

### ***Community-level components***

Community-level submodels include both the environmental characteristics of water balance, fire severity and required intake by grazing animals, and also the shading effect of the vegetation. The inputs and outputs that link the n-Species model to the landscape in Landlord are also included as submodels.

### ***Implementation***

To run the model, the user must first parameterise the model for the desired species. This is achieved by using prepared files (tables) to set the required parameters. Different files can be constructed for different scenarios (for example, different vegetation types in different countries). The model must then be initialised, i.e. given a 'starting point' for the species present, again using prepared files. When the model is run within a Landlord landscape, the user specifies the dimensions of the landscape. A separate instance of the n-Species model is then parameterised for each pixel within the landscape. The different vegetation types that may be present across a landscape are represented by different parameterisation and initialisation of the n-species models across that landscape.

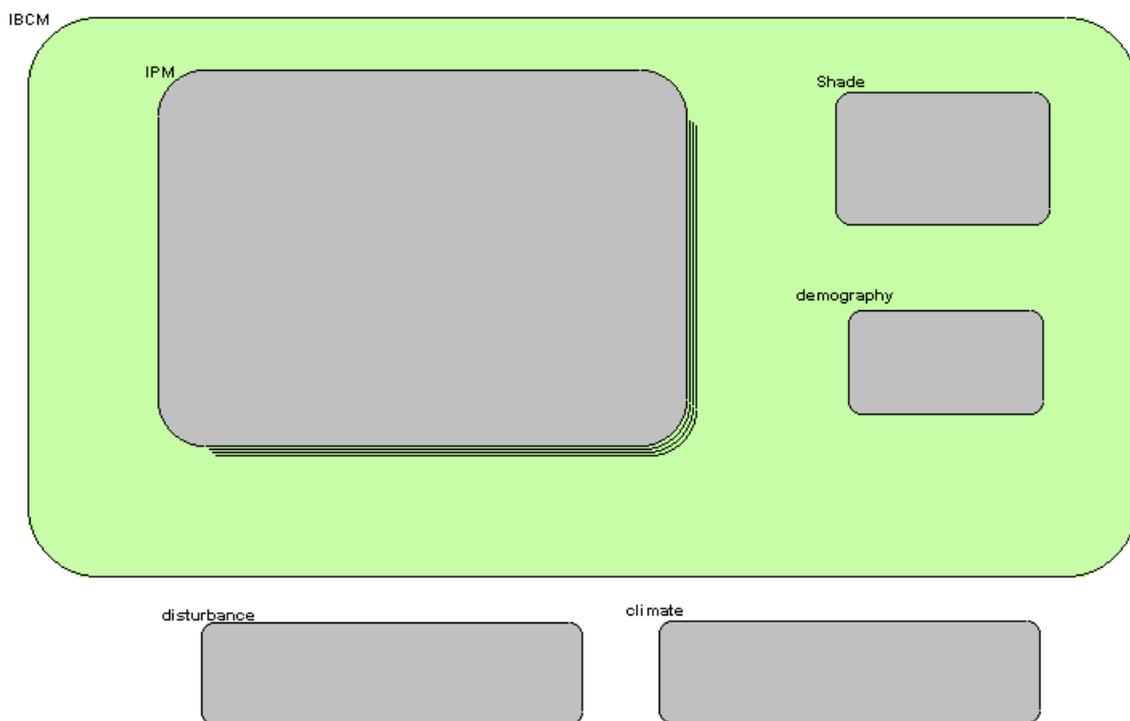
This model has currently been prepared more as a 'proof of concept' and cannot be yet completely parameterised and validated until the final results of the whole ModMED project are available.

# Individual Based Community Model (IBCM)

*Stefano Mazzoleni and Francesco Giannino*

## Introduction

The Individual Based Community Model (IBCM) represents an assemblage of individuals of plant species with an explicit spatial representation of the vegetation community.



Each individual plant is located by its  $x$ ,  $y$  position in the plot and modelled independently from other individuals. This corresponds to the activation of one instance of the Individual Plant Model (IPM). The IPM activates a number of instances equal to the individuals which are in the community.

A shade model defines the shading between neighbour plants.

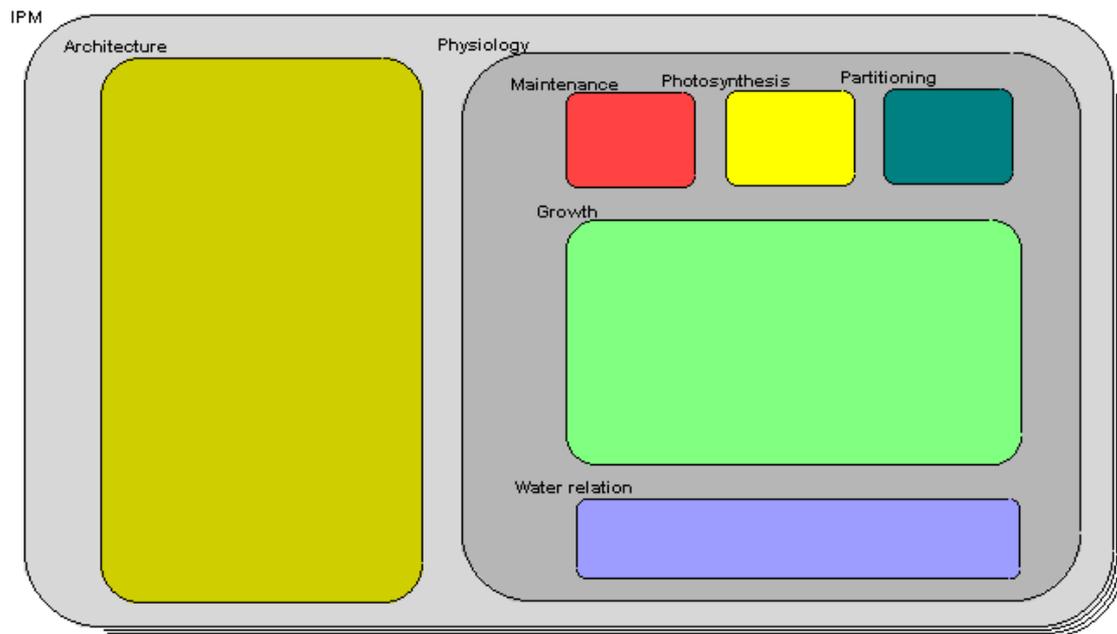
A demographic model is not yet defined but its functionality is already included and it demonstrates the possibility of birth and death of individual plants, i.e. generation and depletion of individuals in and out from the community. For example new seedlings can establish at random position in the plot, but in the next future a new implementation of demographic model will handle establishment by conditioned assessment and the probabilistic rules.

Disturbance and climatic inputs are either loaded from data files or connections with landscape level models.

## IPM - Individual Plant Model

The IPM Individual Plant Model is composed by two major models:

1. the physiology model
2. the architecture model



The physiology model includes several sub-models:

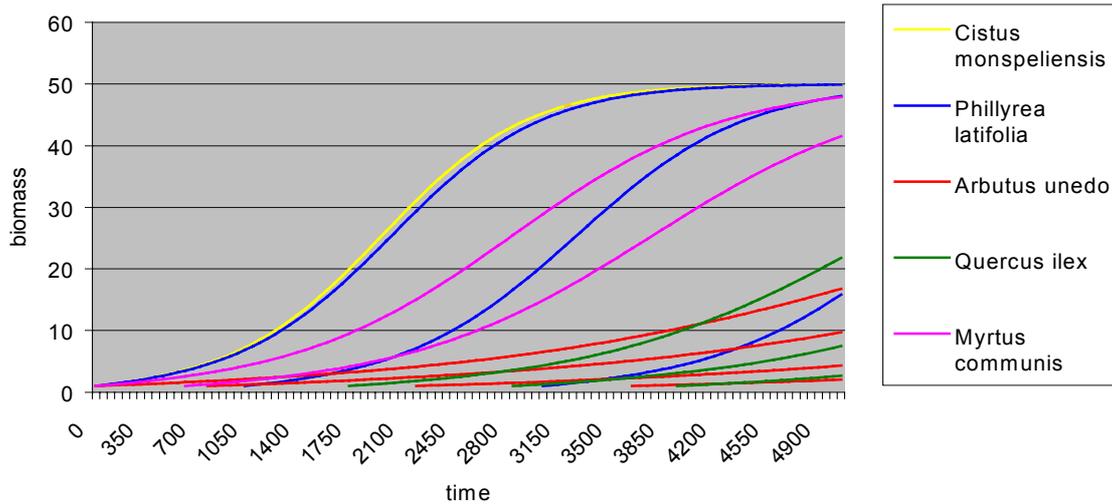
- Photosynthesis
- Maintenance
- Growth
- Partitioning
- Water relation

The architecture model represents the plant size and shape and allocates biomass between structures (leaves, shoots, wood, fine roots, structural roots)

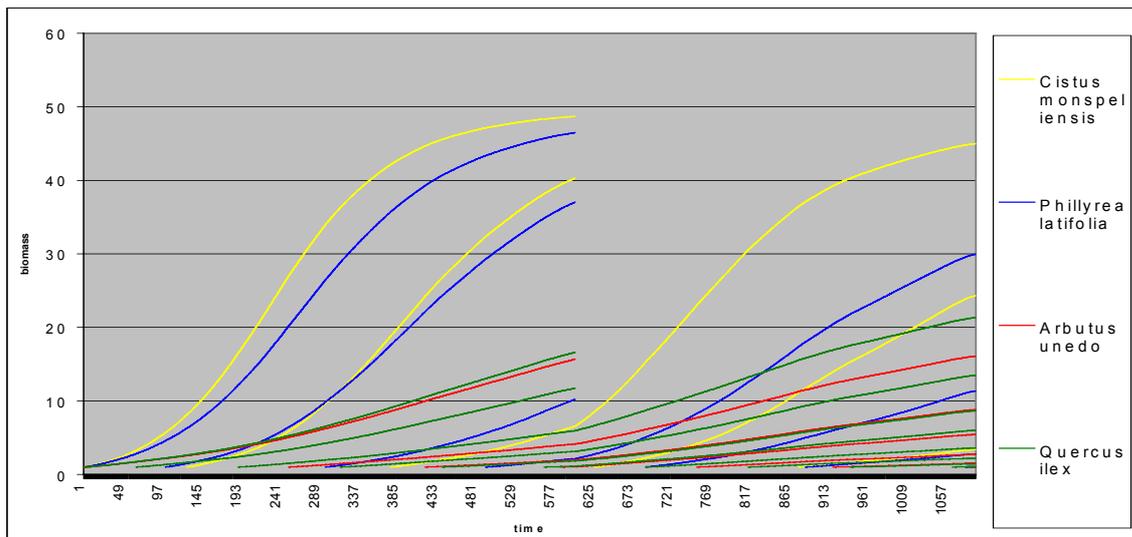
## Example of simulation

The figures below show the results of a simulation exercise of an IBCM with 5 different species and several individuals.

In the first example species differ in their growth rate and establishment of new seedlings of *Arbutus unedo* occur during simulation



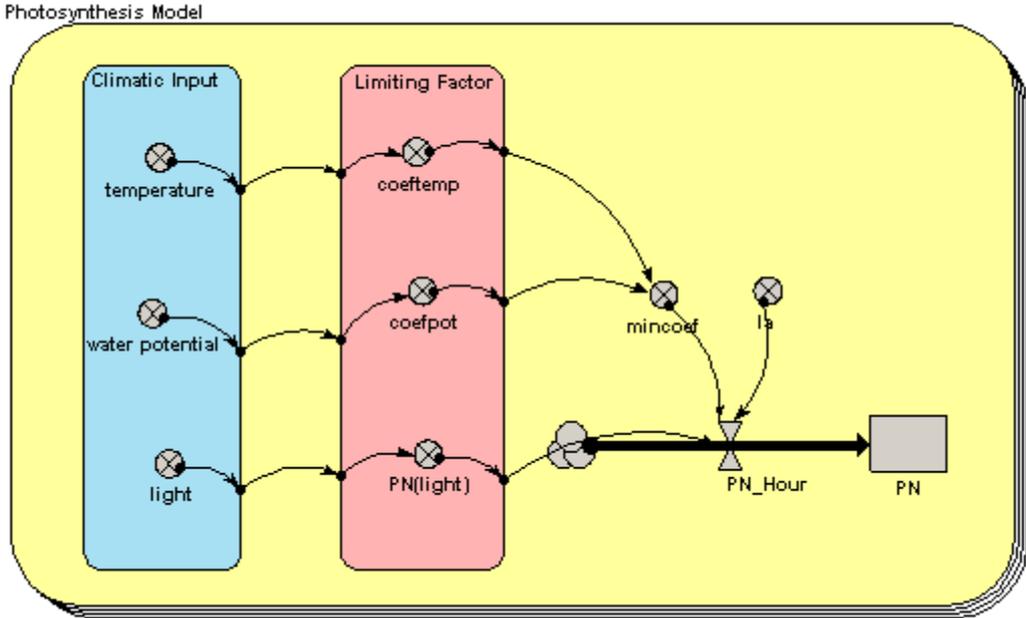
In the second simulation exercise a disturbance by fire occur on the day 600 affecting only individual plants with a biomass above a critical threshold of 10. After fire regrowth some higher growth rates are consequence of a changed allocation pattern. At the end of the growth period some growth rate reduction start to occur as effect of increased shade in the community.





# Photosynthesis Model

Francesco Giannino and Riccardo Gucci



## Description

The photosynthesis model calculates the amount of photosynthate (PN) produced by a plant. PN is driven by light and is calculated as the response of leaves to photosynthetic photon flux density (PPFD), hourly averages of incident irradiance. The resulting values is corrected by two reduction coefficients related to temperature and leaf water potential respectively. The functions relating PN to PPFD, temperature and water potential are species specific. The actual model has been parameterised for 6 different species: *Quercus ilex*, *Cistus monspeliensis*, *Arbutus unedo*, *Phyllirea latifolia*, *Myrtus communis*, *Pistacia lentiscus*.

## Mathematical formulation

### In Connectors

Name	Unit	From Model
Temperature	°C	Climatic input
Light	PPFD ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ )	Climatic input
Water Potential	Bar	Plant Soil Water Balance
Leaf Area (LA)	$\text{m}^2$	Canopy Growth

**Internal Parameters**

Name	Unit	Mathematical Equation	Description
PN(light)	$\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$	$[a]+[b]*[c]^{\text{light}}$ a,b,c function of specie (fig. 1)	photosynthesis function of light
coefPot	Coefficient in [0,1]	Sketch graph (fig. 2)	water potential limiting factor
coefTemp	Coefficient in [0,1]	Sketch graph	temperature limiting factor
Mincoef	Coefficient in [0,1]	$\text{Min}(\text{coefPot}, \text{coefTemp})$	minimum of limiting factors

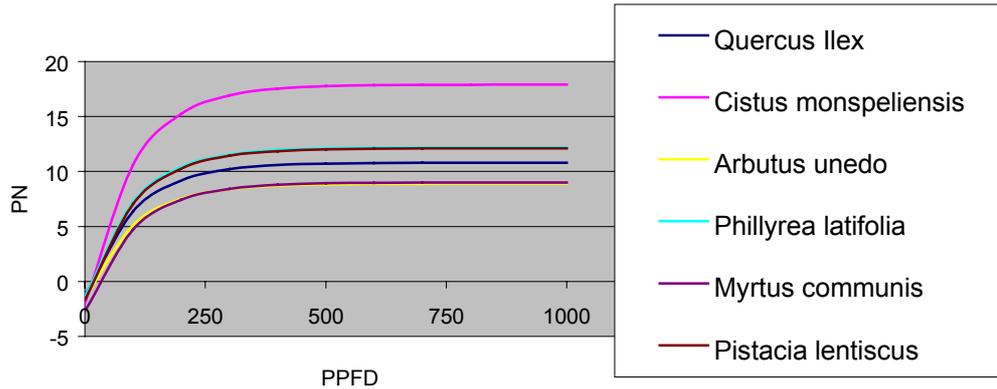


Fig 1 photosynthesis function of light

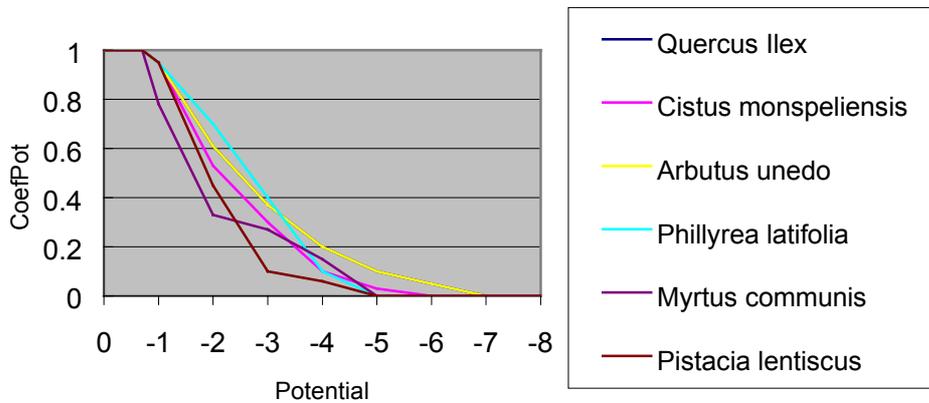


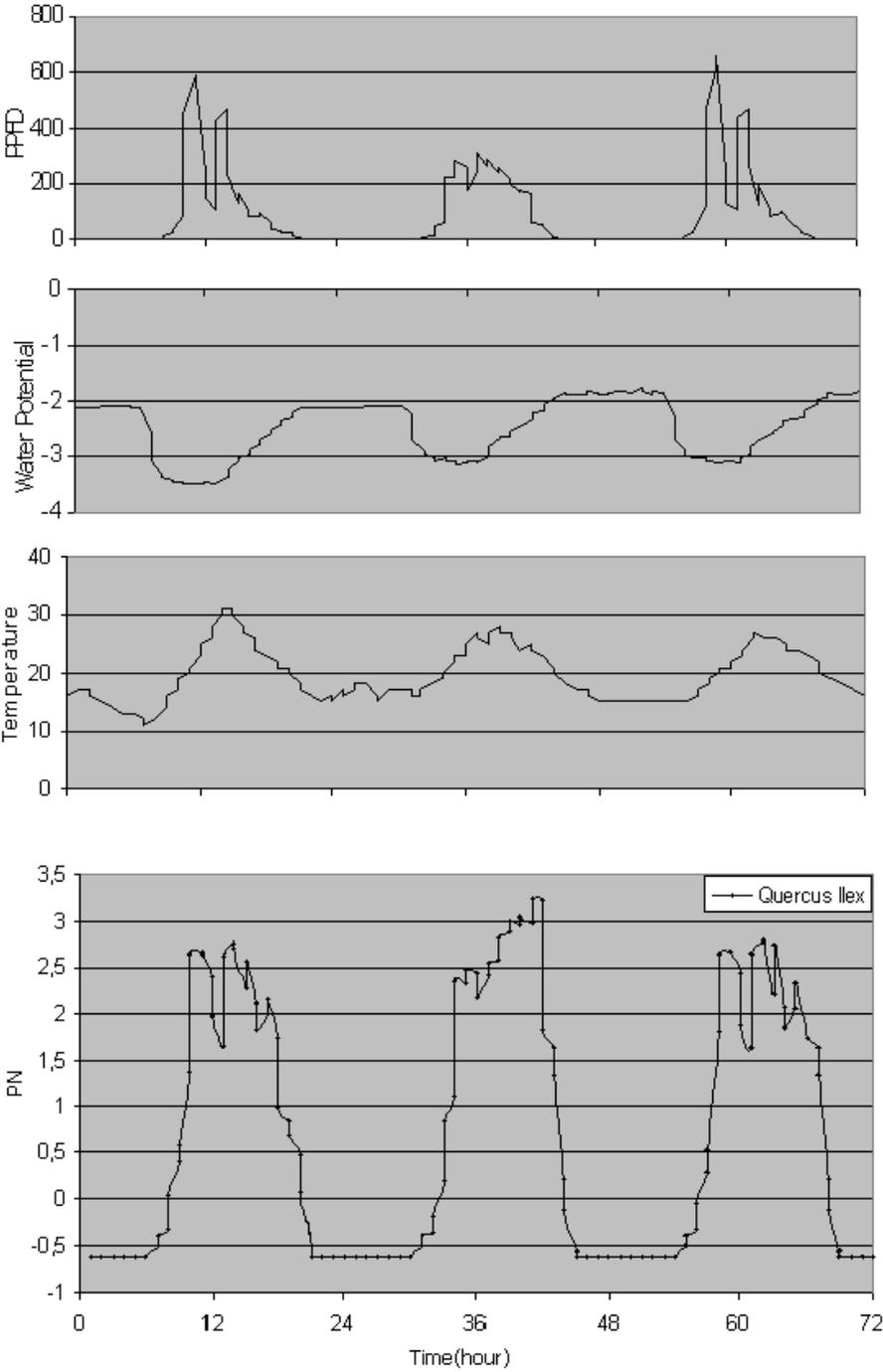
Fig 2 water potential limiting factor

**Out Connectors**

Name	Unit	to Model
PN	$\mu\text{mol CO}_2 \text{ m}^{-2} \text{ hour}^{-1}$	Partitioning Model

**Time step:** 1 hour

### Example of application



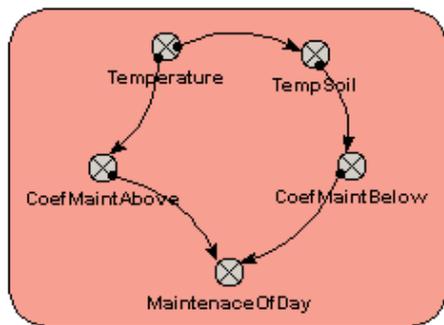
The figures show an example of application of the Photosynthesis model for 3 days. The modelled species is Quercus ilex



# Maintenance Model

*Francesco Giannino, Riccardo Gucci and Carlos Gracia*

Maintenance Model



## Description

It calculates the carbon requirement for maintenance respiration of all plants parts.

The respiration requirement are estimated by the living biomass of different plant structures multiplied by some coefficient related to species and temperature. A similar approach is followed in the GOTILWA model (Gotilwa: An Integrated Model of Water Dynamics and Forest Growth, Ecological Studies, Vol 137 pag,163,179). The maintenance coefficient are mathematically expressed as

$$K * 2^{((\text{temperature}-25)/10)}$$

where k is a species parameters and the potenza of 2 reflects the effects of temperature changes with an optimal reference term of 25°C.

## Mathematical formulation

### ***Inn Connectors***

Name	Unit	From Model
Temperature	°C	Climatic input
TotalBiomassLeaf	g	Canopy Growth
TotalLivingWood	g	
TotalLivingRoot	g	Root Growth

### ***Internal Parameters***

Name	Unit	Mathematical Equation	Description
CoefMaintenanceLeaf	Coefficient	$0.0054 * 2^{((\text{temperature}-25)/10)}$	leaf maintenance coefficient
CoefMaintenanceStem	Coefficient	$0.00884 * 2^{((\text{temperature}-25)/10)}$	stem maintenance coefficient
CoefMaintenanceRoot	Coefficient	$0.00228 * 2^{((\text{tempsoil}-25)/10)}$	root maintenance coefficient
TempSoil	°C	graph(temperature)	soil temperature

Name	Value
Quercus Ilex	$(0,0131 * 0,4) * 2^{((\text{temperature}-25)/10)}$
Cistus monspeliensis	$(0,013 * 0,4) * 2^{((\text{temperature}-25)/10)}$
Arbutus unedo	$(0,0125 * 0,4) * 2^{((\text{temperature}-25)/10)}$
Phillyrea latifolia	$(0,0137 * 0,4) * 2^{((\text{temperature}-25)/10)}$
Myrtus communis	$(0,0131 * 0,4) * 2^{((\text{temperature}-25)/10)}$
Pistacia lentiscus	$(0,0142 * 0,4) * 2^{((\text{temperature}-25)/10)}$

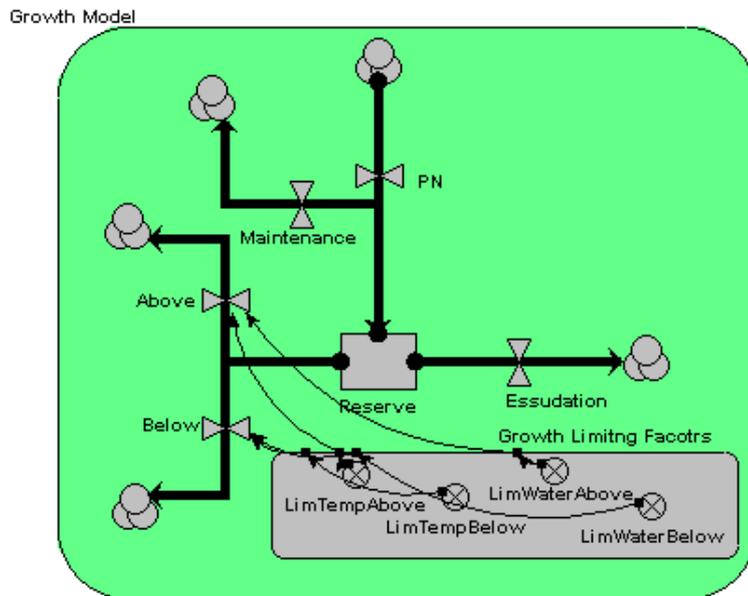
### ***Out Connectors***

Name	Unit	to Model
MaintenanceOfDay	g	Growth Model

***Time step: 1 day***

# Growth Model

Francesco Giannino, Stefano Mazzoleni, Riccardo Gucci



## Description

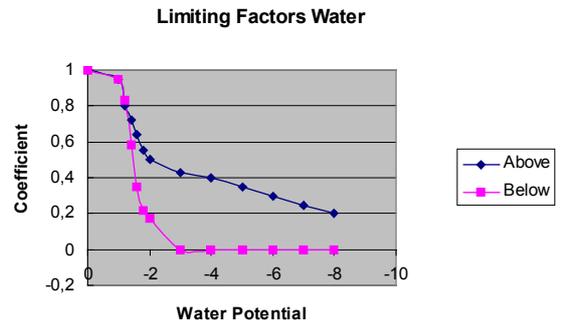
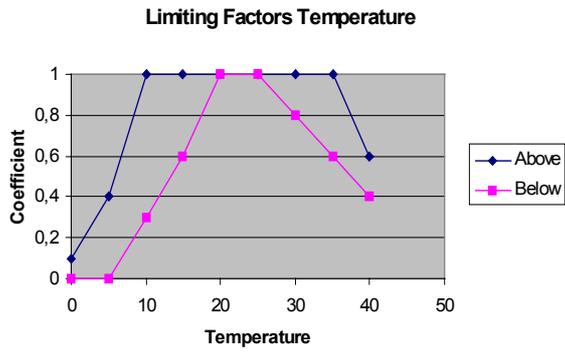
The growth model divides the net photosynthesis PN in maintenance respiration, above and below growth. The remaining amount increases the reserve pool. A surplus in the reserve compartment produces an essudation flow out from the roots.

The partitioning to above and below structures is function of species parameters and is affected by limiting growth factors (effects of temperature and water potential on growth).

## Mathematical formulation

### In Connectors

Name	Unit	From Model
PN	g	Photosynthesis Model
LimTempAbove	coefficient in [0,1]	Growth Limiting Factors
LimTempBelow	coefficient in [0,1]	Growth Limiting Factors
LimWaterAbove	coefficient in [0,1]	Growth Limiting Factors
LimWaterBelow	coefficient in [0,1]	Growth Limiting Factors



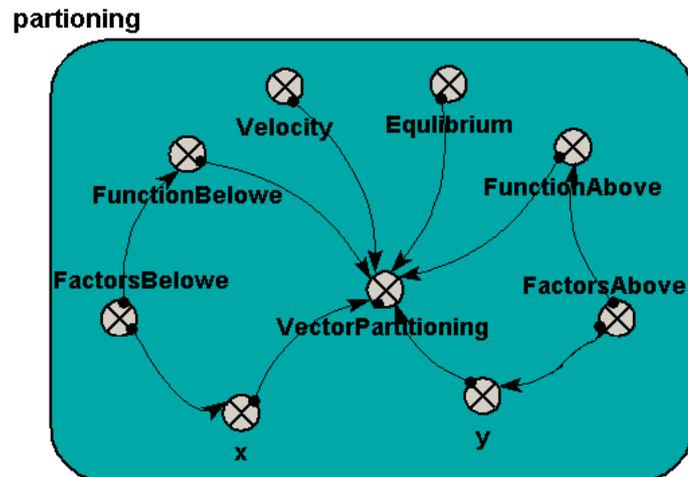
***Out Connectors***

Name	Unit	to Model
Maintenance	g	Maintenance Model
Above	g	Above Model
Below	g	Below Model

***Time step: 1 day***

# Partitioning Model

*Stefano Mazzoleni, Francesco Giannino and Gerardo Toraldo*



## Description

Partitioning of biomass in plants is a complex process which depends on both internal and external factors.

The following premises have been considered:

- partitioning between plant parts change with age;
- fruiting starts above a critical biomass and since then can be considered as a sink of carbon;
- plants do allocate differently above and below ground in order to compensate limiting environmental factors (e.g. limiting light and water conditions induce increased allocation to leaves and roots respectively);
- partitioning behaviour changes in reaction to disturbances (cut, fire, root predation and turn-over) in order to facilitate the recovery of removed structures.

Plant growth models published in the literature either handle partitioning as a constant ratio based on known regression data or, at most, include changes to such ratio in relation to environmental conditions. To our knowledge, no partitioning model has faced the problem of dynamic behaviour in relation to biomass removal following disturbance.

The model presented here solved the above mentioned problems by a rather innovative approach, i.e. by relating the allocation behaviour to the internal status of plants instead of considering external growth conditions. This approach reflects the theoretical assessment of the problem by prof. Franco Zucconi who refers to a balance between Epigeous and Ipogeous factors as drivers of the partitioning behaviour in plants.

The model solution to this subject was achieved in the following integrated way:

1. Photosynthesis production and reserves are compared to maintenance and growth costs. When the ratio is balanced the plant allocation between above and below ground structures follows the average ratio defined as species parameter (cfr. “Pipe model theory”). If there is not enough carbon sources to face the respiration and growth costs without reducing the reserve pool beyond a threshold level, then the partitioning is changed in order to increase above ground allocation. In this way the model captures both consequences of reduced light conditions and removal of photosynthetic tissues.
2. Actual transpiration is compared with potential water absorption. When the water uptake is smaller than the maximal possibility of water absorption the plant can allocate more above ground. If the transpiration demand is equal or higher than the absorption capability of the root system, then the allocation will be shifted toward below ground structures. This again makes possible for the model to react to changing levels of soil water content, but also to biomass removal affecting either the transpiring or the absorbing surfaces.

These two assessment are implemented in the model by defining two coefficients related to above and below ground allocation respectively. The two coefficients define two response curves that change the allocation factor according to the departure from the balanced conditions. These two curves are combined together to create a response partitioning surface that is shown below. At any time the internal balance of a plant is located over this surface and defines the partitioning ratio between above and below ground structures.

The maximum shift between partitioning ratios is defined as “plasticity” of the plant species and corresponds to the capability of changing allocation patterns.

The speed of adaptation to changing conditions is defined as “sensitivity” and reflects the inertial behaviour of the species to maintain a partitioning pattern.

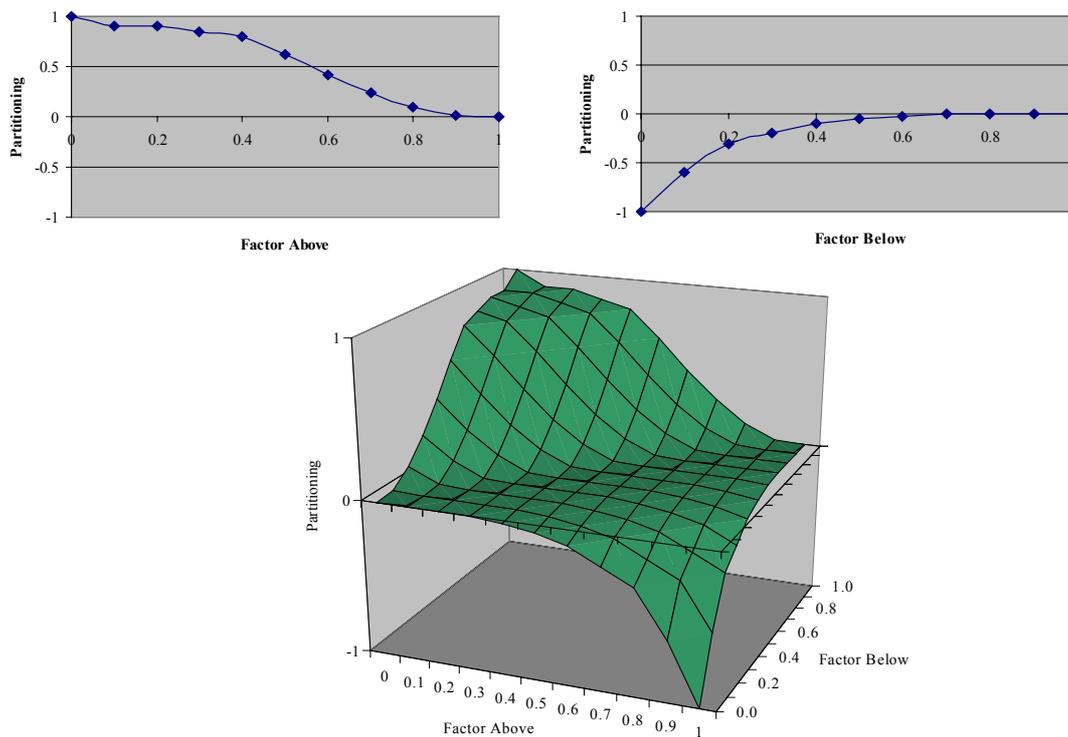


Fig.1 – Partitioning surface for biomass allocation coefficients

## Mathematical formulation

### ***In Connectors***

Name	Unit	From Model
FactosBelow	coefficient, WaterUptake/WaterDomande	Plant Water Balance
FactorsAbove	coefficient, (Above+MaintenancePlant) /(MaxResAbove+Manteinance)	Growth Model

### ***Internal Parameters***

Name	Unit	Matematical Equation	Description
x	mm/mm	WaterUptake/WaterDemand	Comparison between water uptake and absorption capability
y	g/g	(Above+MaintenancePlant) /(MaxResAbove+Manteinance)	Comparison carbon availability by PS and Reserves with Respiration and growth requirements
FunctionBelow	Coefficient in [0,1]	Function of Factors Below	Carbon allocated below
FunctionAbove	Coefficient in [0,1]	Function of Factors Above	Carbon allocated above
Sensitivity	Day	4	It defines the speed of reaction to changing conditions by a moving average over a time window
Equilibrium	%	40	balanced partitioning ratio under steady optimal growing conditions

### ***Out Connectors***

Name	Unit	to Model
VectorPartitioning	%	Growth Model

***Time step: 1 day***

## Example of application

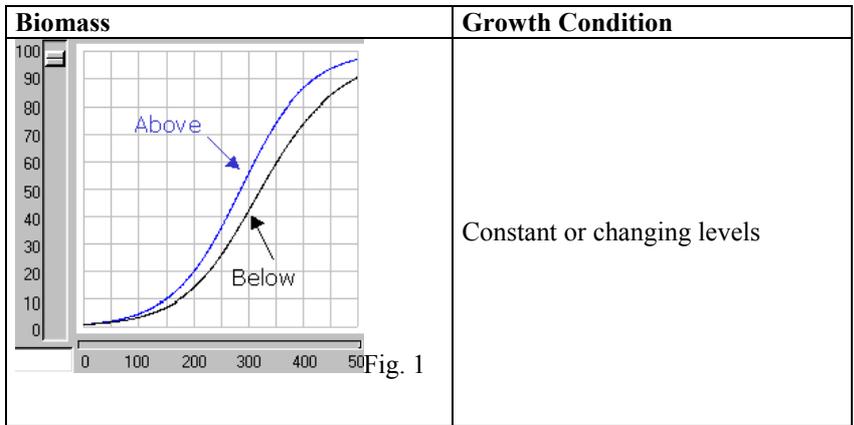
The exercise reported below shows the dynamic behaviour of the partitioning submodel according to both changing environment conditions and/or disturbance occurrence.

A simple model of biomass growth produces a typical sigmoid pattern due to the progressive reduction of the growth rate in relation to the biomass accumulation in time. Partitioning between above and below ground can be set constant according to a known weight ratio (e. g. above biomass 40% of total, fig 1)

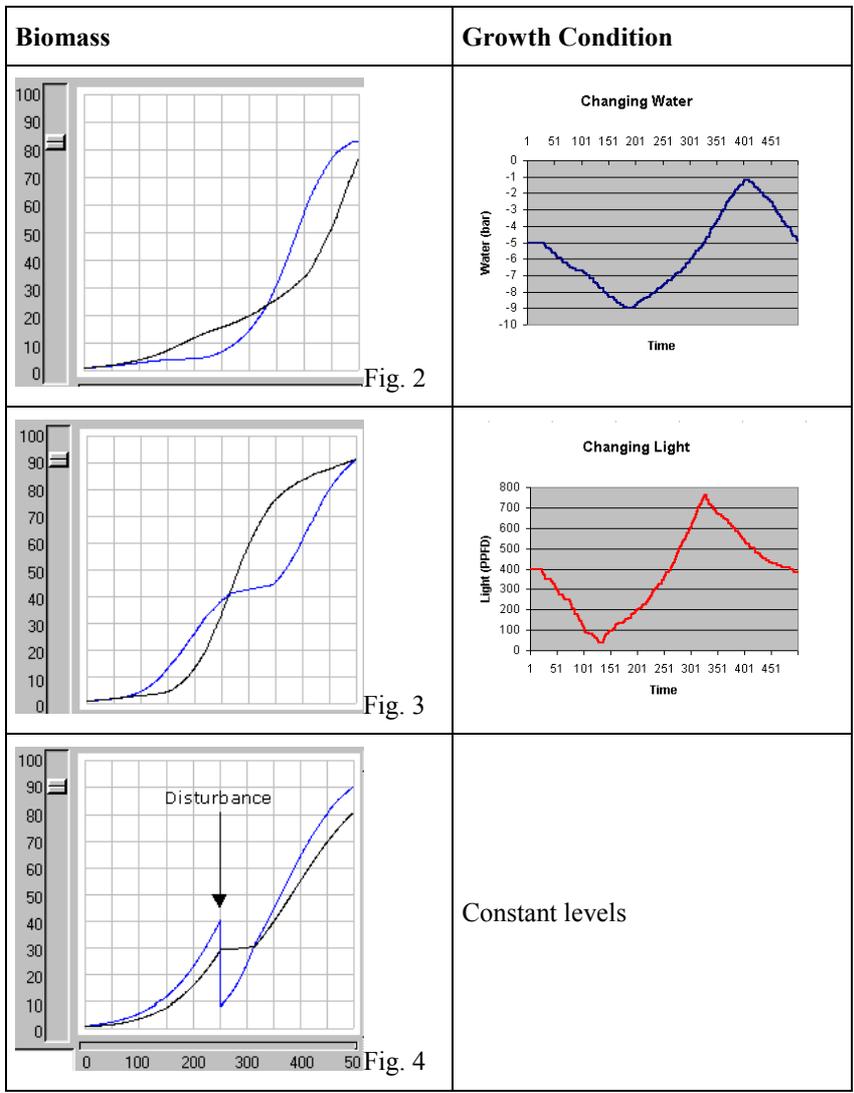
Our partitioning sub-model is able to react to reduced levels of environment factors by increasing the relation allocation to the plant parts that functionally counteract the limiting factors, i.e. higher allocation to leaves under limiting light condition and higher allocation to root under limiting water levels (fig 2 and 3, respectively).

The model is also able to change the relation allocation between above and below ground when an unbalanced partitioning condition is created by the occurrence of a disturbance. Following a biomass removed (e. g. above biomass reduced by fire or cutting) plants temporally change their allocation pattern in order to facilitate the recovery of balanced growth. This is to say that allocation to roots can be stopped to the advantage of recovery of the above ground structure. This pattern is very well reflected by our partitioning model behaviour as shown in fig. 4. To our knowledge this is the first partitioning model which is able to capture the dynamic behaviour of plants in relation to environment factors and disturbance.

**Constant partitioning**



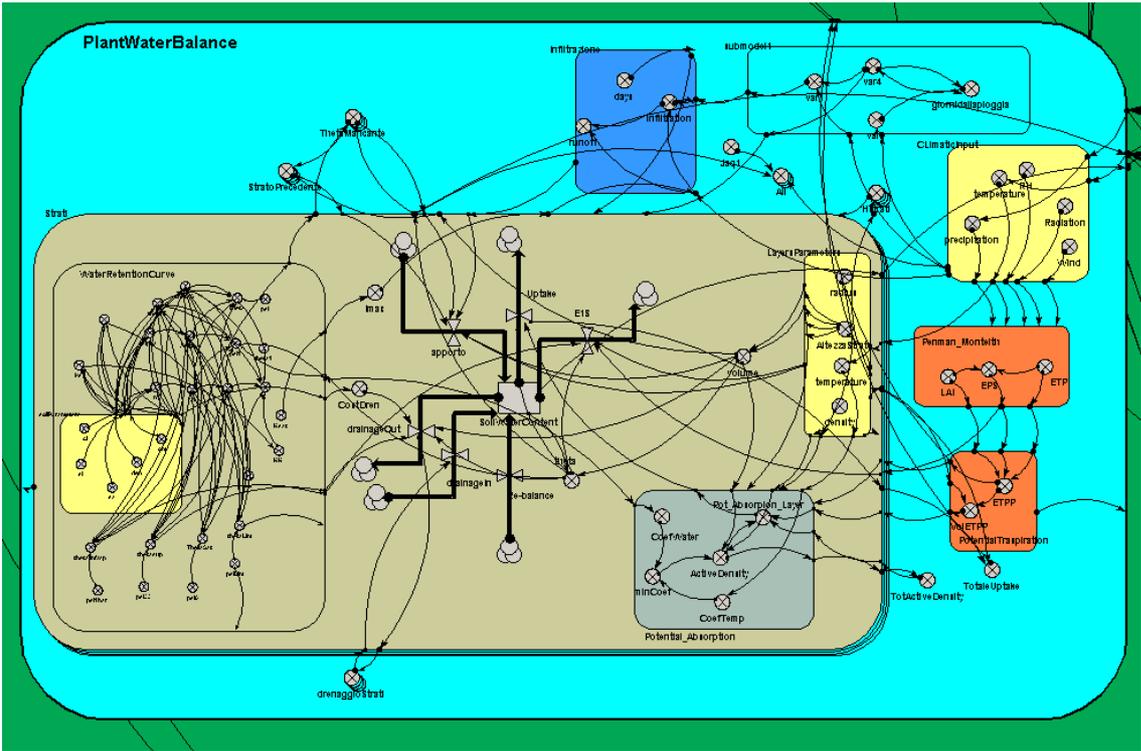
**Dynamic partitioning**





# Plant Soil Water Relation

Mariana Amato, Mark Mulligan, Joaquim Sande Silva, Francesco Giannino and Stefano Mazzoleni



## Description

The model calculates the soil water content and the amount of water transpired by plants. The soil is divided into layers defined by different size and soil characteristic (depth and radius, organic matter, bulk density, and % content of sand, lime, clay). Plants remove water from different soil layers according to their relative root biomass and activity.

Water flows into layers are:

1. infiltration by rain
2. in-drainage from above layer
3. out-drainage to below layer
4. evaporation (only for surface layer)
5. transpiration (water removed by plants)

Soil water retention curves are evaluated by pedotransfer laws which are function of  $\theta$  (water volume fraction) and  $\phi$  (water potential in bars). Potential transpiration can be estimated by two different sub-models. The simpler sub-model uses a Penman Monteith equation and leaf area index values to evaluate the potential transpiration. The actual transpiration is calculated by partitioning the potential value according to  $\theta$ , temperature and root biomass in each layer. The model removes water from different layers taking account the root.

## Mathematical formulation

### ***In Connectors***

Name	Unit	From Model
Air Temperature	°C	Climatic input
Light	PPFD ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ )	Climatic input
Rain	mm	Climatic input
LAI	$\text{m}^2 \text{ m}^{-2}$	Above Biomass
Height Layers	$\text{m}^2$	Layer input
Clay	% $\text{g g}^{-1}$	Layer input
Silk	% $\text{g g}^{-1}$	Layer input
Sand	% $\text{g g}^{-1}$	Layer input
Bulk Density	% $\text{g cm}^{-3}$	Layer input
Organic matter	% $\text{g g}^{-1}$	Layer input

### ***Internal Parameters, variables, flows***

Name	Unit	Mathematical Equation	Description
$\theta$ theta (water potential)	$\text{mm}^3 \text{ mm}^{-3}$		volumetric soil water fraction
Etp	mm	Penman-Monteith modified (CropEvapotranspiration FAO paper 56)	potential evapotranspiration according to CropWat (Penman-Monteith modified)
Eps	mm	if LAI>1 then $\text{ETP}/(1.1*\exp(-0.4*\text{LAI}))$ else $\text{ETP}*(1-0.43*\text{LAI})$	soil potential evaporation (ritchie, 1972)
Etp	mm	if LAI<=3 then $\text{ETP}*(1-\exp(-\text{LAI}))$ else ETP; max value (ETP-EPS)	plant transpiration
Thetalim	$\text{mm}^3 \text{ mm}^{-3}$	Estimating Soil Water, Gupta and Larson, Water Resources Reserch vol. 15, no. 6	threshold value for drainage
Thetasat	$\text{mm}^3 \text{ mm}^{-3}$	Estimating Soil Water, Gupta and Larson, Water Resources Reserch vol. 15, no. 6	threshold value for infiltration
CostDren	Coef in [0,1]	function of soil	from 0 = no drainage to 1 = fast drainage
drainageOut	$\text{mm}^3$	if $\theta > \theta_{\text{sat}}$ then $(\theta - \theta_{\text{sat}}) * \text{volume} * \text{CostDren}$ else 0	amount of water drained to the lower layer

drainageIn	mm <sup>3</sup>	Element([drainageOut],index(1)-1)	amount of water drained from to upper lower layer
Rebalance	mm <sup>3</sup>	$K * (\phi_i - \phi_{i+1}) / ((\text{height}_i - \text{height}_{i+1}) / 2)$	redistribution of water between layers
infiltrazione	mm <sup>3</sup>	If rain > I <sub>max</sub> then I <sub>max</sub> * superficie else rain * superficie	infiltration of precipitation
I <sub>max</sub>	mm	function of ks <sub>sat</sub>	threshold value for infiltration

### Out Connectors

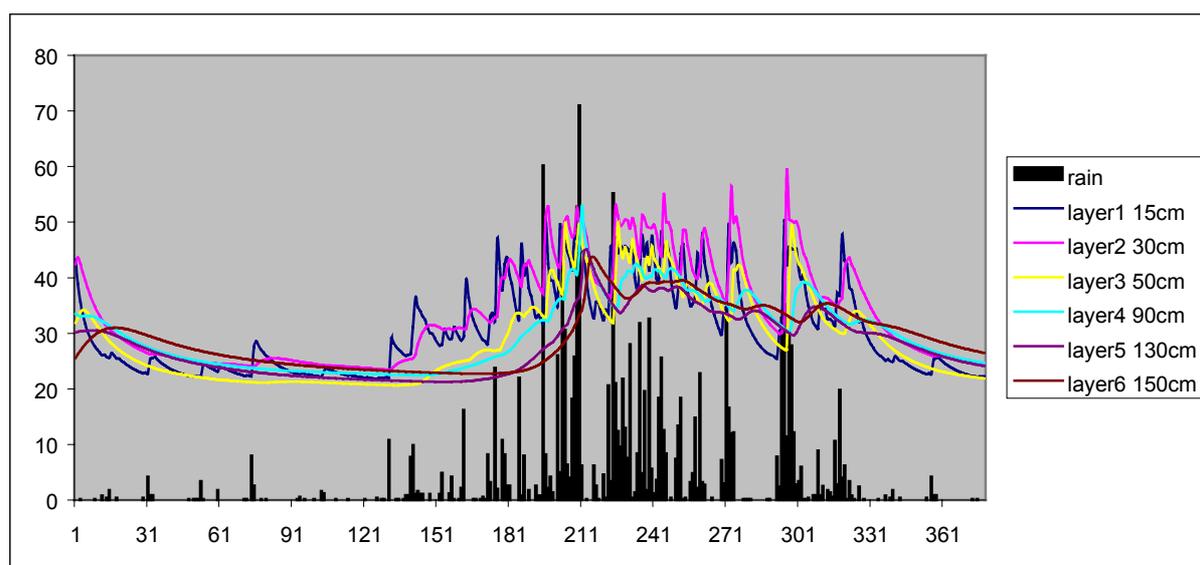
Name	Unit	to Model
Runoff	mm	
θ theta (water content)	mm <sup>3</sup> mm <sup>-3</sup>	Photosynthesis Model
Water Demand	mm	Partitioning Model
Water Uptake	mm	Partitioning Model

### Time step: 1 day

## Example of application

A simulation exercise was done using as inputs the rainfall time series recorded by the meteorological station of Mafra in Portugal and the soil characters from the same site.

The simulate soil water content by soil layer is shown below plotted with the input daily rainfall data. The simulated patterns are significantly consistent with the real measured data reported in the study by Sande Silva at page 95 of this report. A slight over-estimation of transpiration may be explained by no stomatal closure control in the current model version.

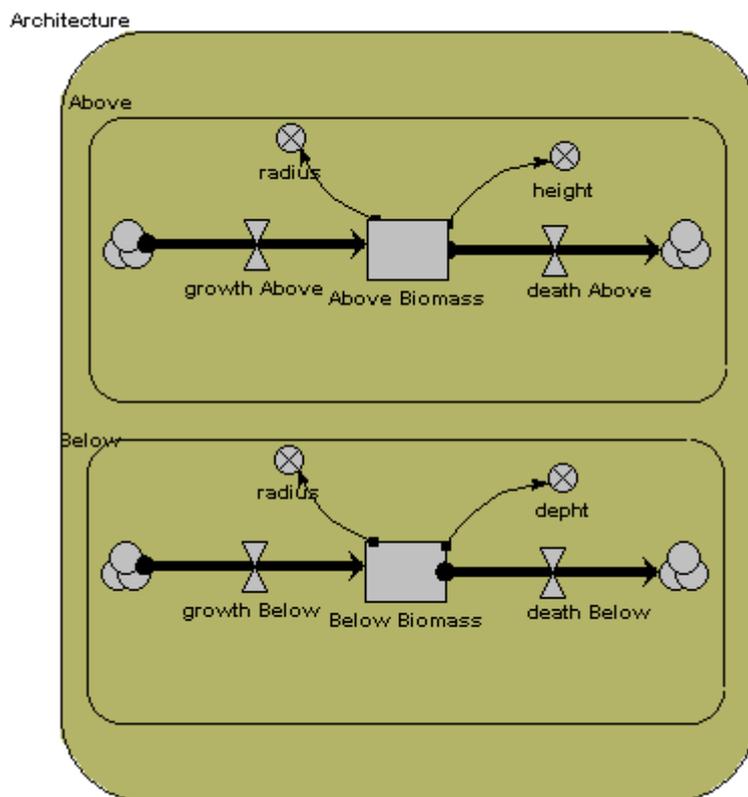




# Architecture Model

Francesco Giannino and Stefano Mazzoleni

## Simple version



## Description

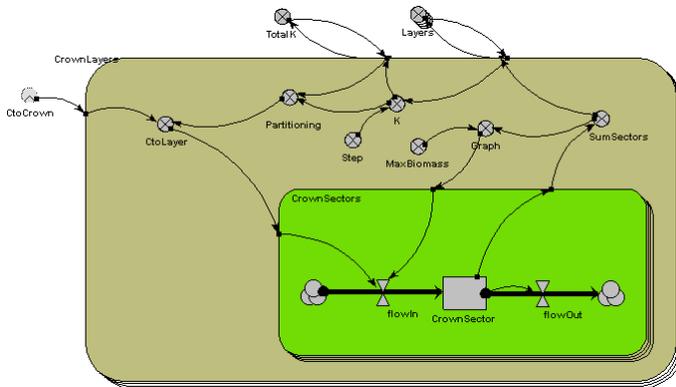
The simplest implementation of the architecture accumulates the biomass in above and below ground structures. The flow in represents the growth whereas the flows out reflects mortality (natural leaf shedding and root turnover) and disturbance (fire, cut, frost, grazing).

In this version the size of plants are calculated directly as function of biomass according to know regression laws.

The figures below show examples of 3D view in Virtual Reality Modelling Language - VRML (see helper description on *SIMILE* chapter) of a plant community in IBCM.

## Detailed version

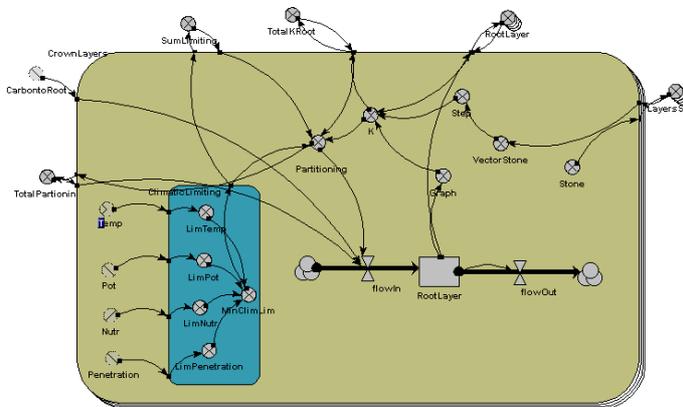
### ***Crown Model***



Each crown of a tree is a number of layers (Submodel Crown Layers), each layers is “split” in different sectors (Submodel Crown Sectors). To split the carbon in the different sectors, the model consider that:

- Layer growth is function of biomass
- Next layers are activated if the previous layers reached a critical threshold value

### ***Root Model***



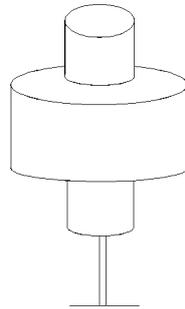
The model allocates carbon in different root layers and considers that:

- Each layer has climatic limiting factors (temp, nutrient, water potential, resistance to penetration).
- The stones in the layers cause to spend more carbon because the roots elongate more (0=no stone, 1=max stone).
- Shape factors related to species parameters affect the activation of root sectors.

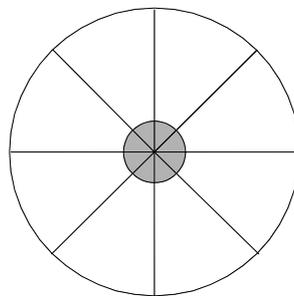
## Description

A more detailed version of the architecture model represents the plants as overlaying layers divided into sectors. This makes possible to recreate different plant shapes and to recover asymmetric developmental patterns.

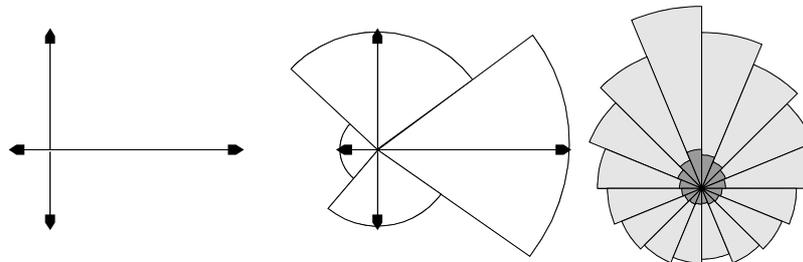
1. The plant is viewed as a system of overlapping cylinders



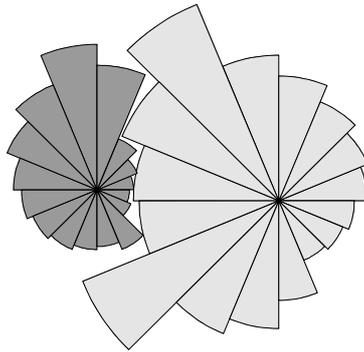
2. The cylinders can be divided into sectors. The number of sectors can be changed according to the level of spatial resolution that is required. Each sector could contain two sections reflecting leaf and wood biomass.



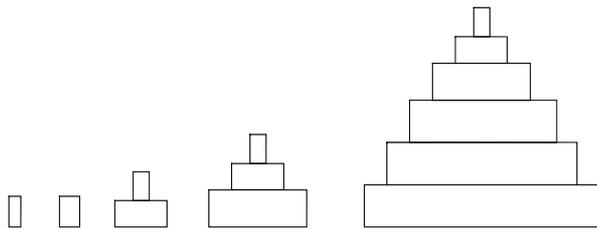
3. During growth a differential allocation between sectors would produce different shapes.



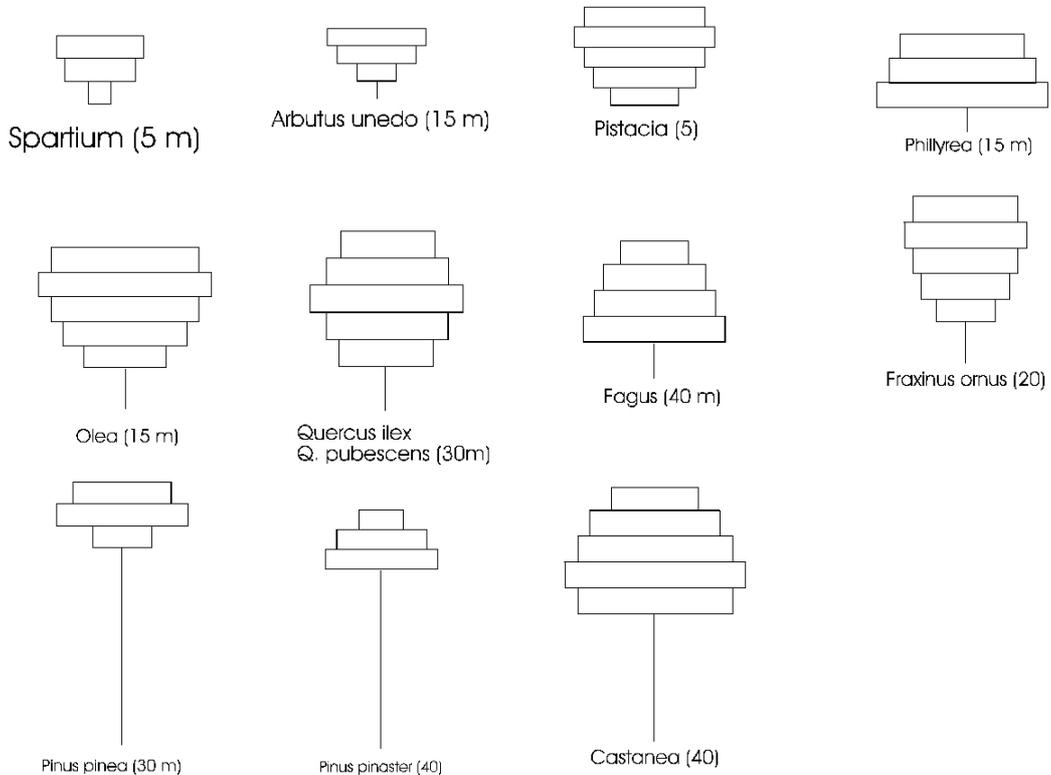
4. The system allows for spatial interactions between crowns of adjacent individuals



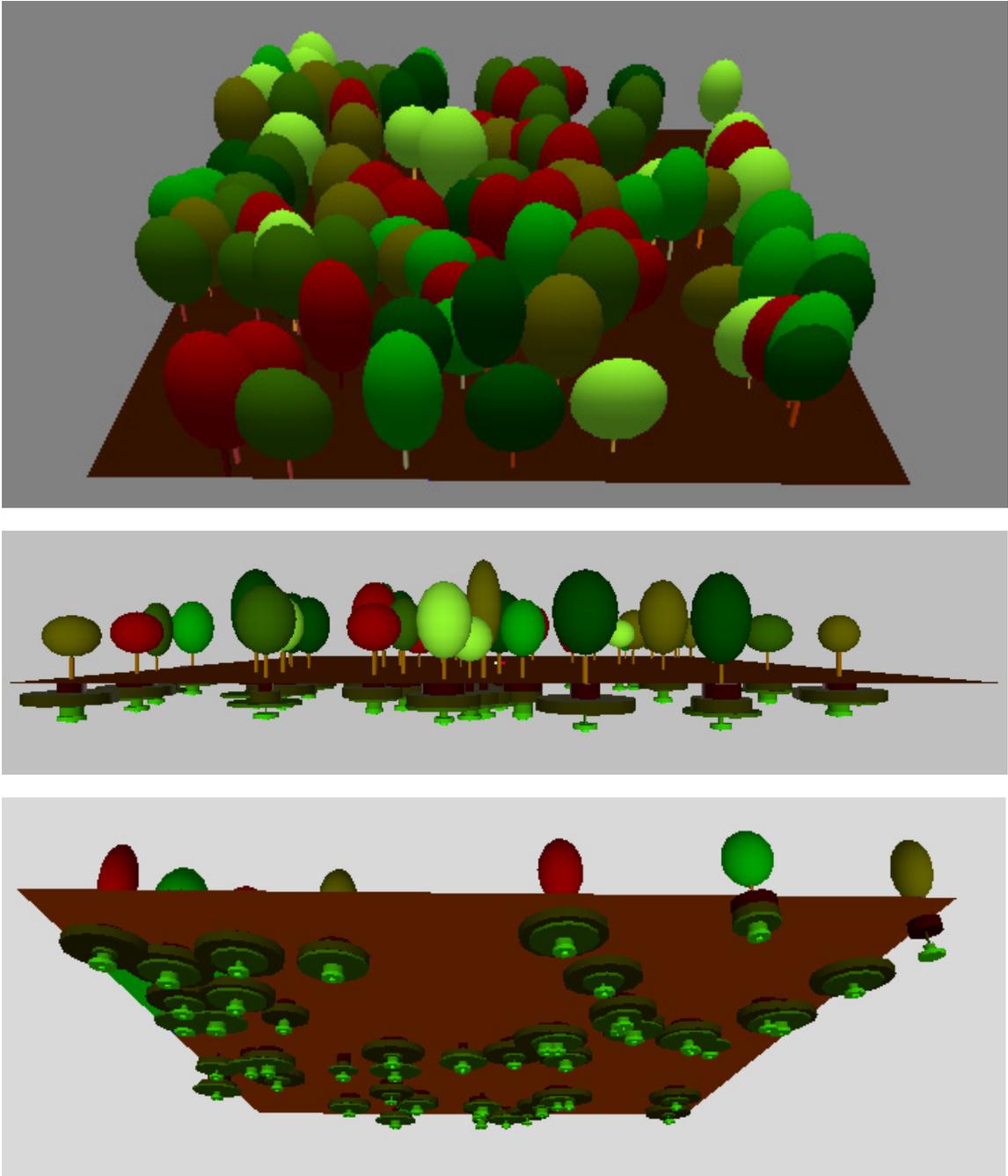
5. The lateral growth would be increase of radial dimension of the different sectors, whereas increase in height would generate the implementation of new overlapping layers of sectored pies. The following example depicts a standard "Abies-like" shape produced by a constant law of activation of new layers in time as function of accumuleated biomass.



6. The information on different crown shapes can be easily implemented by reference representations which are the frame within which the growth actually occurs. The following are examples of different shapes for a few species (in parenthesis reference max height)



Example of application

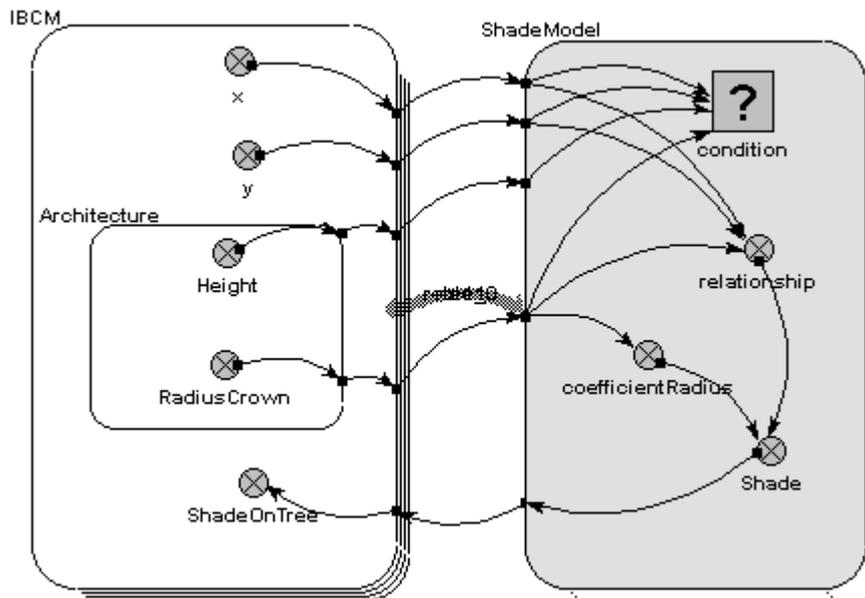


3D view by VRML of simulated plant community in IBCM. Above top view, central lateral view, bottom underground view. In this example the crowns are produced by the simpler version of the architectural model whereas the root systems are generated by a more detailed model version with different root densities in several soil layers.



# Shade Model

Francesco Giannino and Robert Muetzelfeldt



## Description

The model calculates the amount of shedding for every plants in the community, i.e. the reduction of incident light due to shade by neighbours.

In its simpler version with daily time step, the sun position is considered only at zenith. However the model can handle different time steps (e.g. hourly) by adding a simple submodel routine to change the angle of incident light.

In the model each tree is define by its  $x$ ,  $y$  position, radius of crown and plant height. The model uses a “conditional submodel”, i.e. a calculation tool that verifies IF condition is accomplished before executing calculation. The conditions are:

the height of tree  $i$  (target tree for shade calculation) is less than height of tree  $j$  (neighbour tree).

distance between  $i$  and  $j$  is less the sum of crown radii ( $R_i + R_j$ ) of the considered plants.

After verification of these condition the model estimated a shade index by the functions showed below, i.e. relations between shade, distance, size.

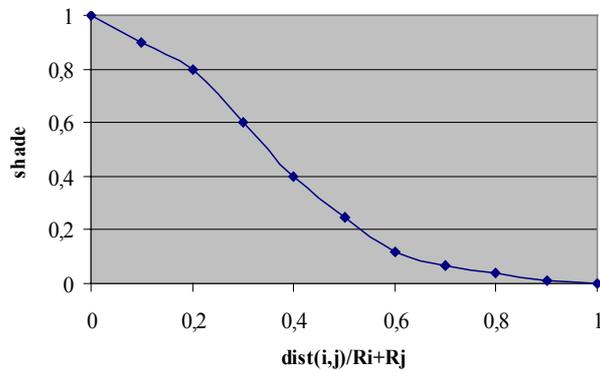


Fig. 1 For two trees in "shade relation" in the model the  $\text{dist}(i,j)$  is always  $<$  then  $R_i+R_j$ .

If  $\text{dist}(i,j)=0$  the shade are max

if  $\text{dist}(i,j) < R_i+R_j$  the shade is still max

if  $\text{dist}(i,j)=R_i+R_j$  the shade is 0

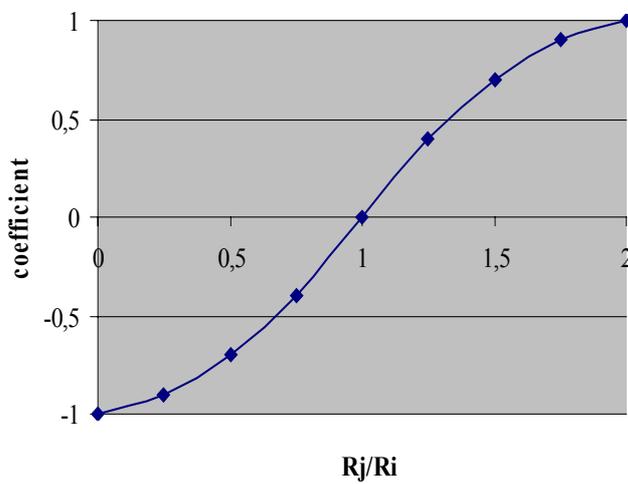


Fig. 2 if  $R_i \gg R_j$  the coefficient decrease the effect of shade of  $j$  on  $i$ , and if  $R_i < R_j$  it increase the effect.

## Mathematical formulation

### *In Connectors*

Name	Unit	From Model
x	m	Plant Water Balance
y	m	Growth Model
Height	cm	Plant Water Balance
Radius_Crown	cm	Growth Model

### ***Internal Parameters***

Name	Unit	Mathematical Equation	Description
relationship	value in [0,1]	graph (FIg.1)	
coeffcientRadius	value in [-1,1]	graph (FIg.2)	

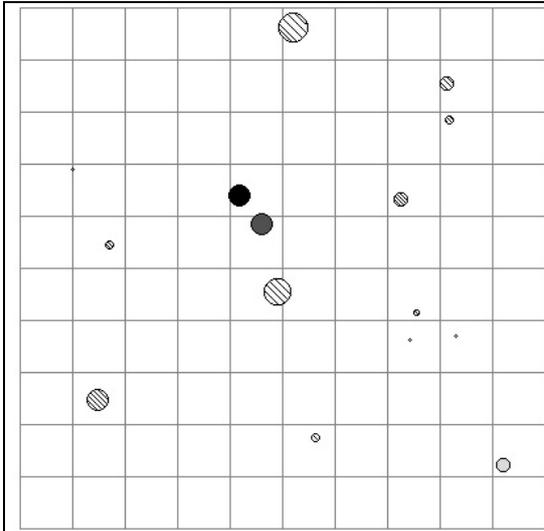
### ***Out Connectors***

Name	Unit	to Model
ShadeOnTree	value in [0,1]	Photosynthesis Model

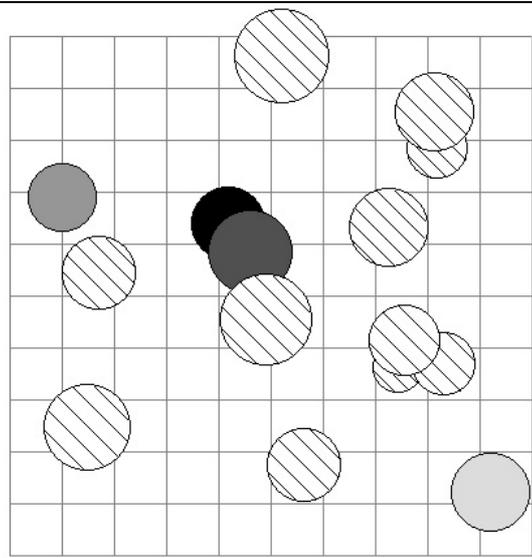
***Time step: 1 day***

## Example of application

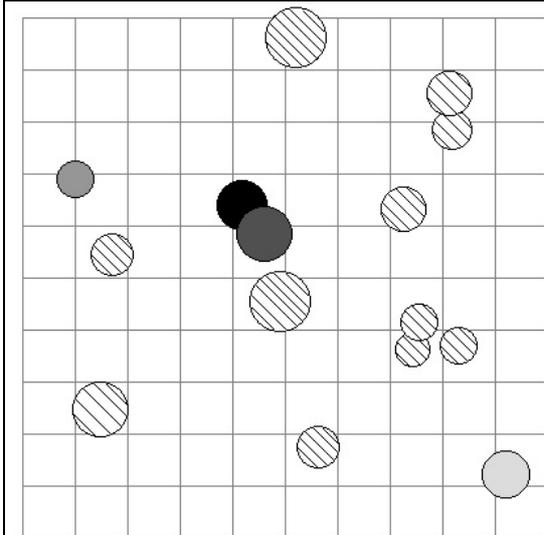
An exercise is applied to a vegetation model with 15 individual plants growing in a plot. Four individuals are shown as targets for shading calculation. Results of the shade model are reported in a table and can be compared to the plant locations, growth and interactions between crowns.



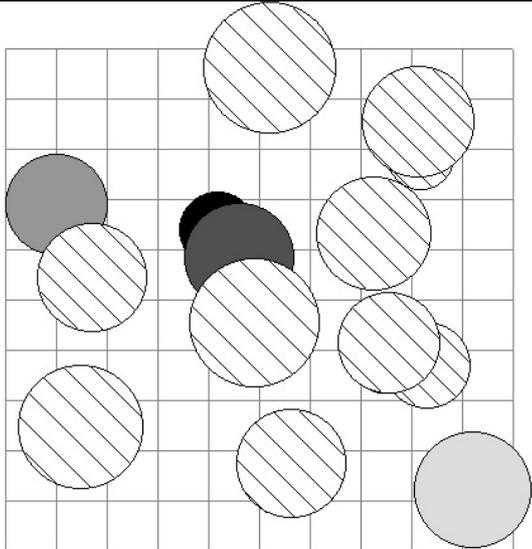
Time= 0



Time= 20



Time= 40



Time= 65

	Shade index			
Time				
0	0	0	0	0
20	0.20	0.05	0	0
40	0.53	0.18	0	0
65	0.9	0.43	0.18	0