SExI-FS

Spatially Explicit Individual-based Forest Simulator

User Guide and Software

Version 2.1.0

Degi Harja and Gregoire Vincént

World Agroforestry Centre (ICRAF) and
Institut de Recherche pour le Développement (IRD)

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2008

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The Smallholder Rubber Agroforestry System Project

The Smallholder Rubber Agroforestry System (SRAS) Project in Indonesia and Thailand (2004-2008) is funded by the Common Fund for Commodities (CFC) and supervised by the International Rubber Study Group (IRSG). The project purpose is to increase smallholder rubber productivity and to contribute to overall sustainability of natural rubber production. The project aims to improve productivity through integrating high yielding clonal rubber in smallholder agroforestry systems; reduce production costs during the immature growth phase of rubber plants; provide more affordable alternatives to small-scale rubber farmers other than monoculture; and to maintain biodiversity and environmental sustainability. At the final stage of the project, appropriate rubber technology for farmers, lessons and recommendations from the project activities are being documented and distributed to rubber-producing countries in Asia and Africa.

The project is led by the World Agroforestry Centre (ICRAF) in collaboration with the Indonesian Rubber Research Institute (Indonesia), Prince of Songkla University (Thailand), Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD, France), University of Helsinki (Finland) and Kasetsart University (Thailand).

The Spatially Explicit Individual-based Forest Simulator (SExI-FS) software was developed under various projects in collaboration between World Agroforestry Centre (ICRAF) and Institut de Recherche pour le Développement (IRD).
The current version of the model is adapted for smallholder rubber-based agroforestry system under the SRAS project.

This manual includes the latest version of the software.

Content

1. General Information

1.1. Overview

The SExI forest simulator focuses on tree-tree interactions in a mixed multi-species agroforest. The high level of structural complexity of such traditional agroforestry systems defies classical forestry approaches when it comes to optimizing management practices. To cope with this complexity, farmers have adopted a tree-by-tree management approach, which is closer to gardening than to any usual tropical forestry or estate crop management model. Individual tree care and regular tending takes the form of seedlings transplanting, selective cleaning and felling, adjusted harvesting intensity.

Farmers' approach appears to be in line with two basic tenets of biology: first, individuals are all different with behavior and physiology that result from a unique combination of genetic and environmental influence, and second, interactions are inherently local. Based on the same premises a computer model was developed to explore different management scenarios.

The model uses an object-oriented approach where each tree is represented by an instance of a generic class of tree. The simulated object trees, mimicking real trees, interact through modifying their neighbors' environment. These modifications are mediated through two major resources: space and light. A 3D representation of a one-hectare plot of forest serves as the grounds for the simulation of this competition.

The major objective of such a model is to get a coherent dynamic representation of a complex system, where complexity refers here to the assemblage of locally interacting individuals with different properties more than to the complexity of the elementary processes involved. The model provides insight on what are the critical processes and parameters of the dynamic of the system. It should also allow exploring prospective management scenarios, help assessing the relevance of present management techniques etc.

Model sensitivity tests confirm the importance of the parameters related to tree geometry. This directly stems from the fact that competition is simulated by means of spatial interactions, so that anything that alters either the shape, the size, or the relative position of the trees have direct impact on the outcome of the competition and therefore on the growth dynamic. These elementary influences are usually straightforward but their effect at different times and scales are difficult to predict without simulating because of the numerous feedback loops at work and the non-linear dynamics of the system.

To illustrate this, let's examine very simple cases. By simulating growth in a mono-specific stand of regularly spaced trees planted at increasing densities, we observe the following response. Planting at medium density translates into growth in height of the trees in the center of the plot being superior to that of border trees, which is a response to the increasingly limited access to light of the trees in the center of the plot. When planting density is increased further though, growth in height of the trees in the center of the plot becomes less than their neighbors: the level of competition is so high that these trees get overtopped and suppressed by border trees in more favorable position with respect to access to light.

Another simple test shows that ability to respond to low light availability by enhanced growth in height (a response, which occurs at the expense of growth in diameter) appears to be advantageous under specific conditions and disadvantageous under others. If all species in the mixture share the same ability and the same sensitivity to light level then this potential competitive advantage turns out to be disadvantageous both for individual tree growth and for overall plot productivity. But when trees with different sensitivity to light level or different ability to alter their allocation of growth between height and diameter occur in a mixture then this capacity proves to be an effective competitive advantage for individual species. By accelerating the establishment of a multi-strata structure it also increases the overall productivity of the plot through better allocation of spatial resources.

Similarly, rather counter intuitively, an increased growth rate for a given crown size appears to be an advantage for a species under certain circumstances but not all: under very crowded conditions large crowns (showing low efficiency in terms of light and space utilization) can show competitive advantage by suffering less from crown encroachment and shading out competitor more efficiently. These are but a few examples of the insight such generic models can bring.

More direct applications of the model include comparing alternative scenarios in terms of financial return for instance involving rotational versus permanent agroforests, etc.

1.2. The SExI-FS Software

SExI-FS software is available on the Internet. It can be downloaded freely from http://www.worldagroforestry.org/sea/Products/AFModels/SExI.

SExI-FS is targeted to be platform independent. It's developed using Java Programming Language. It will be able to run on any platform that supports Java Virtual Machine (JVM). The information about Java Programming Languages and Java Virtual Machine can be accessed through http://java.sun.com.

1.3. The Minimum Requirement

The minimum requirements to run the 3D visualization of SExI-FS are:

1. 60MB Hard disk space (Included JVM)

2. VGA card with 3D graphics accelerator.

3. 128MB of RAM

4. PII 600MHz or equivalent

The minimum requirements to run SExI-FS without 3D Visualization are:

1. 60MB Hard disk space

2. 32MB of RAM

3. Pentium PC 133Mhz

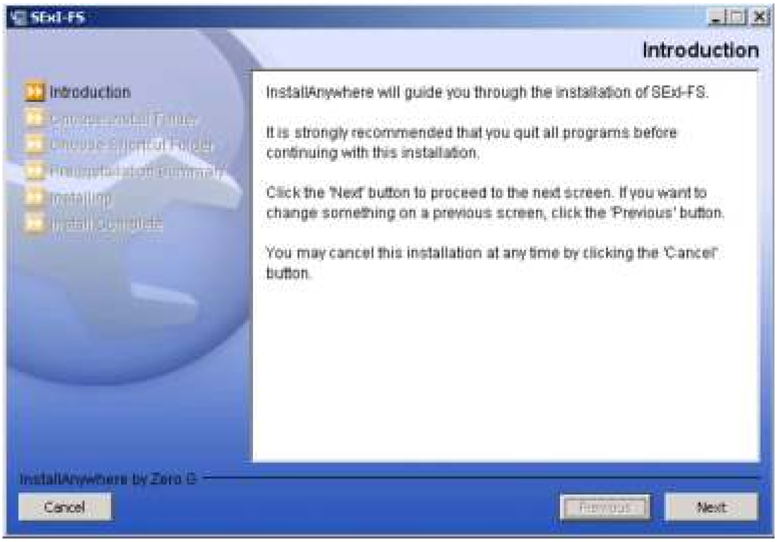
2. Getting Started

There are two installation packages, with built-up Java Virtual Machine (JVM) and without. If you don't have a Java virtual machine installed on your computer, be sure to get the package that includes one.

2.1 Installation

The installation steps are as follow:

Step 1. Introduction
It's displays general information about the software. Press the Next button to continue.



InstallAnywhere will guide you through the installation of SExI-FS.

It is strongly recommended that you quit all programs before continuing with this installation.

Click the 'Next' button to proceed to the next screen. If you want to change something on a previous screen, click the 'Previous' button.

You may cancel this installation at any time by clicking the 'Cancel' button.

Figure 1. Introduction

Step 2. Choose install folder
Write down the installation folder or press Choose button to show the folder selection dialog. Press the Next button to continue (Figure 2).

Step 3. Choose shortcut folder
Write down the shortcut folder or use the other available options. Press the Next button to continue (Figure 3).

Where Would You Like to Install?

C:\Program Files\SExI-FS

Figure 2. Choose install folder

Where would you like to create product icons?

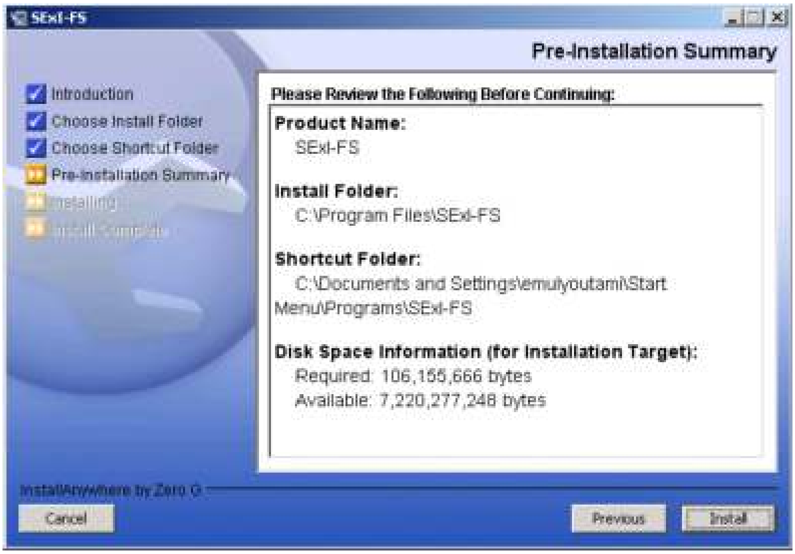
- ● In a new Program Group: SExI-FS
- ○ In an existing Program Group: Accessories
- ○ In the Start Menu
- ○ On the Desktop
- ○ In the Quick Launch Bar
- ○ Other:
- ○ Don't create icons

☐ Create Icons for All Users

Figure 3. Choose shortcut folder

Step 4. Pre-Installation summary

This shows the summary of the installation setting. Press Install button to start the installation.



Pre-Installation Summary

Please Review the Following Before Continuing:

Product Name:
SExI-FS

Install Folder:
C:\Program Files\SExI-FS

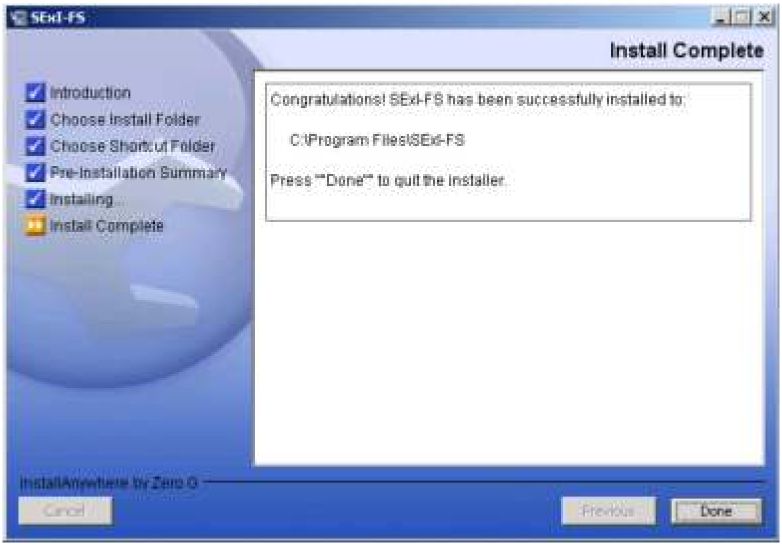
Shortcut Folder:
C:\Documents and Settings\emulyoutami\Start Menu\Programs\SExI-FS

Disk Space Information (for Installation Target):
Required: 106,155,666 bytes
Available: 7,220,277,248 bytes

Figure 4 Pre-installation summary

Step 5. Install complete

Done, you can start using the software



Install Complete

Congratulations! SExI-FS has been successfully installed to:

C:\Program Files\SExI-FS

Press "Done" to quit the installer.

Figure 5 Install complete

2.2 Running SExI-FS

Double click the SExI-FS shortcut on your computer. By default it will be under Start > Programs > SExI-FS on Microsoft Windows.

The application will start with the main window as showed in Figure 6. It consists of Projects windows (left), Welcome windows (center) and Properties windows (right).

Figure 6 Main Window

3. User Manual

3.1 Create New Simulation Project

You can create new projects either via the File menu on the Menu Bar (Figure 7a), or directly by clicking the New project options in Welcome window.

Figure 7a. File menu

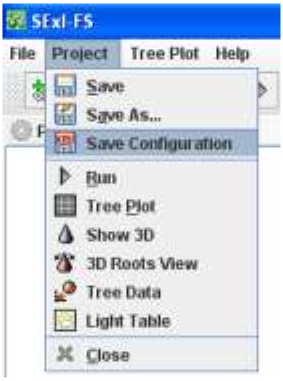


Figure 7b. Save Configuration

If you select the New project menu trough the File menu bar, it will show the same options (Figure 8). You can create a new project either by using default configuration or a pre-defined XML configuration file. The XML configuration file can be created by saving a modified project as a configuration file (see Figure 7b), thus the file can be modified externaly using XML or text editor. If default project option is chosen, the plot size input dialog will show up (Figure 9). Set the simulation Plot Size and click ok.

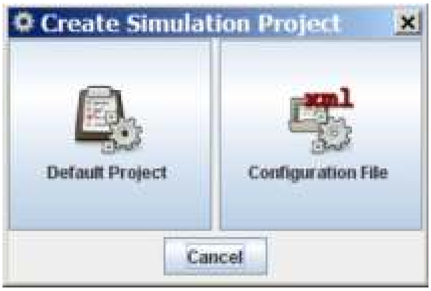


Figure 8. New simulation project options

Width (m): 100
Height (m): 100

Figure 9. Plot size input for default project

New project options tree will be showed on the Projects window (Figure 10).

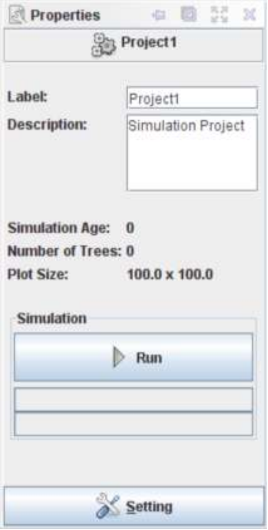
Label: Project1
Description: Simulatio
Simulation Age: 0
Number of Trees: 0
Plot Size: 100.0 x 100.0

Figure 10. New project on main window

3.2 Project Setting

Each project group consists of selectable section items for setting up the general environment, species and plantation plot (Figure 11). Highlighting each project sections will show their property options on the Properties window (Figure 12). If the Properties window is closed, you can double click the Section items to display it again.

Figure 11. Project tree items



Label: Project1
Description: Simulation Project
Simulation Age: 0
Number of Trees: 0
Plot Size: 100.0 x 100.0

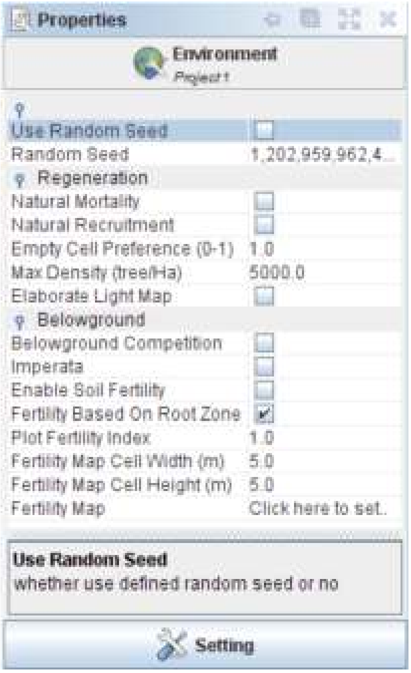
Figure 12. Project properties

Highlight the root project section. The main project property will show in the Properties windows. Define the project name and description.

You can't run the simulation before you plant trees on the plot (or add some pioneer species component). You can use default setting and jump to Tree Plot section to start planting the trees. Or define your preferred setting for this simulation project.

3.2.1 Environment Setting

Under the Environment tab values of some general parameters used in the Regeneration module and the Belowground competition module are set. The random seed is for the user to control the random generator used here.



Use Random Seed	☐
Random Seed	1,202,959,962,4...
Regeneration	
Natural Mortality	☐
Natural Recruitment	☐
Empty Cell Preference (0-1)	1.0
Max Density (tree/Ha)	5000.0
Elaborate Light Map	☐
Belowground	
Belowground Competition	☐
Imperata	☐
Enable Soil Fertility	☐
Fertility Based On Root Zone	☑
Plot Fertility Index	1.0
Fertility Map Cell Width (m)	5.0
Fertility Map Cell Height (m)	5.0
Fertility Map	Click here to set.

Use Random Seed
whether use defined random seed or no

Figure 13. Environment Setting

3.2.1.1 Regeneration

- Natural Mortality
  Set this setting to true for enabling natural mortality

- Natural Recruitment
  Set this setting to true for enabling natural regeneration

- Empty Cell Preference

  Controls the regularity of spacing of juveniles (0 completely random, 1 most even)

- Max Density

  Maximum density (trees per ha). Recruitment ceases once max density is reached.

- Elaborate Light Map

  Set this to true to use the more detailed light calculation to compute available light at ground level.

  By default the light calculation for each grid cell on the light map uses Simple Vertical Light Calculation. The plot is divided into a grid of cells (default size 5 by 5 m). For each cell at each time step a coarse index of light availability is computed based on overhead light of target cell and 8 immediate neighbors (a single vertical direction originating from center of cell is explored for each cell). The average of canopy openness on each grid cell is used in the recruitment process to assess suitability of light regime.

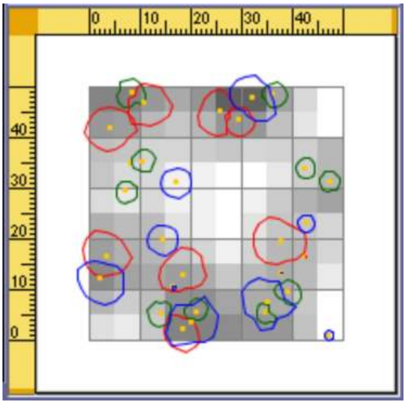


Figure 14. Light map sample

  The elaborate light map uses the hemispherical photograph method, which can capture a more realistic light penetration to the ground. This option will require more computation time but is necessary for proper simulation of the recruitment process.

3.2.1.2 Belowground

- Belowground Competition

  Enable Belowground competition option to simulate below ground competition between neighboring trees. The parameters for root influential zone are explained in section 3.3.7

- Imperata

  Set this to true for enabling the Imperata (obnoxious weed) competition.

- Enable Soil Fertility

  Set this to true for enabling the Soil Fertility map.

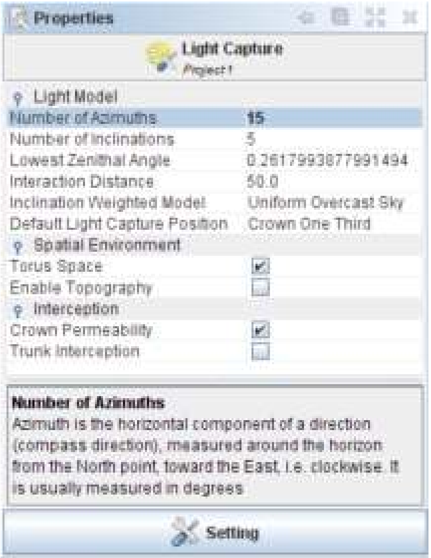
  Soil fertility is set manually for each cell of a grid covering the plot or read from a text file. Missing data are interpolated using bilinear 3 dimensional interpolation (Press, et al. 1992).

Fertility values vary between 0 and 1; a fertility of one meaning there is no soil fertility related limitation.

- Fertility Based On Root Zone
  If true, the fertility experienced by a tree will be computed as the average of cells fertility value of cells within the tree root influential zone. Otherwise, the fertility information will be taken at the exact cell location of the tree.
- Plot Fertility Index
  This is an index of soil fertility of the plot (between 0 and 1)
- Soil Fertility Cell Width
  The fertility map cell width (m)
- Soil Fertility Cell Height
  The fertility map cell height (m)
- Fertility Map
  Click on the input field to open the fertility map editor

3.2.2 Light Capture Setting

There are three categories of parameters to be documented in order to set-up the light capture module: light model, spatial environment, and light interception options (Figure 15).



Light Model	
Number of Azimuths	15
Number of Inclinations	5
Lowest Zenithal Angle	0.2617993877991494
Interaction Distance	50.0
Inclination Weighted Model	Uniform Overcast Sky
Default Light Capture Position	Crown One Third
Spatial Environment	
Torus Space	☑
Enable Topography	☐
Interception	
Crown Permeability	☑
Trunk Interception	☐

Number of Azimuths
Azimuth is the horizontal component of a direction (compass direction), measured around the horizon from the North point, toward the East, i.e. clockwise. It is usually measured in degrees

Figure 15. Light Capture Setting

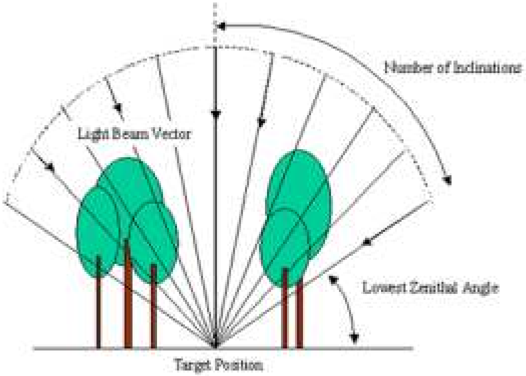


Figure 16. Horizon Projection of Beams Vector
(here the number of inclination = 6)

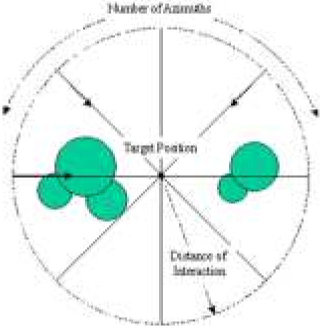


Figure 17. Vertical Projection of Beams Vector
(here the number of azimuth = 8)

a. Light Model

Light Model settings control the level of detail used for exploring the sky vault, i.e. the number of light beams and their weighting. The number of inclinations and azimuths defines the number of beams. The parameters of the light model are:

- Number of Azimuth
  Azimuth is the horizontal component of a direction (compass direction), measured around the horizon from the North point, toward the East, i.e. Clockwise.

- Number of Inclinations
  Inclination is the angular distance of the orbital plane from the plane of reference (usually planet's equator or the ecliptic).

- Lowest Zenithal Angle
  Lowest Zenithal Angle defines the lowest angle considered for light calculation (in radian).

- Interaction Distance
  The interaction area is limited by the Distance of Interaction setting. The trees outside the radius of interaction distance and are not included in light attenuation calculation for target tree.

- Inclination weighted model
  There are three models you can choose from:
  1. SOC (Standard Overcast Sky)
     This model weights each direction according to surface of sky vault fraction

moreover assuming a decrease in light intensity from zenith to horizon, using the formula:

$$Light(x,\alpha)=\frac{1}{3}x*[1+2*\sin(\alpha)]$$

2. UOC (Uniform Overcast Sky)
   This model weights each direction according to the relative surface of the sky vault explored by each beam.

3. Homogeneous
   This option gives equal weight to each direction sampled.

- Default Light Capture Position
  These are the position within a tree where the light (hemiphot) is captured and used as light info for the subject tree. The available position options are:
  1. Tree apex
  2. Crown center
  3. Crown base
  4. Crown one third
  5. Tree base

b. Spatial environment

- Torus Space
  If selected then the plot is assumed to be toric, in such case the plot has no borders as the trees from one side of the plot act as neighbors for the trees on the opposite side. If not selected then the plot is limited by the border. (Note that the area outside the border is considered as an open area).
  In geometry, a torus (pl. tori) is a doughnut-shaped surface of revolution generated by revolving a circle about an axis coplanar with the circle. The sphere is a special case of the torus obtained when the axis of rotation is a diameter of the circle. If the axis of rotation does not intersect the circle, the torus has a hole in the middle and resembles a ring doughnut, a hula hoop or an inflated tire. The other case, when the axis of rotation is a chord of the circle, produces a sort of squashed sphere resembling a round cushion. Torus was the Latin word for a cushion of this shape.

- Topography
  If topography is selected, the plot will using the topography data (if any), else the plot is assumed to be flat.

c. Interception

- Crown Permeability
  If Crown Permeability checkbox is selected, the crown is considered as partially transparent (transparency is also referred to as crown porosity in the following). If Crown Permeability is not selected, it is assumed to be totally opaque.

- Trunk Interception
  If Trunk Interception checkbox is selected, the trunk is considered to intercept the light. If Trunk Interception is not selected, it's neglected.

3.2.3 Fertility Map Setting

Soil fertility is set manually for each cell of a grid covering the plot. Missing data are interpolated using bilinear 3 dimensional interpolation (Press et al., 1992). Fertility values vary between 0 and 1; a fertility of one meaning there is no soil fertility related limitation.

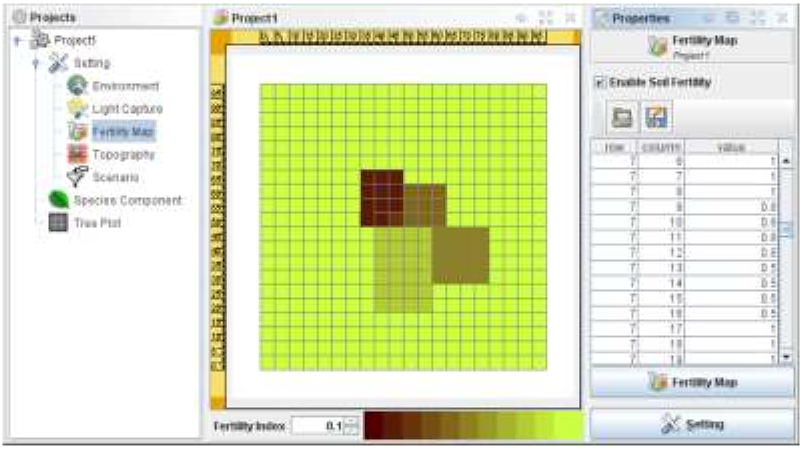


Figure 18. Fertility map setting

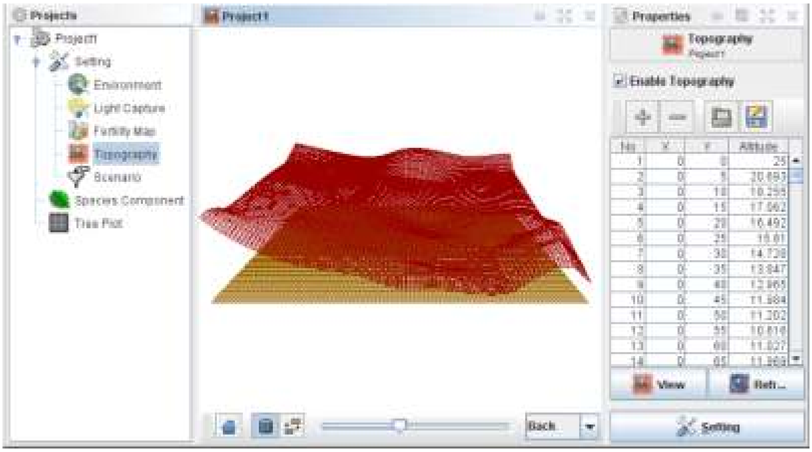
To show the fertility map, highlight the Fertility Map project item on Projects windows, check the Enable Soil Fertility checkbox on Properties window and click the Fertility Map button below the table (Figure 18).

You can modify the fertility by either changing the fertility value on the table, or by clicking the cells of the fertility map. Change the fertility index value below the map, and then click on the map. The legend color shows the gradation of index value between 0 and 1 (you can also click the legend color for changing the fertility index value).

The fertility map can be saved and used for other simulation project.

3.2.4 Topography Setting

A particular topographic settings can be specified. But enabling this option will disable the torus space model. The area outside the border will be considered as an empty space.



☑ Enable Topography

No	X	Y	Altitude
1	0	0	25
2	0	5	20.693
3	0	10	18.255
4	0	15	17.062
5	0	20	16.492
6	0	25	15.81
7	0	30	14.728
8	0	35	13.847
9	0	40	12.965
10	0	45	11.984
11	0	50	11.202
12	0	55	10.818
13	0	60	11.027
14	0	65	11.968

Figure 19. Topography setting

To add the topography information, you can insert one by one the altitude data to the table. Or load the file that consists of altitude data. The file can be as tabulated data format with one line of header. Each line of data should consist of three values: X, Y and Altitude. The unit is meter (m). The example of the format data is as follow:

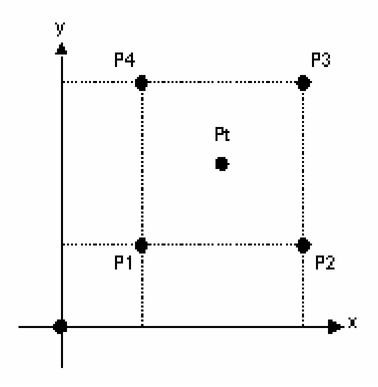
X	Y	Altitude
0	0	25
0	5	20.693
0	10	18.255
0	15	17.062
0	20	16.492

The altitude at any location on the plot will be interpolated using bilinear 3 dimensional interpolation (Press et al., 1992) based on the available topography information.

The topography can be check using 3D visualization by clicking the View button below the table. The data can still be modified, and click Refresh button to update the visualization.

The 3D Visualization object can be dragged using to view the other angle. The toolbar below the 3D panel can be used to changes the projection (Perspective or Parallel), zooming (the slider) and view the exact object side (combo box).

Bilinear interpolation (Press et al., 1992) is used to determine exact altitude of tree base when trees are positioned on an existing topography map



$$P1 = (x_1, y_1, z_1) \qquad P2 = (x_2, y_2, z_2)$$

$$P3 = (x_3, y_3, z_3) \qquad P4 = (x_4, y_4, z_4)$$

$$Pt = (x_t, y_t, z_t)$$

Pt is tree location and P1, P2, P3, P4 are topography data. Then:

$$z_t = (1-a)(1-b)z_1 + a(1-b)z_2 + abz_3 + (1-a)bz_4$$

$$a = \frac{x_t - x_1}{x_2 - x_1} \quad b = \frac{y_t - y_2}{y_3 - y_2} \quad \text{where} \quad x_1 \le x_t \le x_2, y_2 \le y_t \le y_3$$

3.2.5 Scenario Setting

The scenario module is viewed as a flowchart model (Figure 20 Scenario setting). The flow will be executed on each iteration for all the trees. The charts are editable. The available Processes include only Cut Tree and Yield Harvest (future version may include more Processes in the scenario). The Condition chart controls the flow condition based on the tree variable.

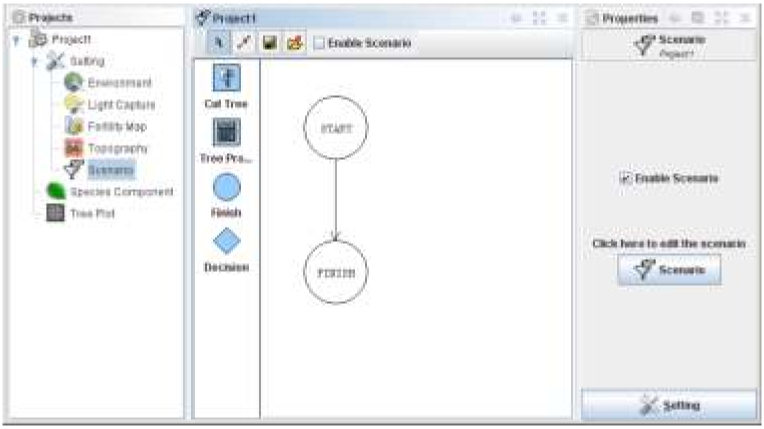


Figure 20. Scenario setting

3.3 Species Settings

To add a species to the project, highlight the Species Component section on Projects window (Figure 21). The first time add a species, the Properties window will show an empty species list (Figure 22). Click add button (+) to add species component to the list. Or you can load the previous saved species list by pressing load button (▨).

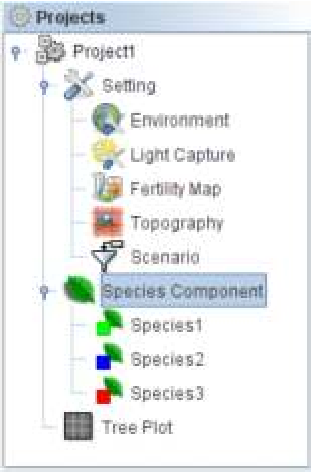


Figure 21. Species component section

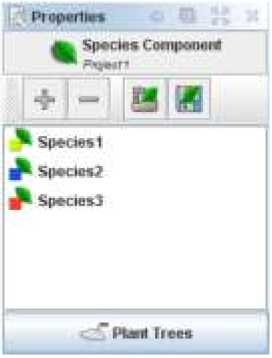


Figure 22. Species component properties

Once you have added some species component to the list, highlight one of the species item on the Projects window or double click the one on Properties window (both will have the same list of species). The properties window will show the parameters of the species selected (Figure 23).

You can directly modify the parameters according to your preferences.

Label and description are identification for the species. And the color is used for visualization purposes only (legend). It is not meant to simulate the real color of the tree species .

Other parameters are grouped according to their function as explained right.

Label	Species1
Description	Species Description
Legend Color	🟩 R:0 G:255 B:0 - ...
Basic Characteristics	
Initial DBH	0.01
Crown Porosity	0.5
Crown Shyness	1
Survival Probability	0.9
Mortality Modifier	15.0
2nd Mortality Probability	0.5
Adult Size (DBH)	10.0
DBH Function	
DBH Maximum	1.0
DBH C	1.17
DBH K	0.05
Height Allometry	
Height A	19.0
Height B	0.45
Height Max Absolute	50.0
Crown Allometry	
Crown Width A	1.19
Crown Width B	23.54
Light Sensitivity	
Mininum Light Level	0.15
Optimum Light Level	1.0
Flexi Tree	0.3
Flexi Crown	0.3
Sensi Tree	1.0
Sensi Crown	1.0
Regeneration	
Beta Shape 1	2.0
Beta Shape 2	2.0
Immigration Rate	1.0
Relative Abundance	1.0
Belowground	
Root Zone Modifier	1.0
Imperata Competition Factor (0-1)	0.2

Label
Species name identity

Figure 23. Species parameters

3.3.1 Basic Characteristics

Here are the general characteristics of a species:

- Initial DBH
  The initial diameter for newly recruited trees (default is 1 cm dbh)
- Crown Porosity
  A measure of crown transparency, here the crown is considered as partially transparent (0-1)
- Survival Probability
  The annual survival probability value of a completely suppressed plant

(no growth) In addition, a systematic mortality is assumed once 5% of reference tree crown size has been reached. See Documentation chapter for more details.

- Mortality Modifier
  Mortality Modifier modulates the shape of survival probability curve as growth rate is reduced (higher m values imply higher mortality rates at identical growth rate). Default value is 15. See Documentation chapter for more details.
- 2nd Mortality Probability
  2nd Mortality Probability is the probability that a tree dies from a neighbouring tree fall (0-1) if it lies in the sector affected by tree fall. Default value is 50% (see Documentation chapter for further computational details).
- Adult Size
  The DBH at which a tree species reaches sexual maturity (determines start of recruitment for non pioneer species).

3.3.2 DBH Function

The evolution of DBH over time (t) is modeled by a classical Chapman Richards function:

$$\text{dbh} = \text{dbh\_max} * \left(1 - e^{-k*t}\right)^{c}$$

Approximating DBH annual increment with the first derivative of DBH with respect to time (t) one can express dbh increment as a function of current dbh as follows:

$$\text{dbh\_inc} = \text{dbh\_init} * \text{c} * \text{k}\left(\left(\frac{\text{dbh\_init}}{\text{dbh\_max}}\right)^{\frac{-1}{c}} - 1\right)$$

(See Documentation chapter for detail)

The parameter of c and k can be obtained from Non-linear regression of DBH - DBH_increment plot (Calibration Procedures on Chapter 6).

3.3.3 Height Allometry

A reference allometric function relates tree height to tree dbh :

$$height = \alpha * dbh^{\beta_h}$$

Height A is parameter name for α (alpha) and Height B is parameter name for β (beta).

Where Height Max Absolute is species maximum possible height.

3.3.4 Crown Allometry

The crown width is linearly related to tree dbh by the following function:

Crown Width = A+ B*DBH

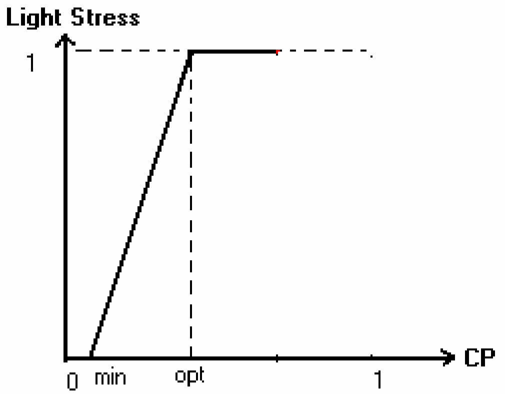
The parameters Crown Width A and Crown Width B refer to A and B in the above formula (See Documentation chapter for detail).

3.3.5 Light Sensitivity

The parameters here define the light stress factor of the tree growth.

- Minimum Light Level
  The minimum light level for a tree to grows.
- Optimum Light Level
  The optimum light level for a tree to grows.

The curve below shows the light stress factor derived from the parameters:



(CP is Crown Position, an index, a measure of light ratio receipt by a tree)

- Flexi is a parameter which measures the ratio of height growth rates under the most contrasted light conditions (between 0 and 1)
- Sensi is a measure of how sensitive the species is to shading, sensi > 1 (e.g. 2) typical of a shade avoiding species and sensi < 1 (e.g. 0.5) of a shade tolerant species

3.3.6 Regeneration

- Beta Shape 1
  Beta distribution function parameter 1

- Beta Shape 2
  Beta distribution function parameter 2

- Immigration rate θ
  θ (theta) is the relative weight of a species frequency in regional community versus its frequency in the local community. It is used to compute the effective contribution to local recruitment of any given species.

- Relative Abundance
  The relative abundance of the species in the meta-community (regional flora). See documentation chapter for more details.

3.3.7 Belowground

- Root Influential Zone Modifier
  Species specific factor of root influential zone from default 20*DBH meters

- Index Of Root Anchoring
  calculated as Dv2 / dbh2 where dbh is tree diameter at breast height (1.3 m height) and Dv is the diameters of all vertical roots (van Noordwijk 1999; Akinnifesi et al., 2004)

- Index Of Root Binding of Soil
  calculated as Dh2 / dbh2, where Dh is the diameters of all horizontal roots (Van Noordwijk 1999; Akinnifesi et al., 2004)

- Imperata Competition Factor
  Modifier factor for Imperata competitions

The Index of Root Anchoring and Binding is a new added module. Currently these parameters are used for the 3D visualization purpose only (Figure 24). Future implementation will include this root module for belowground competition and soil stabilization model.

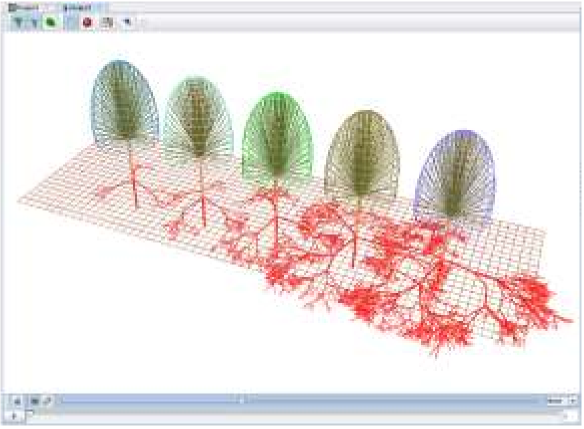


Figure 24. Roots visualization

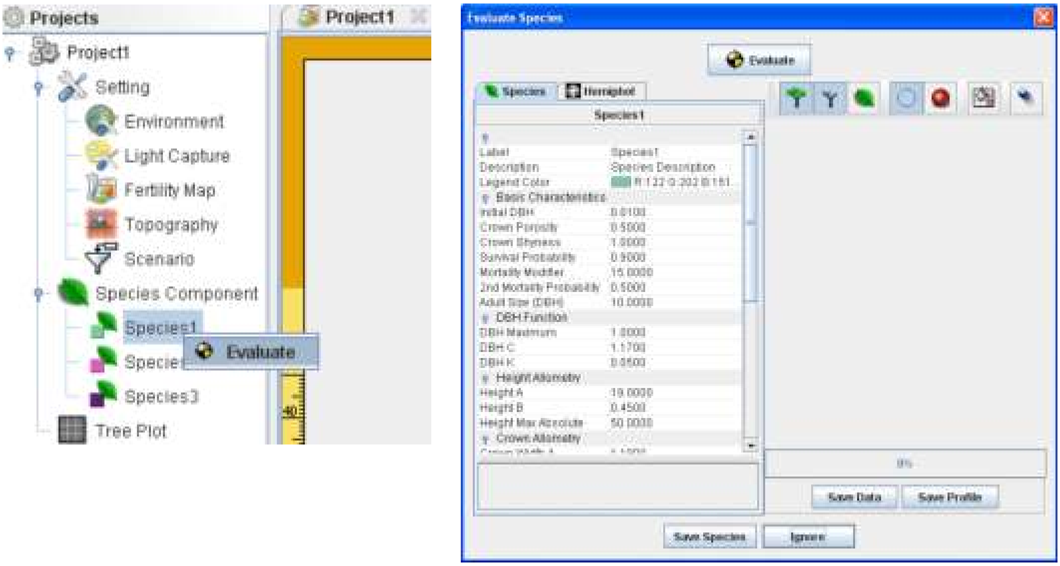
3.4 Evaluate Species

The species setting behavior can be tested using Evaluate option. Right click the species item on the Project tree windows and select Evaluate menu.

The species setting can be modified here and tested by growing a tree in an isolated environment or using a static defined hemiphot. The defined hemiphot is act as hemiphot captured by the tree as it grow. On the real simulation this hemiphot will changes dynamically as the surrounding environment. This static hemiphot is used to see the plasticity response of the species.

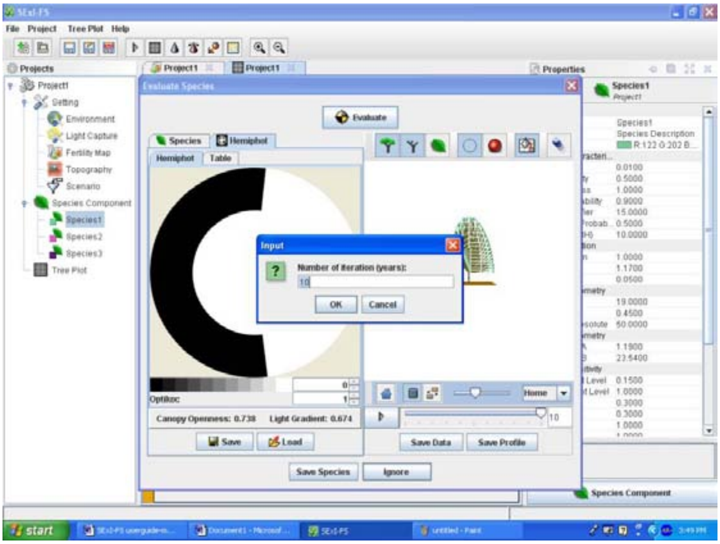
To edit the hemiphot, click the Legend bar below or fill in manually the light field, then click on the Hemiphot canvas. You can save the hemiphot for further use.

To start testing the species, click on the Evaluate button, and fill in the number of iteration, click Ok. The growth process of the tree will show on 3D visualization.



Label	Species1
Description	Species Description
Legend Color	🟩 R:122 G:202 B:181
Basic Characteristics	
Initial DBH	0.0100
Crown Porosity	0.5000
Crown Shyness	1.0000
Survival Probability	0.9000
Mortality Modifier	15.0000
2nd Mortality Probability	0.5000
Adult Size (DBH)	10.0000
DBH Function	
DBH Maximum	1.0000
DBH C	1.1700
DBH K	0.0500
Height Allometry	
Height A	19.0000
Height B	0.4500
Height Max Absolute	50.0000
Crown Allometry	

Figure 25. Evaluate species



Number of iteration (years): 10

Canopy Openness: 0.738 Light Gradient: 0.674

Figure 26. Evaluate species using hemiphot modification

3.5 Tree Planting

Once you have set-up the species component for your simulation, you need to plant trees. Highlight the Tree Plot component in the Project window, the Properties window will show an empty tree table (Figure 27). To start planting trees, you should move to Tree Planting tab, or you can click the button click here to plant trees inside the empty tree table.

Figure 27. Tree table tab

Figure 28. Tree planting tab

Planting trees can start with creating the template trees (Figure 28). The spatial arrangement along which trees are planted is either random, manually specified for each tree or created by repeating a user defined regular planting pattern.

3.5.1 Manual Planting

To plant the trees manually, press the Manual button on Tree Planting tab (Figure 28). The manual planting dialog will show up (Figure 29). Select the tree species and click Plant Template.

Species: Species1

Figure 29. Manual planting dialog

The tree plot will show up (it remains hidden until then), and you start to plant the trees by clicking on the plot. A tree will be planted on the location you click (Figure 30). To stop the planting model, right click the mouse. And to plant other tree species, repeat the above procedure.

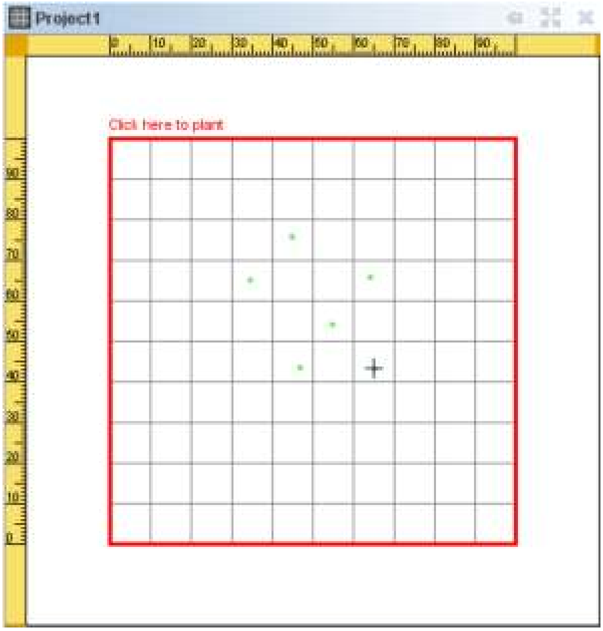


Figure 30. Manual planting plot

After creating the plantation template, click the Apply Template Trees! button, below the template table (Figure 28). The template trees will be cleared and the real trees are added to the plot.

3.5.2 Randomize Planting

To use the randomized template for tree planting, press the Random button on Tree Planting tab (Figure 28). The random planting dialog will show up (Figure 31). Select the species and set the number of trees to be planted. You can specify the random seed, for controlling the random generator. Click Plant Template.

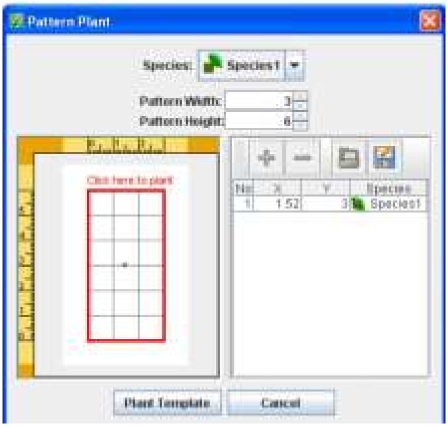
Species: Species1
Number of Trees: 50
☐ Random Seed: 0

Figure 31. Random planting dialog

To add more trees, repeat the above procedure. Click the Apply Template Trees! button below the template table (Figure 28) to finish the plantation. The template trees will be cleared and the real trees are added to the plot.

3.5.3 Pattern Planting

To plant the template trees using pattern, press the Pattern button on the Tree Planting tab (Figure 28). The pattern planting dialog will show up (Figure 32). Select the Species and set the size of the pattern. Click on the pattern plot to place the tree template as pattern. The plot will show a preview of the current pattern (Figure 33).



Species: Species1
Pattern Width: 3
Pattern Height: 6

No	X	Y	Species
1	1.52	3	Species1

Figure 32. Single species planting pattern

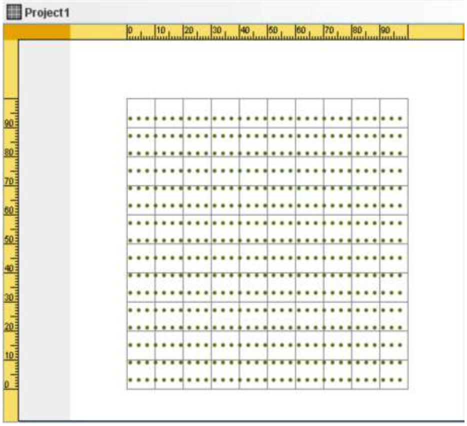
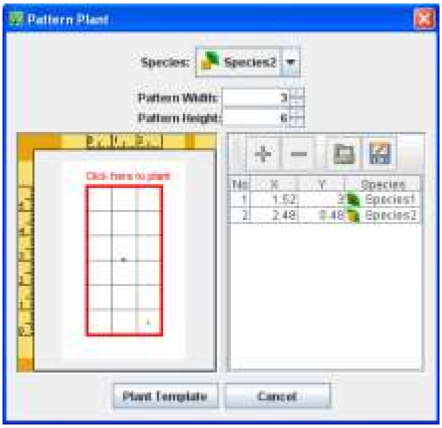


Figure 33. Single species planting pattern preview

You can create pattern with more than a single tree species (Figure 34). The plot preview will immediately show-up (Figure 35).



Species: Species2
Pattern Width: 3
Pattern Height: 6

No	X	Y	Species
1	1.52	3	Species1
2	2.48	0.48	Species2

Figure 34. Multiple species planting pattern

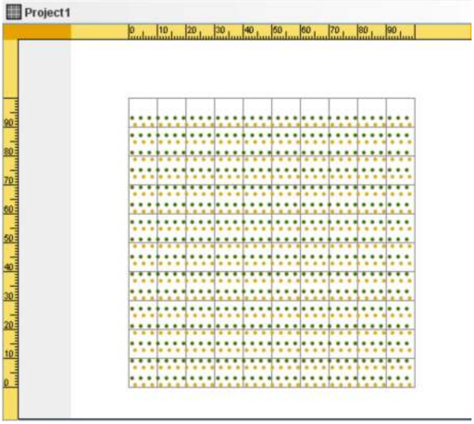


Figure 35. Multiple species planting pattern preview

The tree pattern location and species can still be edited trough the tree table on the right of the plot pattern. After creating the pattern click Plant Template button to create the template trees. And click the Apply Template Trees! button to finish the plantation.

3.6 Construct Tree

Users are able to reconstruct an established plot into SExI-FS. The geometry structure is as follow:

1. X: the x position of the tree base (m)
2. Y: the y position of the tree base (m)
3. Species: the species label, if the label is match with the one in the species list then it will be linked, otherwise new species definition will be created
4. DBH: the diameter at breast height of the tree (m)
5. Height: the height of the tree (m)
6. CR Depth: crown depth (m),
7. CR Curve: crown curve (m),
8. CR Radius: crown radius in vertical projection, can be more then one value separated by semicolon (m),
9. Rotation: a rotation of the vertical projection of the crown geometry (degree).
10. CP: crown position index (0-1)
11. CF: crown form index (0-1)

Figure 36 shows the parameters description of the tree geometry. The definition of crown radius is shown by the vertical projection of the crown. If there are only one radius information (r1, the leftmost) the vertical projection will be a circular shape, but if there are more then one radius information, the vertical projection will look like on following the graph in Figure 36 (the rightmost graph use 5 radius information). The horizontal and vertical projection information of the tree geometry is then converted into 3D shape object.

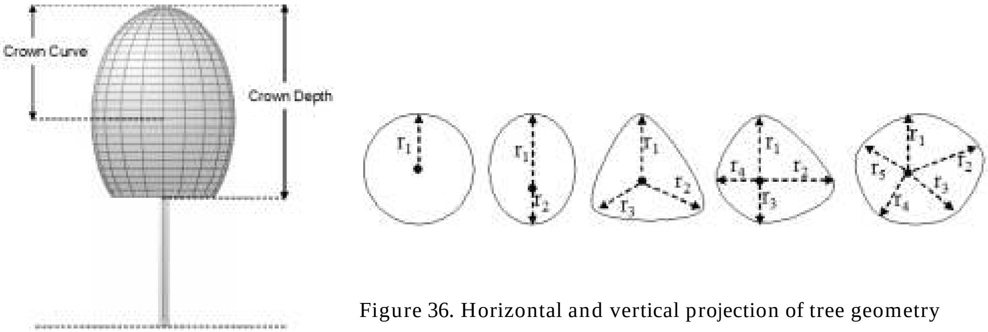
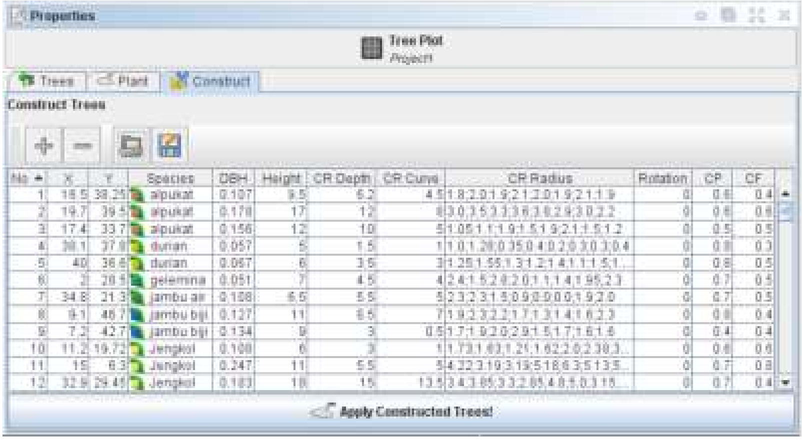


Figure 36. Horizontal and vertical projection of tree geometry

The geometry information of the trees can be inserted manually using the table interface shown in Figure 37. The table is also able to load a text data file (tab separated) with the format shown below:

iid	x	y	spesies	dbh	height	cr_depth	cr_curve	cr_radius	rot	cp	cf
1	16.5	38.25	alpukat	0.10668	9.5	6.2	4.5	1.8;2	0	0.6	0.4
2	19.7	39.5	alpukat	0.17834	17	12	8	3;3.5	0	0.6	0.6
3	38.1	37.8	durian	0.05732	5	1.5	1	1;1;3;4	0	0.8	0.3



Construct Trees

No	X	Y	Species	DBH	Height	CR Depth	CR Curve	CR Radius	Rotation	CP	CF
1	16.5	38.25	alpukat	0.107	9.5	6.2	4.5	[illegible]	0	0.6	0.4
2	19.7	39.5	alpukat	0.178	17	12	8	[illegible]	0	0.6	0.6
3	17.4	33.7	alpukat	0.156	12	10	5	[illegible]	0	0.5	0.5
4	38.1	37.8	durian	0.057	5	1.5	1	[illegible]	0	0.8	0.3
5	40	36.6	durian	0.067	6	3.5	3	[illegible]	0	0.8	0.5
6	2	28.5	gelemina	0.051	7	4.5	4	[illegible]	0	0.7	0.5
7	34.8	21.3	jambu air	0.108	6.5	5.5	5	[illegible]	0	0.7	0.5
8	9.1	46.7	jambu biji	0.127	11	6.5	7	[illegible]	0	0.8	0.4
9	7.2	42.7	jambu biji	0.134	9	3	0.5	[illegible]	0	0.4	0.4
10	11.2	19.72	Jengkol	0.108	6	3	1	[illegible]	0	0.6	0.6
11	15	6.3	Jengkol	0.247	11	5.5	5	[illegible]	0	0.7	0.8
12	32.9	29.45	Jengkol	0.183	18	15	13.5	[illegible]	0	0.7	0.4

Figure 37. Construct trees

3.7 Running the Simulation

To start running the simulation, highlight the Project Root section on Project window. The Properties window will show the project properties and the Run button (Figure 12). Click the "Run" button, and enter the number of iterations, click Ok. The simulation will run for the specified number of iterations (years). While the simulation is running, you can see the progress bar that indicates progress of simulation.

Number of iteration (years): 20

Figure 38. Running simulation

4. Simulation Output

You can explore the simulation output by either inspecting the tree plotting in Two Dimension (2D) and Three Dimension (3D) graphic or plotting the tree data on statistical chart.

4.1 Vertical Projection Plot

The vertical projection plot is showing a 2D view of tree crowns vertical projection (Figure 39). You can monitor the dynamic growth of the tree and its crown through this plot. The plot management also can be done through this plot.

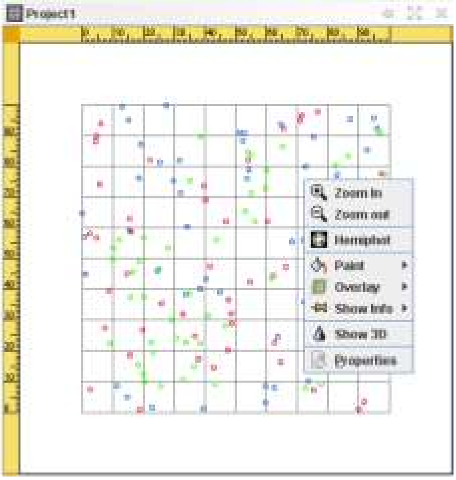


Figure 39. Vertical projection plot

4.1.1 Plot Options

Right click on the plot area, you will find menus for configuring the plot.

Zoom In : Magnify the plot

Zoom Out : Zooming out the plot

Hemiphot : Show hemispherical photograph model for the selected location

Paint : Vertical projection paint model

Outline : Outline paint model

Opaque : Opaque paint model

Transparent : Transparent paint model

Shaded : Shaded paint model

Show Info : Show information label of each tree on the plot (Species, ID, DBH, etc)

Overlay : Overlay the layer plot

Light Map : Overlay the light map layer

Root Map : Overlay the root map layer

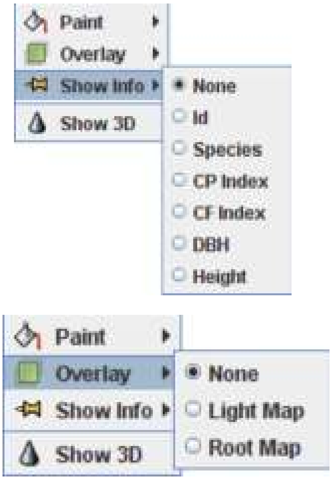


Figure 40. Plot menu

Figure 41 shows the hemiphot for some location selected on the plot and Figure 42 is the overlay of light map. Figure 43 Show info of tree (tree ID) overlay with root map.

Figure 41. Hemiphot

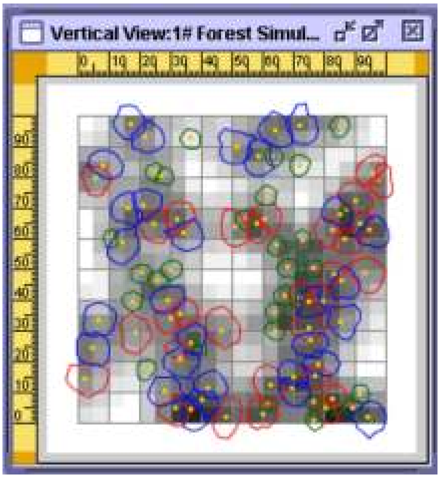


Figure 42. Light map

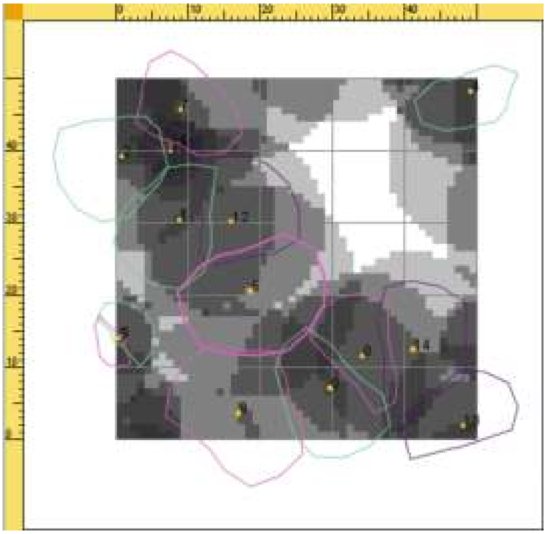


Figure 43. Show info of tree (tree ID) overlay with root map

Figure 44 Paint type for the tree, clockwise from top-left, outline, opaque, transparent, and shaded. Shows various paint type for vertical projection of the crown

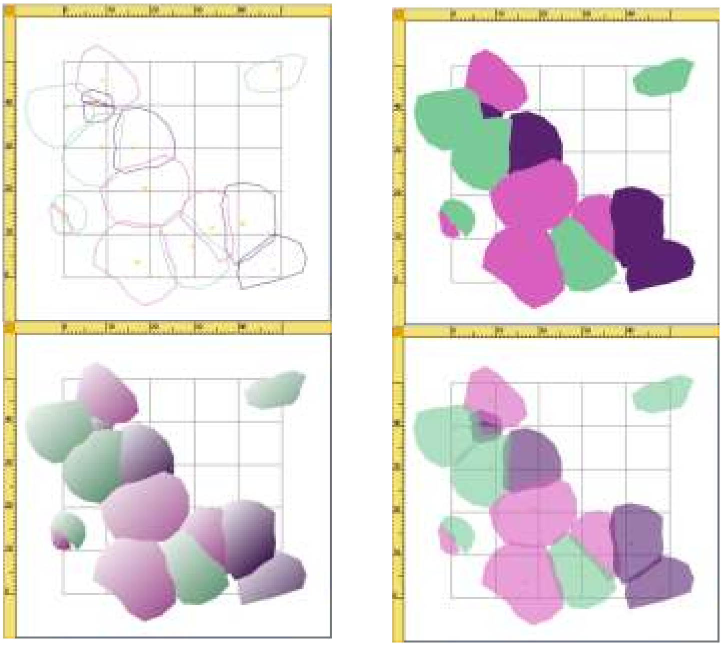


Figure 44. Paint type for the tree, clockwise from top-left, outline, opaque, transparent, and shaded

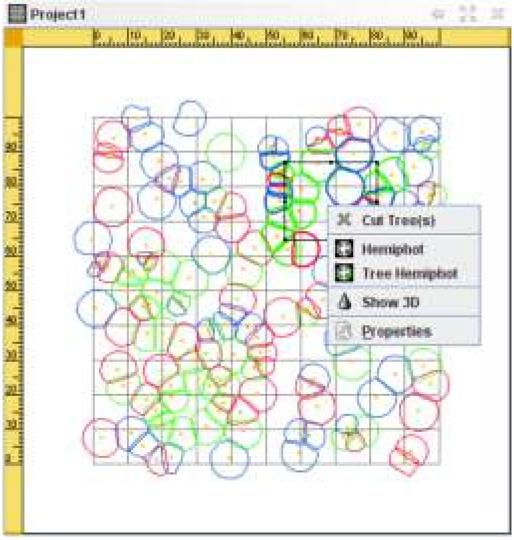


Figure 45. Tree selection menu

Cut Tree(s) : Cutting / removing the selected tree(s) from the plot. This can be assumed as a manual plot management. You may cut the trees for logging purpose or others. Figure 45 show the simulation plot after 10 years of simulation using default parameters. You can select and cut the trees, and run the simulation again for a number of iteration.

Tree Hemiphot : Show hemispherical photograph model as viewed by the selected tree

Show 3D : View the 3D visualization of the trees

4.2 3D Visualization

You can explore the tree in 3D Graphics. Make sure that you have minimum requirement for viewing the 3D graphics (see section 1.3 Minimum Requirement). Select the trees and right click, then select the Show 3D option. The 3D visualization will show up (Figure 46). You show the 3D visualization without selecting the trees to show the whole plot.

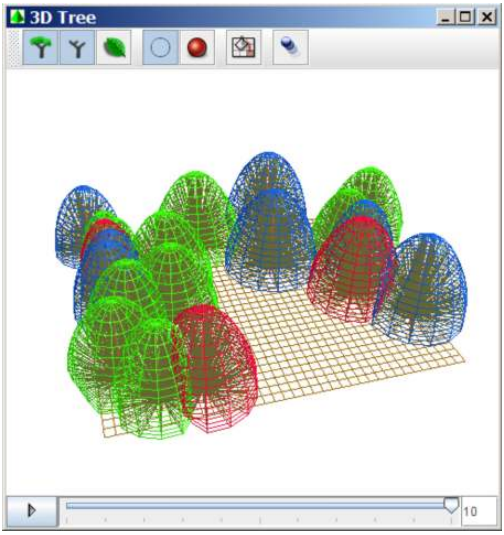


Figure 46. 3D visualization

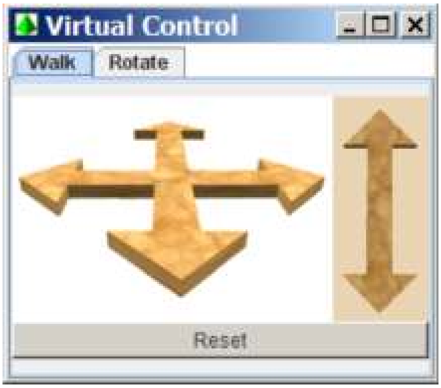


Figure 47. Virtual Control

The 3D view options are as follow:

Crown : View the crown

Branches : View the branches

Leaves : View the artificial leaves visualization

Wireframe : Show in wireframe mode

Solid : Show in solid mode

Textured : Show the textured object

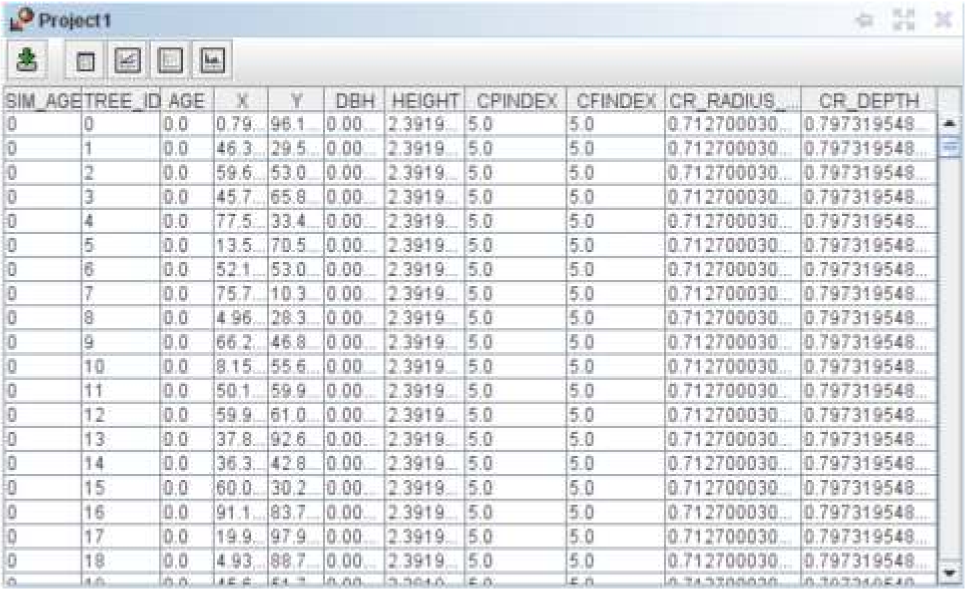
Morphing : Show a smooth change between animation steps

You can control the angle view of the 3D visualization using the virtual control shown on Figure 47. Or you can directly use your mouse to rotate the 3D object on 3D window.

In this 3D visualization you can play the animation by pressing the Play (▶) button. The animation shows the changes of trees from step to step of iteration.

4.3 Tree Data

Tree data output can be viewed through the Menu bar or Project popup menu. It shows all the tree data history (Figure 48). Next you can either download the data to be processed with some statistical software or directly view the plot and distribution using the available chart tools.



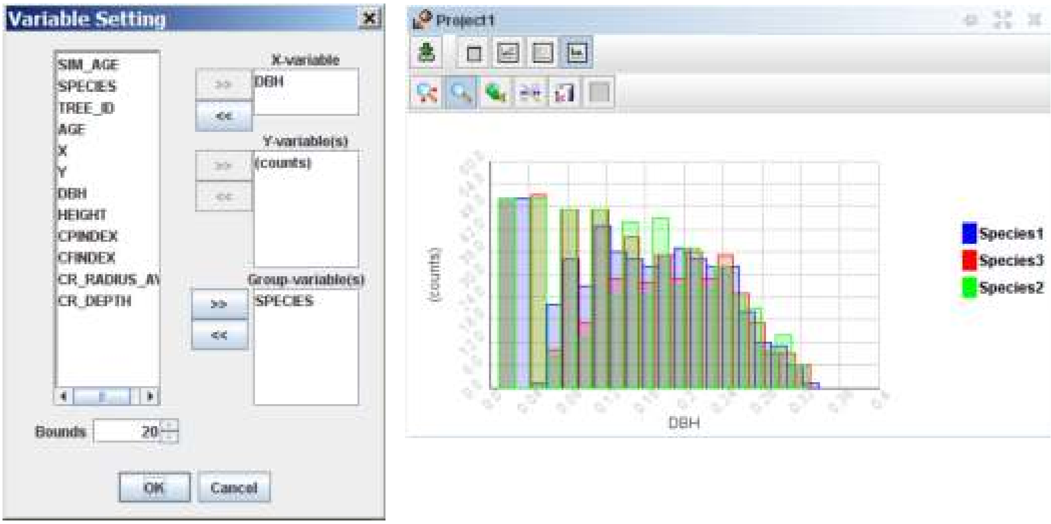
SIM_AGE	TREE_ID	AGE	X	Y	DBH	HEIGHT	CPINDEX	CFINDEX	CR_RADIUS_…	CR_DEPTH
0	0	0.0	0.79…	96.1…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	1	0.0	46.3…	29.5…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	2	0.0	59.6…	53.0…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	3	0.0	45.7…	65.8…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	4	0.0	77.5…	33.4…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	5	0.0	13.5…	70.5…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	6	0.0	52.1…	53.0…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	7	0.0	75.7…	10.3…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	8	0.0	4.96…	28.3…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	9	0.0	66.2…	46.8…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	10	0.0	8.15…	55.6…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	11	0.0	50.1…	59.9…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	12	0.0	59.9…	61.0…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	13	0.0	37.8…	92.6…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	14	0.0	36.3…	42.8…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	15	0.0	60.0…	30.2…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	16	0.0	91.1…	83.7…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	17	0.0	19.9…	97.9…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…
0	18	0.0	4.93…	88.7…	0.00…	2.3919…	5.0	5.0	0.712700030…	0.797319548…

Figure 48. Tree data

There are three types of charts that can be used to analyze the data, Bar Chart, Line Chart and Scatter Plot.

4.3.1 Bar chart

Select the variable on the left panel and move it to the x and axis panel on the right. By default the y axis is the number of trees based on the x variable class. You can also group the data by moving some of the variable to Group variable list. The “Bounds” setting is the number of x axis class.



X-variable: DBH

Y-variable(s): (counts)

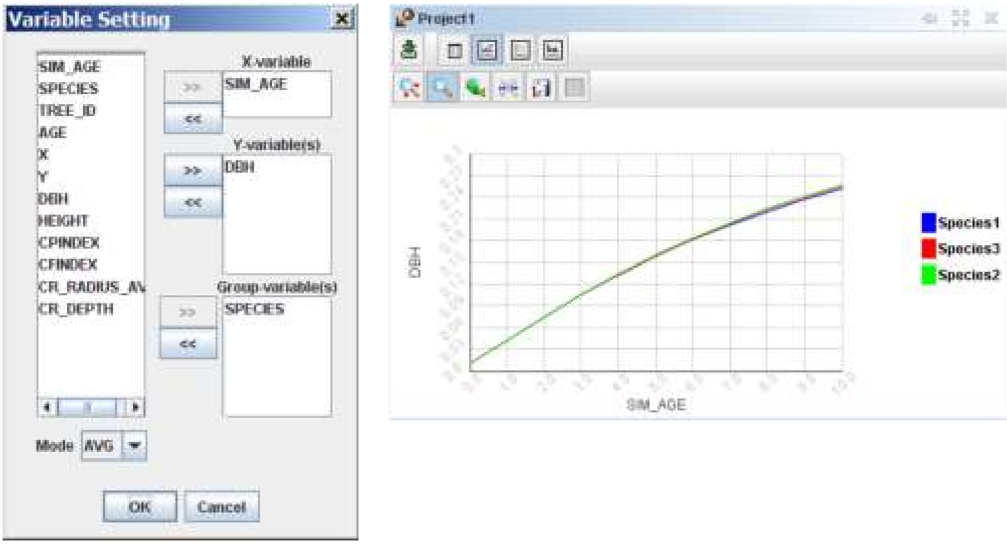
Group-variable(s): SPECIES

Bounds: 20

Figure 49. Bar Chart

4.3.2 Line chart

On the line chart you can define the X and Y variable from the available variable list. And define the calculation method (Mode) in case the Y value is more the one per C category. The calculation method available is average, sum and count.



X-variable: SIM_AGE

Y-variable(s): DBH

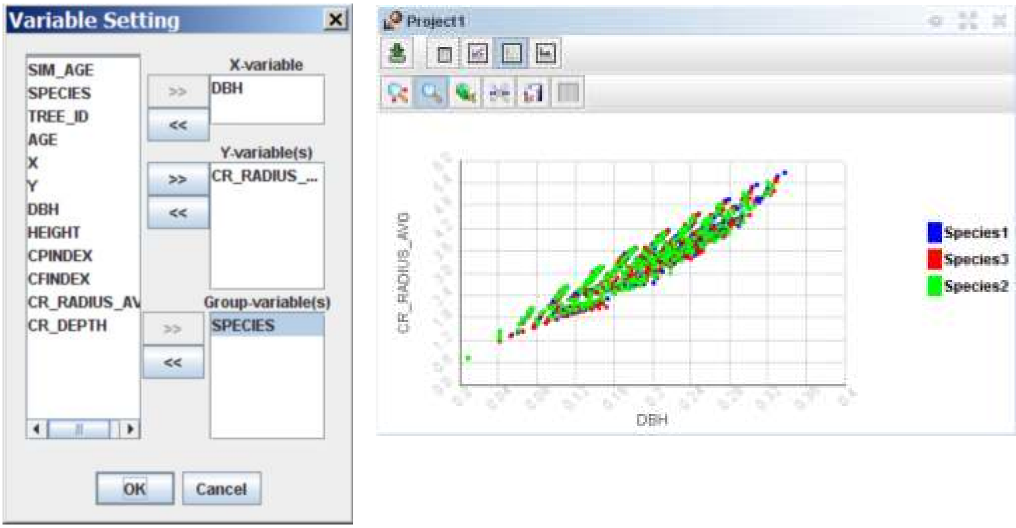
Group-variable(s): SPECIES

Mode: AVG

Figure 50. Line chart

4.3.2 Scatter plot

The X and Y axis can be set for by variable from the variable list.



X-variable: DBH

Y-variable(s): CR_RADIUS_...

Group-variable(s): SPECIES

Figure 51. Scatter plot

5. Documentation

5.1 Model description and main algorithms

5.1.1 Main loop

The loop is run on a yearly time step. It starts with an initialization step, the initial trees are recorded into the module as individual objects. Next the trees crown attributes (Crown Form Index (CF) and Crown Position Index (CP)) are updated. Crown Form is an index of how well developed a crown is and Crown Position is an index of light availability. Simulation data is then recorded after this step.
Tree growth is then computed (diameter, height and crown volume increment).
At each step in time, for each tree a survival test is made. Finally at stand level a recruitment test is conducted.

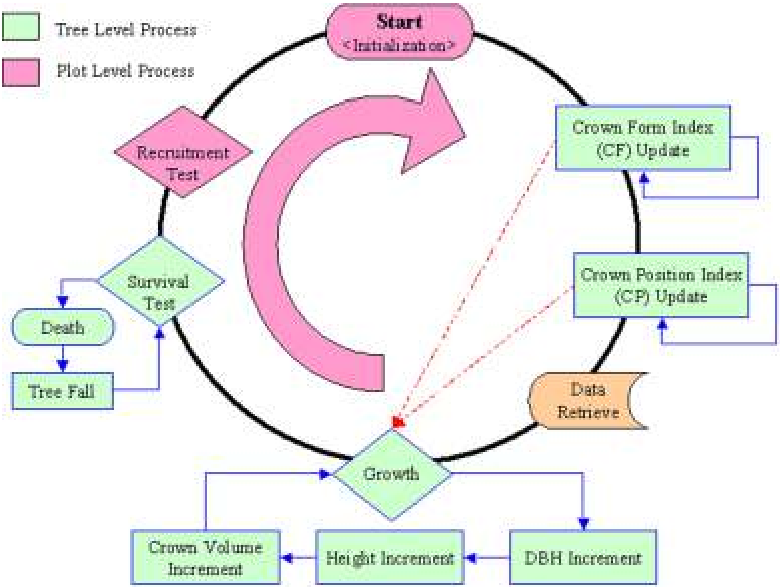


Figure 52. Main of SExI simulator

5.1.2 DBH Increment and growth reducers

DBH as a function of time (t) follows a Chapman Richards function:

$$\text{dbh} = \text{dbh\_max} * \left(1 - e^{-k*t}\right)^{c}$$

And approximating DBH annual increment with the first derivative of DBH with respect to time (t) one can express dbh increment as a function of current dbh as follows:

$$\text{dbh\_inc} = \text{dbh} * \text{c} * \text{k}\left(\left(\frac{\text{dbh}}{\text{dbh\_max}}\right)^{\frac{-1}{c}} - 1\right)$$

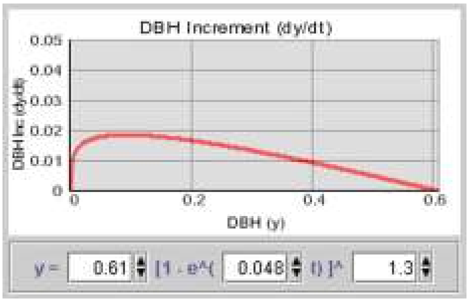
One can note that maximum increment is then

$$\text{dbh\_inc\_max} = \text{dbh\_max} * \text{k} * \left(1 - \frac{1}{c}\right)^{c-1}$$

which is attained when

$$dbh = dbh\_\max * \left(1 - \frac{1}{c}\right)^{c}$$

Default initial diameter is one cm.



y = 0.61 [1 - e^(0.048 t)]^ 1.3

Figure 53. DBH Increment Function

Potential DBH increment as defined above is reduced by the effect of aboveground and belowground competition. Thus the actual DBH increment is:

dbh_inc_act = dbh_inc * growth_reducer

Growth reducers considered in this model are:

a. Light Stress (Crown Position Index)
b. Crown Form Index
c. Local fertility index
d. Tree Production Effect (competition for carbon allocation between growth and production of resin, latex, or fruit)
e. Belowground competition (based on local crowding)
f. Other possible growth reducers could relate to other ecological constraints such as pest pressure, diseases, etc. (not yet implemented)

a. Light Stress

Light stress is related to light capture (i.e. crown position index value) in a species specific way :

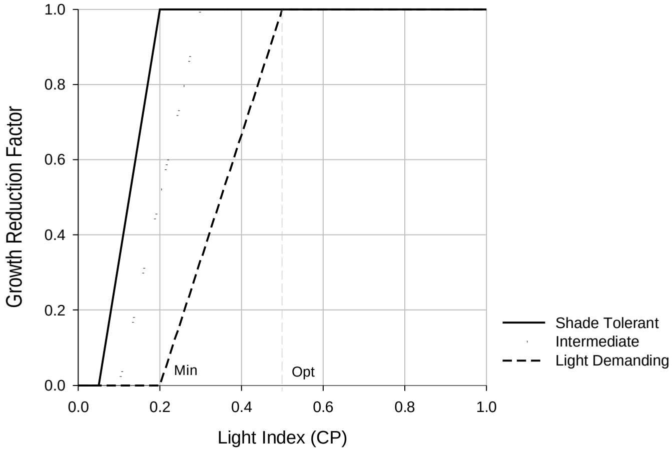


Figure 54. Typical shape of the relation between light index and growth reduction factor for different levels of shade tolerance (Min: Minimum level for growth to occur, Opt: Optimum level for growth

CP stands for Crown Position, which is an index of access to light. The computation of this index is explained in details in section 3.2.2 Light Capture Setting.

In short Crown Position is computed based on a virtual hemispherical photograph that would be taken at tree crown base, the target tree crown itself being completely transparent.

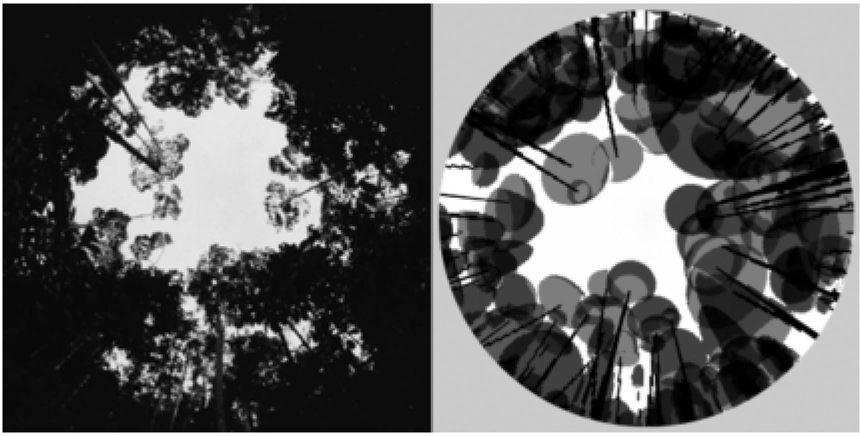


Figure 55. Hemispherical Photograph (left) compare with the model calculated (right) in high-resolution method

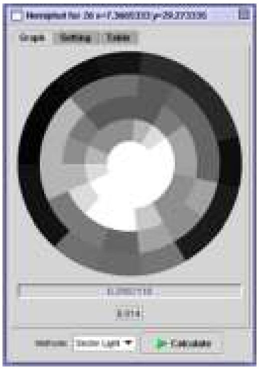


Figure 56. Low resolution Hemiphot, shows
a CP = 0.398 on range 0 1

b. Crown Form (CF)

Crown Form is an index based on the ratio of actual crown size to normal crown size of a tree with same DBH. The crown size is defined by the surface area (or alternatively the surface area of the convex envelop) of the crown. The difference between actual and normal crown size may result from encroachment from neighboring crowns, suboptimal light level or asymmetric development of the crown. The asymmetric development of the crown is explained in the section presenting the STRETCH module below:

$$cf = \frac{crown\_surface\_actual}{crown\_surface\_normal}$$

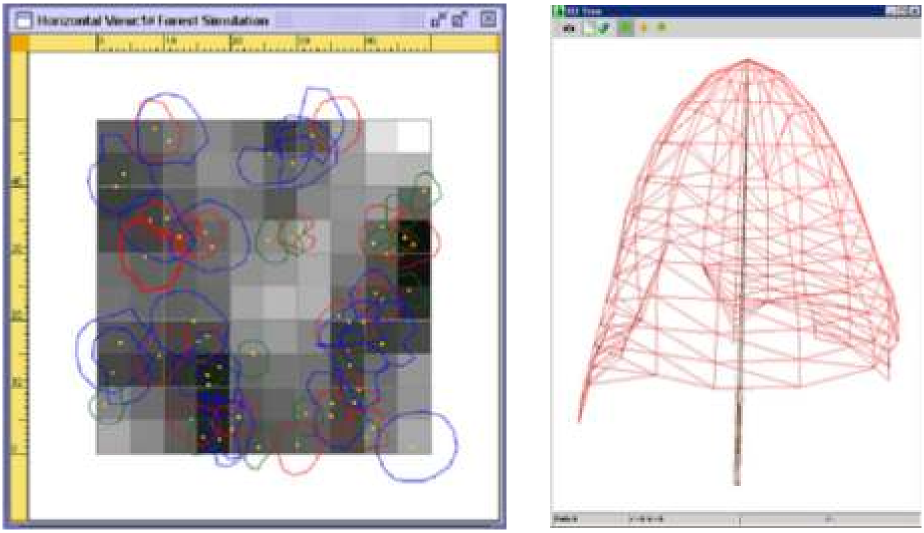


Figure 57. An asymmetric development of crown shown on the model

c. Belowground Crowding Index

Below ground competition is based on the following simple assumptions.

1. Root influential zone (IZ) of a tree is proportional to its size and symmetric in shape (circular).
2. A crowding index is computed for any tree based on the overlap of neighbours' IZ with target tree influential zone.
3. More competitive species have relatively larger IZ (i.e. higher resource capture efficiency).
4. Overall below-ground crowding index effect on growth is site specific (dependent on overall level of resources).

The relationship used to relate growth reduction to below-ground crowding index is illustrated in the graph below, where *s* is the site index fertility value.

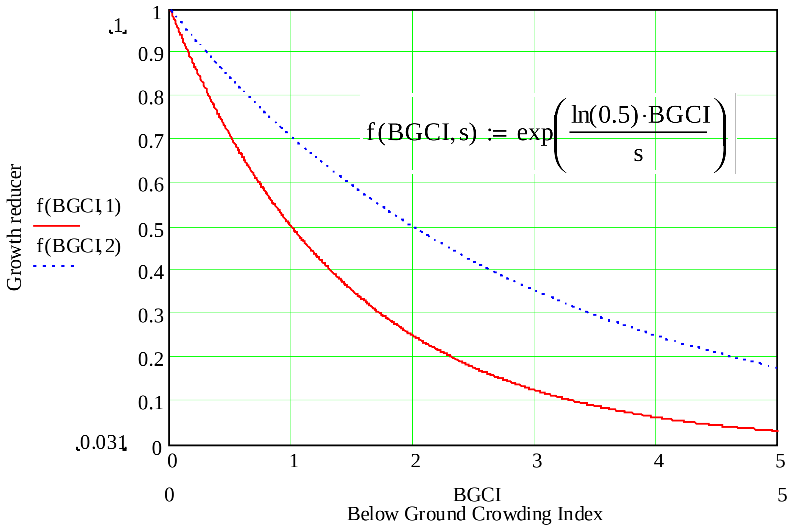


Figure 58. Relationship used in SExi to compute growth reduction as a function of BGCI

d. Fertility

Local variation of soil fertility can also be simulated. A soil fertility map can be entered manually for each cell of a grid covering the plot or read from a text file. Missing data are interpolated using bilinear 3 dimensional interpolation (Press, et al., 1992). Fertility values fall between 0 to 1, a fertility of one meaning there is no local soil fertility related limitation (in addition to the overall fertility level defined in the step above).

The fertility experienced by a tree will then depend on tree position in the plot. Fertility index used for computing reduction in growth of a particular tree is simply the average value over the cells included in the tree's influential zone. All cells which center is included in the crown projection are used in mean fertility calculation.

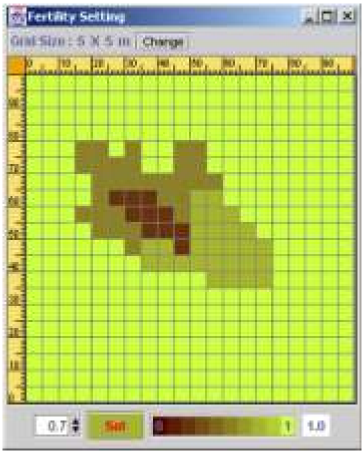


Figure 59. Fertility Map

e. Tree Production Effect

Tapping of rubber trees slows tree growth. Annual DBH increment decreases with increasing tapping frequency. Research on rubber trees shows that after 200 days of tapping, DBH increments decrease by about 50% (see review in Grist et al., 1998) and data in (Vincent et al., Submitted for Agroforestry System). However the decrease is not simply proportional (the simple fact that trees are tapped albeit lightly seem to induced a strong decrease in dbh increment. The default function used is:

GrowthReduction= 1/ (Exp((number_of_tapping_days_per_year/365)^0.5)

And is plotted below:

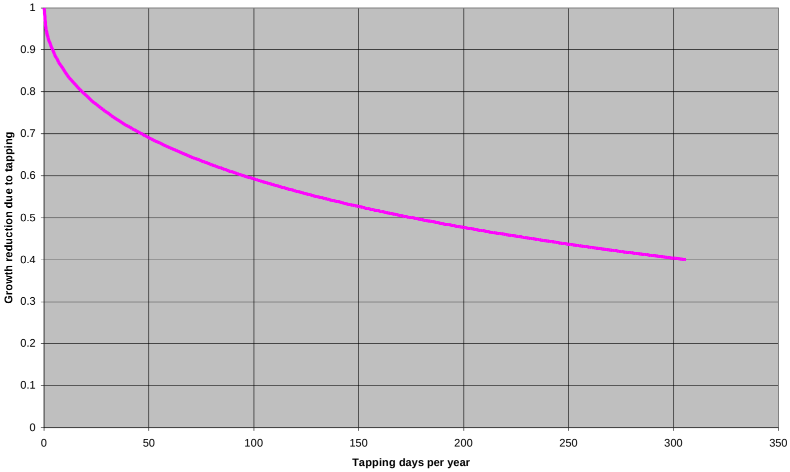
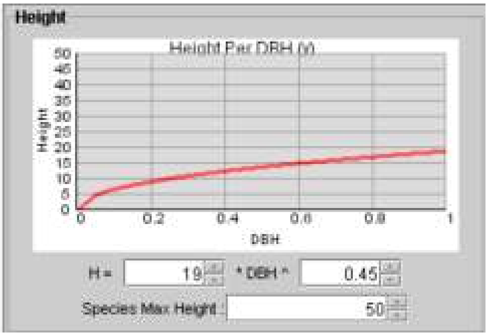


Figure 60. Growth reduction as function of number of tapping days (hevea default calibration in SExI)

5.1.3 Height Increment

A reference allometric function relates tree height to tree dbh:

$$height = \alpha_h * dbh^{\beta_h}$$



H = 19 * DBH ^ 0.45

Species Max Height 50

Figure 61. Height -DBH function

Thus height increment, which is the function of DBH increment, is:

$$height\_inc = \alpha_h * [(dbh + dbh\_incr)^{\beta_h} - dbh^{\beta_h}]$$

And the height increment corrected by the elongation factor is:

$$height\_inc\_elong = height\_incr * c * break\_function$$

Where c is the elongation factor:

$$c = 1 + flexi * (1 - CP)^{1/sensi}$$

Where:

- flexi is a parameter which measures the ratio of height growth rates under the most contrasted light gradients (0 and 1).
- CP is the crown position index (between 0 and 1).
- sensi is a measure of how responsive the species is to shading , sensi > 1 (e.g. 2) typical of a shade avoiding species and sensi < 1 (e.g. 0.5) of a shade tolerant species.

and the break_function which is simply meant to ensure a smooth height growth reduction when approaching asymptotic height is defined as follow:

$$height\_break = 1 - e^{k(\frac{h}{h\max} - 1)}$$

where h is current height, hmax is asymptotic height and k curvature parameter that is taken to be 20 for all species.

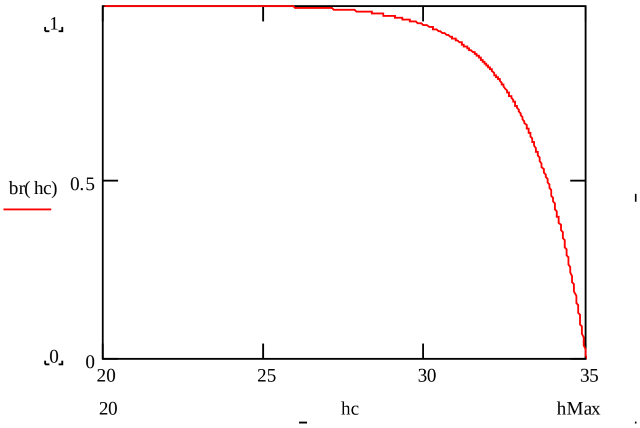


Figure 62. Height Break Function (hc=current height)

Enhanced height growth is achieved at the expense of dbh increment. Assuming that total stem biomass scales isometrically with the product of stem cross sectional area and tree height, the maximum possible height increment is then limited by actual dbh increment.

$$height\_inc\_\max = \frac{\Delta h * dbh^2 + 2h * \Delta dbh * dbh + 2\Delta dbh * \Delta h * dbh + h * \Delta dbh^2 + \Delta dbh^2 * \Delta h}{dbh^2}$$

Note that max_height increment is independent of tree current slenderness!

Then actual height increment is:

Height_inc_actual = Min(height_inc_elong, height_inc_max)

Adjusting the actual dbh increment as the factor of slenderness:

- if height_inc_actual = height_inc_max then dbh_inc_actual = 0
- If height_inc_actual < height_inc_max then

Dbh_inc=

$$dbh\_inc = -\frac{-\sqrt{(dbh^2(h*s*+\Delta h) + h*\Delta dbh^2 + 2\Delta dbh(h*dbh + \Delta h*dbh + *\Delta h))(h*s + \Delta hc) + dbh*h*s + dbh*\Delta hc}}{h*s + \Delta h*c}$$

Where s is the slenderness coefficient (current height / height of reference tree grown in the open) dbh, Δdbh, h, Δh refer to dbh, dbh_inc, height and height_inc of reference tree and hc and Δhc stand for current height and height increment of actual tree.

5.1.4 Crown Growth

A tree crown is represented as a deformable solid. Crown deformation can be global in response to increased shading or local in response to radial anisotropy of incident light or spatial constraint.

Local deformation is mediated via a set of vectors stemming from crown base and subtending the crown envelope. Extension of the subtending vectors is affected by local light and space availability as determined by species-specific parameters.

Crown deformation algorithm is detailed in the STReTCH module (Section 5.2) below.

5.1.5 Latex Production

So far only latex yield of rubber and fruit production has been implemented. The relationship between size (DBH) and maximum latex yield is considered to be linear (Vincent et al., 2000):

$$latex = a * DBH + c$$

Latex production is considered to decrease after a certain number of tapping incisions due to bark consumption and diseases, etc.

By default, the decrease in latex production is set to start after 2000 days of tapping (say + ten years of intensive tapping) and latex flow will completely dry up after 8000 days of tapping. Then prediction of actual latex production after corrected by frequency of tapping (*f*):

$$latex\_act = latex * \left(1 - \left(\frac{f - 2000}{6000}\right)^2\right) \text{ and 0 if >8000 days}$$

Fruit production and timber production can be specified as a function of tree size through the user interface.

5.1.6 Recruitment

Species defer in their preferred light environment for establishment. This light preference is captured by a probability distribution function (which can be estimated by the experimentally determined frequency distribution of saplings per light classes).

A beta distribution is used which is defined as:
$f(x) = G(n+w) / [G(n)G(w)] * x^{n-1}*(1-x)^{w-1}$, with $0 < x < 1, n > 0, w > 0$).
Some typical values for the two parameters are reported below and the corresponding function plotted in the graph below where X refers to canopy openness. Shade tolerant: shp1=2 shp2=10 (e.g. duku) RED
Light demanding: shp1=4 shp2=12 (e.g. damar, rubber) BLUE
Pioneer: shp1=12 shp2=8 (e.g. pulai) GREEN

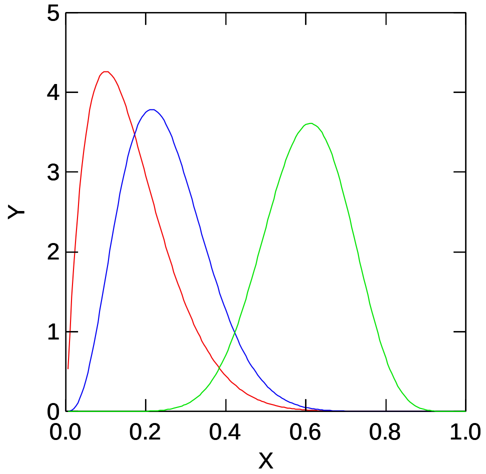


Figure 63. Hypothetical density probability functions of sapling presence as a function of canopy openness

The recruitment rate (number of saplings recruited per unit area per unit time) is a function of the level of saturation of the plot carrying capacity. Carrying capacity is itself considered to increase linearly from 0 to maximum carrying capacity as canopy openness ranges from 0 to 1.

Contribution to the recruitment rate of the various species depend on the meta-community composition (relative abundance in regional floristic pool) and local community composition (relative abundance of adult trees per species in plot). Let è be the relative weight of meta-community composition in recruitment. It may be hypothesized that everything else being equal è will decrease with increasing size of plot and with plot compactness (area / border).

The algorithm is based on a light map available at 1 m above ground level and a map of distribution of the existing trees, and is outlined below.

Outline of recruitment algorithm:

Step 1. Light map segmentation
Sort light map elementary cells into 5 light classes. The segmentation uses intervals equal to one fifth of the available light range. K-means clustering algorithm into homogeneous light classes or quantile based segmentation could be used as an alternative (not yet tested).

Step 2. Determining the number of recruits
For each light class, determine recruitment rate from a recruitment function assuming that recruitment rate is a function of degree of saturation of the stand carrying capacity (maximum sapling density) which is itself limited by light availability; Median value of light class is used to estimate carrying capacity per light class.

The default function used assumes that maximum density is proportional to the available light or its proxy, canopy openness (CO). Default parameterisation uses sets maximum density in high light (i.e. CO=1) to 5000 individuals per ha. It is further assumed that sapling density will be 0 if CO=0. Recruitment rate is then fixed as proportional to each light class density deficit (defined as max(0,(max density - obs. density)). The suggested default value for recruitment rate is half of the density deficit (and expressed as a number of recruits per unit area). In other words it is assumed that the plot density would asymptotically reach its target maximum density (with a rapid initial increment as 95% of maximum density would be reached in just 4 time steps using the default parameterisation *if the light conditions would not change).*

Step 3. Identifying cells that will host the recruits.
Select cells to be colonized in current time step (if any).
For each light class the number of recruits is known and equal to the total area of that light class x recruitment rate. The random allocation of those recruit to particular cells is done according to a parameter α which reflects the relative bias towards preferential establishment in empty cells (hence á controls spatial regularity in recruitment) and may be set to 1 by default assuming that only empty cells will be considered as potential location for new recruits. Conversely if α is set to 0 all cells within a particular light class will be selected with the same probability. Hence as overall density per light class governs the total recruitment rate this will result in a spatially totally random distribution of seedlings within a light class (provided that the draw is done on the whole set of cells for each individual). See last section for details of the proposed algorithm (section 5.2.3 b and section 5.2.6).

Step 4. Determine to which species a recruit belongs
We now have identified the individual cells that will carry a recruit and the number of recruits per cell. For each recruit, we then randomly draw the species to which it belongs using the following procedure.

Let F_i be the relative weighted frequency of the species *i*, i.e. the relative “effective” abundance of species contributing to regeneration inside the plot. By definition

$$\sum_i F_i = 1$$

Let F_i be the relative “effective” abundance of species contributing to regeneration inside the plot. F_i is defined as

$$F_i = \frac{\theta_i (F_{i\_metacom}) + (1\text{-}\theta_i)(F_{i\_local})}{\sum_i \left(\theta_i (F_{i\_metacom}) + (1\text{-}\theta_i)(F_{i\_local})\right)}$$

where $1 >= \theta i >= 0$ can be viewed as a measure of a species' efficiency of dispersal

Suppose that there are M light classes and let Aij be the relative abundance of species *i* in light class *j*. By definition

$$\forall i, \sum_j A_{ij} = 1$$

We further note Lj the relative frequency of recruits which fall into class j, hence
$\sum_j L_j = 1$ (which is determined in steps 2 and 3)

We then compute the probability of recruiting a sapling of species i in a cell belonging to light class *j* as *Rij*

$$R_{ij} = P(S = i / L = j) = P((S = i) \cap (L = j)) / \mathrm{P(L = j)},$$

Noting that

$$P((S = i) \cap (L = j)) = P(S = i) * P(L = j / S = i) = Fi * Aij$$

we obtain

$$R_{ij} = \frac{F_i * A_{ij}}{L_j}$$

Step 5. Fine location of individual saplings within cells
We have now defined for each cell the number of recruits and to which species they belong. We then locate those randomly within their cell.

<u>Parameters specific to the recruitment step</u>

Species specific parameters:

- Relative species abundance in overall community
  Each species in a scenario is attributed a weighting factor such that the ratio of this weight to the sum of weights over all species is equal to the relative abundance of that species in the metapopulation. By default a new species is created with a weight of one.

- Species dispersal limitation
  1- θ reflects species dispersal limitation should be close to 0 for pioneer species and may be close to 0 for strongly aggregated species.

Overall parameters

- α relative preference for empty cell (default alpha=1)
  This is implemented in the following way. Cells are given a weight of $(1 - \alpha * 1_{\text{occupied cell}})$ where $1_{\text{occupied cell}}$ is 1 if cell is occupied and 0 if it is empty. If α = 0 then each cell is drawn randomly from the complete set of cells, if α =1 then each cell is drawn randomly from the subset of empty cells (note that after each draw the cells are re-weighted to reflect change in occupancy). Practically for 0< α <1, cells are “placed on a line” in an arbitrary order from 0 to sum of cell weights. Cell i and cell i+1 being separated by a distance equal to weight of cell i+1. Then a random number between 0 and Sum of weights is drawn and the recruit is allocated to the

cell whose associated interval contains the value obtained randomly (the cell corresponding to the first graduation larger than the random number drawn).

- maximum sapling density
  The default value is set to 5000 per ha but may be changed according to local data and developmental stage considered for the recruitment step.

The light map used in the recruitment module is computed for a 1x 1m grid using the similar light calculations as for trees light index (i.e. the so called “detailed” light map as opposed to the “simple” light map as described in the SLIM section).

5.1.7 Mortality

Survival probability is computed from two parameters: Min survival probability and m. Min survival probability is the survival probability value of a completely suppressed plant (no growth). m is a parameter affecting curvature of the relationship between growth rate and survival probability.

This formulation is equivalent to a logistic model (which is strictly equivalent mathematically speaking)

Log(sp / (1-sp))=ax+b equivalent to sp=1 / (1+ exp(-ax-b))

By default x should rather be a measure of relative growth rate (instead of growth rate relative to max growth rate given current size as this would incorporate senescence). However note that this will most probably not by easy to calibrate for all tree size and may have to be refined (one way would be to have size as a explicit predictor in addition to relative growth rate).

Survival probability increases with the ratio between actual and maximum growth rate r:

$$r = \frac{dbh\_inc}{dbh\_inc\_\max}$$

$$sp = \min\_sp + \left(\left(1 - \min\_sp\right) * \left(1 - e^{-m*r}\right)\right)$$

Where m is mortality modifier.

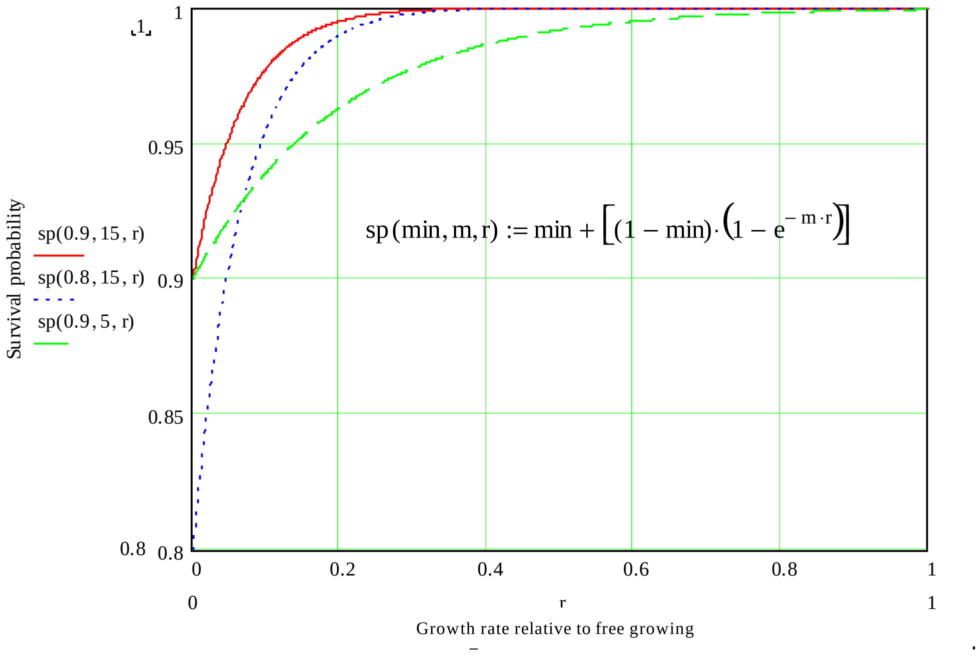


Figure 64. Relationship used in SExI to relate survival probability to growth rate relative to free growing tree of similar size.

In addition, systematic mortality is assumed once tree crown size has reached 5% of normal crown size[1].

By default annual survival probability is a function of current growth rate relative to max growth rate given current size, i.e. it does not take into account senescence as tree approaches maximum size. Senescence may be incorporated simply by using growth rate relative to species absolute maximum growth rate (rather than growth rate relative to max growth rate at current size). Alternatively tree size relative to species maximum could be considered as an additional predictor.

The trees that don't survive enter the tree fall module.
The tree fall module deals with secondary damage due to tree fall. The direction of fall is random. Any tree smaller that 0.9 times the height of the falling tree and which is located in the area of potential damage is damaged. Area of potential damage is a sector defined by the direction of tree fall and the crown width of fallen tree and initial position of tree.

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[1] The latter might be replaced by a probability value function of CF that would look like 1-EXP (-(SRCF1*CF))

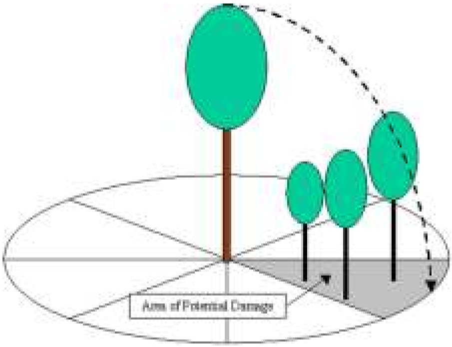

Figure 65. Diagram of tree fall sectoral damage

Potentially damaged trees less than half the size of the falling tree are either killed (in a proportion equal to a parameter referred to as secondary mortality probability parameters) or damaged. Tree damage here means a deterioration of crown form (ca 50% decrease of crown volume). This is achieved by shedding half of the VBs on one side of the crown.

5.1.8 Reference Tree

Reference tree is a tree which grows in an optimum environment (isolated). The tree is grown for a number of years, and its various features (dbh, height, crown size, etc) are stored in an array. The relation between dbh and other dimensions of reference tree is sometimes referred to as “normal” relation.

When computing reference dimension value for a particular dbh “local” Lagrange interpolation method is used. The interpolated polynomial is calculated from the 3 closest value indexes. This procedure is meant to avoid large interpolation error on curve shape by linear section interpolation. The fact that only 3 values are used for interpolation should avoid Runge oscillations which can become problematic with high degree polynomial interpolation (e.g. Http://sonia_madani.club.fr/Cloaque/Arithmurgistan/Interpolation/lagrange.html).

5.2 STReTCH Module

5.2.1 Introduction Statement of objectives

Despite a wide range of development strategies - architectural models sensu (Hallé et al., 1978) - all trees face the same fundamental constraints in terms of light capture and notably need to strike a balance between investment in support structure and assimilatory organs. The objective of the Stretch module is to propose a generic

model to represent crown shape flexibility in response to light and space limitations independent of the detailed tree architecture.
We reckon that a proper crown model should in particular be able to allow for the simulation of a number of “typical” development trajectories.

Responses expected to be covered by the crown model include:

- Flexible growth allocation either towards lateral crown expansion or towards growth in height depending on the prevailing light environment. Ex: a sapling growing slowly (with limited crown development) in the understorey until a gap occurs in the canopy above it, the successive release in growth (“rush towards the light”) and the subsequent vigorous lateral expansion of the tree crown once the tree has reached the upper canopy (or possibly its death if the canopy gap closes by lateral growth before the tree makes it to the top).

- The model should be able to reproduce the change in crown ratio (crown depth / total tree height) as well as the change in height / dbh allometry coefficients observed for trees under different planting densities.

- The model should also be able to simulate the asymmetric growth resulting from row planting which allows an efficient occupation of space without significant decrease in overall tree growth rate (cf. low sensitivity of rubber dbh increment to planting pattern for a given planting density).

In the Stretch approach the crown is represented by a growing deformable solid. This expanding polyhedron is defined by a set of vectors (later referred to as “Virtual Branches”) all stemming from the crown base.
The growth rate of those Virtual Branches (VB) is a function of (local) light conditions (local response) and their relative position (to capture the crown elongation a species specific characteristic). The way in which VBs are affected by (local) light conditions or constrained by their relative position within the crown is species dependent.

5.2.2 Ecological basis Biological Principles

While overall growth - as captured by the dbh increment will decrease under sub-optimal or supra optimal light levels, crown shape may also be affected by sub-optimal or anisotropic light and in return affect overall growth performance. Two major mechanisms may contribute to crown shape alteration under specific light conditions.

A. Local asymmetric competition between branches within a tree.
The so-called branch autonomy theory states that the local carbon balance between production and demand for growth and respiration determines the fate of the branch and notably whether it will be shed. However there is increasing evidence that such a simple view is not tenable (Henriksson 2001, Sprugel 2002, Lacointe et al., 2004). Notably it was shown that the light level at which a branch will be shed depends on the relative light level (to the rest of the crown) rather than the absolute level of light experienced. Even though dominant trees have more resources to allocate, branches on suppressed trees are able to grow and produce new foliage at solar irradiances where branches on dominant trees die. Thus branches are sufficiently interdependent that a positive carbon budget by itself does not ensure branch survival; branch position relative to other branches on the same tree is also important (Sprugel et all, 2002). Furthermore, the increased growth of non-shaded branches in trees where only two branches were shaded suggests that resources were preferentially allocated to branches in more favourable positions (Henriksson 2001). Hence we expect that local deformation of a crown (for example the opportunistic development of a part of the crown in response to local abundance of light side gap, row planting etc will be better modeled as a combination of the overall growth potential modulated by local gradients.

B. *A whole tree active shade avoidance response* under low light (notably lateral shading) by which crown growth is reoriented towards height at the expense of lateral growth and which is commonly observed under high tree population density or low light levels. This response may result from a combination of biological mechanisms. Relative or absolute increase of growth in height may also be a response of internal competition of allocation of “growth potential” within the crown as a decreasing gradient of light (or space) availability from apex to base is common. Hence the distinction made here between global or local response is somewhat arbitrary and is made for operational purposes. Vertical light gradient of increasing intensity towards the top of the canopy is not only common under dense planting where overhead light is abundant while lateral light is very much restricted but also in the forest understory where a similar gradient (though probably less pronounced) may prevail in many cases (Montgomery and Chazdon 2001). Hence new leaves are produced where light resource is most abundant (a local response) which translates into a global deformation of the crown: only the upper-most part of the crown receives adequate light to maintain active growth and therefore elongation of crown occurs.

The strategy of "compression" in the understorey and accelerated growth under gap as described in (Sterck 1999) for example would indicate that for canopy species

whose juveniles start to grow in the understorey, the relevant signal to trigger accelerated growth in height might be the light gradient rather than the light level. It has been shown that poplar trees can alter their growth rates under modified red / far red ratio and noticeably increase their relative growth in height (Gilbert et al., 1995). This may be a widespread response to shading (Ritchie 1997). Our measurements of hundreds of trees belonging to a dozen species growing either in dense plots while receiving overhead light or overtopped in the understory reveal very similar overall h-dbh alteration (ICRAF unpublished). Hence overall light level is the environmental cue used in SExI to model vertical stretching of tree.
A number of casual observations suggest that crown rise is accelerated by increased light gradient (e.g. durian with low branches until it reaches the upper canopy and emerges, shorter rubber trees with reasonable crown depth under dense stand of rubber trees themselves having the crown reduced to the most extreme top of the tree). This would illustrate a change in growth strategy (growth allocation pattern) in response to gap opening for example. In the proposed implementation of the model increased slenderness will force crown rise.

5.2.3 Crown shape modeling

a. Analytical framework

Crown development is decomposed into vertical extension and horizontal extension of VBs (“Virtual Branches”), and light may affect each directional component differently.

Growth of an individual VB will depend on:

1. Overall growth potential: Individual VB growth will depend on the overall (potential) crown volume increment associated with dbh increment (which notably depends on overall light limitation). The relationship between crown volume increment and dbh increment is controlled by h-dbh and dbh-CW power relationships[2].

2. Species crown profile (default implementation is half ellipsoid): in order to maintain the general shape of crown profile (ellipsoidal, conical, paraboloid of revolution,etc) in the absence of deformation due to competition, the growth of any VB is a function of its relative position in the crown.

---

[2] Dbh-CW is entered by user as a bilinear relationship linear from 0 to 0.05 m dbh and then from 0.05 to max dbh but is re-implemented as a power function to avoid discontinuity problems

3. Vertical stretching resulting from reallocation of growth from lateral expansion to height increase (a response to the light gradient) it is constrained by species specific plasticity (flexi). Vertical stretching of crown is done by co-limiting its lateral extension through associated limitation in dbh increment assuming that total stem biomass scales isometrically with the product of stem cross sectional area and tree height. Crown size is further reduced (shedding lower VBs) via the relationship linking maximum crown volume to dbh established for free growing trees.

4. A local deformation factor. The impact of local light level (spatial heterogeneity of the incoming light = light anisotropy) is modeled by modulating the horizontal extension as a function of the relative (to average) illumination of light sector associated to each VB. The degree of crown plasticity is assumed to be identical to flexi and is hence species specific. Some additional species-specific parameter might be necessary to refine species differences. This flexibility can be adjusted through the amplitude of the sectoral light used to define the local light level (the larger the sector the lesser the difference in light perceived by neighbouring VBs)

b. The Algorithm

Vertical stretching of crown

Compute vertical and horizontal growth component of VBs of reference tree based on species specific shape and actual overall growth reducers.

Computation of stem height and dbh increments are described in section 2.3 Height Increment. Those values are then used to compute crown stretching by computing. VB increments based on crown profile.

Half ellipsoid profile

(vi_a) VB_incr_ver=cos (theta) * height_inc

(vii_a) VB_inc_hor= sin(theta) * CW_increment

theta is the angle of VB with vertical, and CW_increment is calculated in the following way (i.e. replacing the experimental bilinear relationship between dbh and CW with a power function to avoid discontinuity).

<u>Step 1.</u> Using the parameters of the estimated linear relation between CW and dbh which holds for dbh>=5 cm, compute (x1,y1) (x2,y2) the coordinates of the points of the curve CW=f(dbh) where:

X1= 0.05, y1=0.05*b+a, x2=dbhmax, y2=dbhmax*b+a

Step 2. Compute the corresponding A and B parameter values of the power function such that CW=A*dbh^B

$$A = \frac{-\log[y1] + \log[y2]}{-\log[x1] + \log[x2]}$$

$$B = e^{\frac{-\log[x2]\log[y1] + \log[x1]\log[y2]}{\log[x1] - \log[x2]}}$$

Step 3 Compute the crown width increment as the expected crown increment for the normal tree given the current dbh hence

CW increment = A*((dbh+incr)^B-(dbh^B))

If the tip of a VB is inside a neighboring crown the horizontal component of growth of that VB is set to 0 (but height increment is still applied to ensure decent crown profile).

Conical profile
Assumptions identical to above (implicit assumption: dbh =dcbh)
To maintain conical profile we compute the expected displacement (absolute increment) of all VBTips as a function of height growth and lateral extension of crown base.

Let H be the crown depth length and L the expected (not necessarily equal to actual!) crown radius at crown base for previous dbh (before current time step increment), then expected VB length of angle with vertical is

l= (sin / L + cos / H)^-1

let L'=L + height increment and H'= expected crown radius at crown base for new dbh (previous dbh + dbh_inc) then expected new length of VB with angle with vertical is

l'=(sin / L' + cos / H')^-1

and the current increment in length of VB of angle is computed as l'-l

Where L= (a*dbh +b) / 2

Lateral deformation of crown

Based on the sky map and the light model adjust VB_inc_hor only for anisotropy of incoming light. At this stage we assume that the number of VBs per tree is fixed and set to the following:

Default number of VBs on vertical direction is 15 (6 degrees each), and 15 Vbs for lateral direction (12 Degrees). Then the default number of azimuths of the sectoral light map is set to 15 (same as the number of VBs for a given inclination. The number of inclinations of the sectoral light map is set to 5 (equal to number of inclination in the light model, medium precision). Orientations of VBs is randomized by choosing the first VB randomly.

Note: *Number of VBs and sectoral light resolution is not accessible to user*

```
Sectoral map calculation algorithm outline
If
        number of sectoral_Map azimuths is less than number of light_model azimuths  or number of sectoral_Map inclinations is less then number of light_model inclinations
then
        for each sector of sectoral light map, find all light model sectors which intersect with the sector of sectoral light map. Then set the value for the selected sector of sectoral light map  as the average of intersected light model sectors value.
Else
        Set the sector value of sectoral light map to the value of the closest sector of light model.
```

For each of the (15-1) * 15 VB directions (excluding vertical VBs) we compute an index of efficient lighting for each direction and the average value of the index. Note that this is done for all directions (whether there is or not a corresponding VB alive).

The ratio of this light level to the average light level is used to adjust the horizontal component of growth for each growing VB.
Note that whether there are VBs missing or halted does not affect the deformation of the remaining Vbs. Also note that the growth modifier may theoretically reach values as high as the number of directions! This would happen in case all directions but one have effective light of zero (completely opaque) in which case the growth

modifier for the only growing VB would be equal to the effective light of that particular azimuth / average effective light = number of azimuths. Such extreme cases are however not possible with the default parameterization due to built-in correlation between the levels of light perceived by adjacent VBs (overlapping of sectors). Finally extreme departure from the mean value are only likely to occur when a large majority of VBs perceive very low light levels which is necessarily associated to low CP and low overall growth and hence individual growth of VBs should remain within reasonable boundaries.

Let G(i) be the standard growth rate (equal for all azimuth) computed in previous step.
Let L(i) be the sectoral light associated to VBazimuth i.
The following algorithm is used to adjust G(i) to L(i).

Step 1

"Effective" light level L'(i) is first computed for each VB direction as:

```
If $L(i) > optilum$
    then $L'(i)= optilum$
    else $L'(i)=L(i)$
```

Step 2

For all VB present, not halted by collision, and receiving sufficient light (see section 5.2.4 on step 1 for details and notably additional condition that limits the total crown surface that may be lost in one time step through shedding due to low light) G'(i), the modified growth rate is computed as:

```
If $L'(i)>AVG(L'(i))$
$G'(i)=G(i)*(1+flexi* (1-(AVG (L'(i) / L'(i)))^sensi))$
IF $L'(i)<AVG(L'(i))$
$G'(i)=Max(G(i)* (1-flexi* (1-(L'(i) / AVG (L'(i)))^sensi)),0)$
```

The above formulation is consistent with the way flexi and sensi are used to implement whole tree response to shading. Flexi essentially controlling the maximum departure from reference (here symmetric) growth, and sensi an index of sensitivity to shading either local or global.

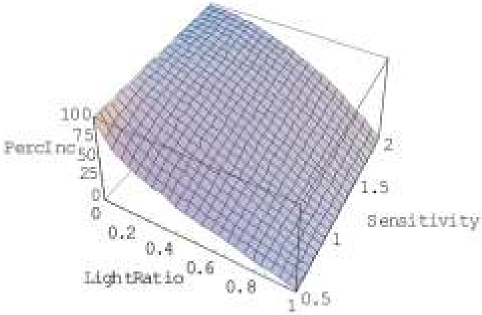

Figure 66. Percentage increase in VB extension in high light microsites as a function of sensitivity and light ratio (average light / local light). flexi=1

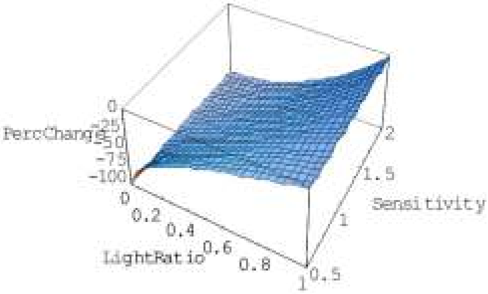

Figure 67. Percentage change (decrease) in growth rate of vertex as a function of light ratio (local light / average light) and sensitivity when local light is less than average light. flexi=1

Finally if VB is inside neighboring crown (i.e. has intruded a neighbouring crown G'(i) is set to zero (no growth through neighbor's crown envelope).

5.2.4 Branch shedding

Branch shedding always starts with lower most VB in any azimuth.

1. A first test for VB survival is made prior to VB growth. If VB sectoral light-level is below a certain threshold then it is dropped. Threshold light level at which lower most VBs are shed is set to be equal to minimum.

2. Once VB have grown the crown surface is checked against the expected crown surface (cf allometric relation between dbh and crown volume in reference open grown trees). In case current crown surface is above reference crown surface additional selective branch shedding will occur until crown surface is reduced to the maximum possible crown surface. VBs are dropped one by one starting with the VB receiving the lowest light (comparing lower most vb along all azimuths). As an alternative crown volume may be used instead of crown surface as a measure of crown size. The procedure is similar to using crown surface as a control. First, each VB is assigned a weight approximating its contribution to crown volume. The elementary volume associated to a VB used to compute is weight is the volume of the 2 tetrahedra defined by the three vertices defined by the closest 3 neighbouring VBs. left, right and top neighbours, and the target VB itself. The weight of a VB is then computed as the sum of the elementary volume assigned to it to the sum of all such elementary volumes. When a particular VB is dropped the total crown volume is reduced proportionally to the weight of the shed VB.

Notes:

- *If systematic crown rise of reference tree occurs, it should be specified through the graphic user interface can.*
- *NO significant crown overlapping is tolerated in the model except for possible in-growth of a tree within a larger overhanging crown.*
  At present a species with low flexibility and high shade tolerance will show higher crown boldness as it will retain its VBs longer and fail to reallocate growth preferentially to well lit VBs. Differential "crown shyness"[3] could further be controlled by limiting the number of steps a VB may survive if prevented from extending laterally. As a consequence species tolerant to low light may in fine be even more tolerant to crown collision as they may be halted only temporarily and resume growth once the other crown has shed its branches.
- *At each time step VBs are resampled (along a set of fixed directions) and VB tips new position interpolated from previous VBs positions. If VBs are missing, the lower most remaining VB is always located along the vector immediately below (larger angle with vertical) the existing VB at the same distance from tree vertical axis. If all VBs along a particular azimuth have been dropped a new VB is regenerated with length equal to average length of all VBs of same inclination.*

5.2.5 Collision detection

Collision determines halt of growth of VB. The collision between neighboring crowns is detected if there is intersection between the horizontal vector joining VB tip to tree crown vertical axis and any triangle defined as a result of triangulation of VB tips location in 3D of neighboring trees.

Note that as a result of this implementation vertical growth rate of tree top apex is not affected by collision. However the VB growing from inside another crown will be halted if they come to intersect with containing crown envelope.

---

[3] Note that crown shyness is used here to refer to the reaction of a tree crown colliding with another tree rather than in the more restricted meaning it usually refers to ("individual subcrowns and crowns which grow clearly separated from one another, with intervening vegetation-free borders; most common in single-specie and single-cohort stands and in stands on windy sites"). Two primary hypotheses have been put forth to explain canopy shyness - the first that wind-blown branches abrade each other at tree boundaries and damage buds, preventing leafing, and the second that mutual shading at the boundaries of trees prevents growth (Putz et al., 1984) and see Rudnicki et al., (2003). "Stand structure governs the crown collisions of lodgepole pine." Can. J. For. Res. 33(7): 1238-1244..

5.2.6 Triangulation algorithm

A proprietary triangulation algorithm is used which takes advantage of the fact that VBs are regularly spread and notably that on a given azimuth there can be no missing VB between lower most VB and apex.

Let n be the number of azimuth and p the number of inclinations. The total number of VBs (including apex) in a full crown (no missing VB) is then n*(p-1) + 1 and the associated number of triangles is n*(2(p-2) + 1)=n* (2p-3).

Each time a non-vertical VB is dropped, so are two triangles as can be seen from the algorithm below and illustrated in the figures.

The algorithm:

Let H(i,j) be a VBTs height at inclination index i and azimuth index j. (Assuming that each VBTs has height and horizontal distance from axis).

i = 0 is the lowest VBT for each azimuth direction.

The following algorithm iterate the VBTs through the inclination index on the two following series of VBTs per azimuth directions H(Ia, Jc) and H(Ib, Jc+1).

Step a:

For each increments of Ia and Ib, start from a=0 and b=0, find Min(H(i1, Jc), H(i2, Jc+1)) , store the result as one of triangle element. If the lowest VBT is in J series then a++ else b++ (increase one step).

Find next element Min(H(i1, Jc), H(i2, Jc+1)), store it (VBTs with the same index) as the second element of triangle.

Step b:

If the two stored triangle element is on the same series of azimuth then the third element should be the lowest element on opponent series.

Else increase the i of the lowest VBT series and find next Min(H(i1, Jc), H(i2, Jc+1)) as the third element of triangle.

Store the last two elements of the previous triangle as the elements for the next triangle.

If there is more than 1 VBT left in both series then Go to step b.

Else put the last VBT as the third element, and Repeat from step a for the next j (azimuth direction index; j++).

Note: *the algorithm below is used for triangulation of semi-irregular VBs location (previous crown type algorithm). And it's quite robust.*

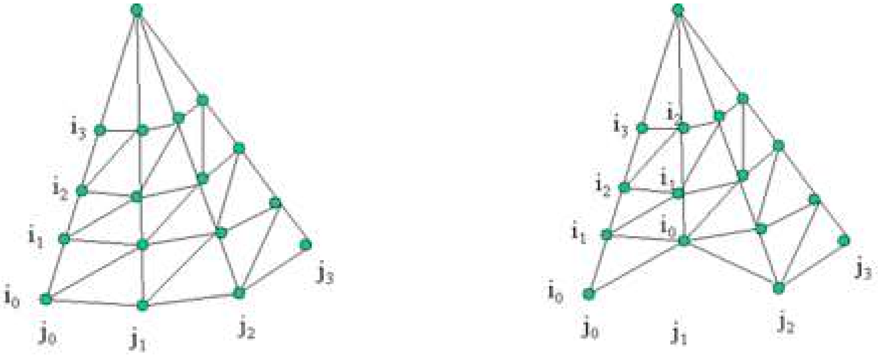

Figure 68. Left figure shows the initial VBTs connection (subpart of a crown VBTs); right figure shows the VBTs connection after a VBT shed at i=0 and j=1. the series of VBTs at j1 then re-indexed for i.

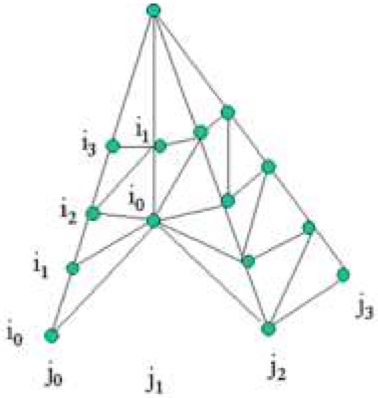

Figure 69 Connection after a VBT shed along the same line

5.2.7 Algorithm for crown volume computation

Volume of the crown is calculated as the sum of all connected tetrahedra, one face of which is a triangle of the crown envelope (as a result of the triangulation described above). Each triangle is then connected to the center of crown base (added to each triangle as one other vertex to form a tetrahedron).

Then tetrahedron volume is calculated using the formula below:
Let the tetrahedron be specified by its polyhedron vertices at (x_i, y_i, z_i) where i=1, ..., 4. Then the volume is given by:

$$V = \frac{1}{3!}\begin{vmatrix} x_1 & y_1 & z_1 & 1 \\ x_2 & y_2 & z_2 & 1 \\ x_3 & y_3 & z_3 & 1 \\ x_4 & y_4 & z_4 & 1 \end{vmatrix}$$

(http://mathworld.wolfram.com/Tetrahedron.html)

5.2.8 Crown deformation and the pipe model theory

We may need to explore further the application of the pipe model in order to link more formally crown volume and dbh values.
To maintain consistency between overall crown volume and tree diameter we further assume that leaf area and stem cross sectional area are linearly related. This allometric relationship based on the functional relation between sapwood area and leaf area, is expected to be robust (Morataya et al., 1999) and hold under the following provisions:
a. Stem diameter is measured just below crown (instead of breast height).
b. Relationship is location specific (under different evaporative demand this relation may be significantly altered).

Then LA is further broken down into crown volume and leaf area density (per unit volume). Assuming LAD to remain stable across time and space within a particular tree this implies that we can extend the allometric relation between stem diameter and LA to stem diameter below crown and crown volume (or crown surface if we consider that leaves are predominantly located on a thin layer on the outer most side of the crown). This relation is used to enforce branch shedding under extreme deformation (elongation) of tree in response to light gradient, i.e. as crown volume is constrained the lower most branches are shed.

A tapering equation could be used to link dbh and diameter below crown so that the assumption of linear relation between stem cross sectional area and leaf area would be more robust. In first approximation a conical truncated shape may be used (based on data collected by Hubert de Foresta in Krui for example) for the part between diameter at breast height and diameter at crown base height (but see also, for a discussion of the various approaches that may be used, http://sres.anu.edu.au/associated/mensuration/shape.htm#equation).

In fact the model should be able to compute cross-sectional area of stem at any height based on any kind of stem profile if such information is provided by user. This could be implemented simply using numerical approximation to compute deltadb-h and delta-h in the Stretch module.

6. Calibration Procedures

Below are some guidelines and examples on how to collect tree data to be used for calibrating the SEXI-FS model, with emphasis on the STReTCH module (crown deformation).

6.1 Allometric Data

The purpose is here to define relationship between various tree dimensions and how those allometric relationships are affected by tree environment

6.1.1 Tree selection

Trees from the following three categories are purposefully sampled over the whole range of diameter of interest (e.g. 5 to 50 cm dbh); all trees should have a CF score > 3.

The three categories considered are:

- Isolated trees
- Co-dominant trees in dense stands (usually pure stands) i.e. CP>=4
- Suppressed trees (CP<=2)

6.1.2 Tree parameters to be measured

- Tree height (h)
- Height of crown base (hcb)
- Height of maximum crown width (hmcw).
- Height of maximum crown width may coincide with height of crown base. The height of maximum crown width (a shape parameter) is used to compute crown volume.

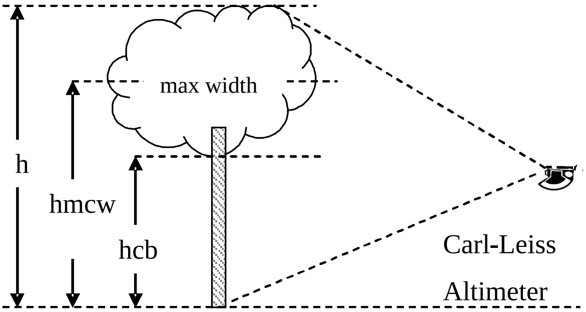

Figure 70. Height measurement

- Crown width
  Crown diameter is measured in two perpendicular directions. Crown projection

diameter is first measured along maximum crown width axis and then perpendicularly to this first direction. The average is used for crown width (Figure 71).

For the purpose of recording the whole stand into SExI-FS and get more accurate prediction of crown width, the radius projection of crown can be measured with more then 4 direction. Figure 72 shows how the eight radiuses are measured while also keeping the relative direction angle info.

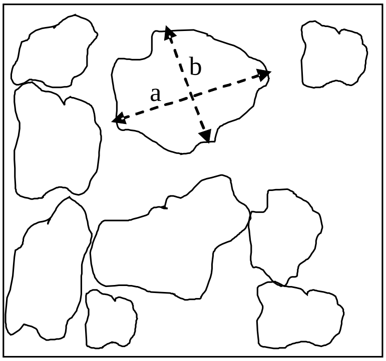

Figure 71. Crown width measurement

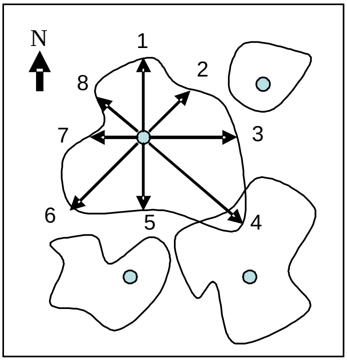

Figure 72. Crown radius measurement

- Crown Position (CP)

The crown position index, which depends on the relative position of the crown within the canopy, reflects the light conditions prevailing at a particular moment (Figure 73). Crown Position scale is defined as follows (Alder and Synnott 1992):

5 = Emergent: Crown plan exposed vertically and free from lateral competition at least within the 90° inverted cone subtended by the crown base.

4 = Full overhead light: Crown plan fully exposed vertically but adjacent to other crowns of equal or greater height within the 90° cone.

3 = Some overhead light: Crown partially exposed vertically but partly vertically shaded by other crowns.

2 = Some side light: Crown plan entirely vertically shaded but exposed to some direct

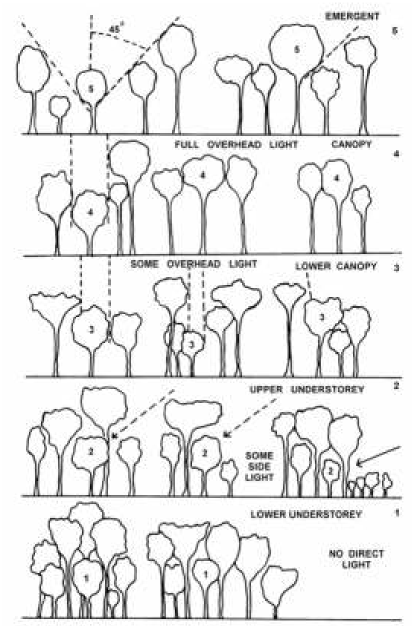

Figure 73. Dawkins crown position classification (in Alder and Synnot 1992)

light due to a gap or edge of overhead canopy.
1 = No direct light: Crown plan entirely shaded vertically and laterally.

- Crown Form (CF)
  The Crown Form index tries to capture the photosynthetic potential of a tree. It is an architectural characteristic and will tend to reflect the development history of the tree (Figure 74). Crown Form scale is defined as follows (Alder and Synnott 1992):
  5 = Perfect. The best size and development generally seen, wide, circular in plan, symmetrical.
  4 = Good: Very near ideal, sylviculturally satisfactory, but with some slight defect of symmetry or some dead branch tips.
  3 = Tolerable. Just sylviculturally satisfactory, distinctly asymmetrical or thin, but apparently capable of improvement if given more space.
  2 = Poor: Distinctly unsatisfactory, with extensive dieback, strong asymmetry and few branches but probably capable of surviving.
  1 = Very Poor: Definitely degenerating or suppressed, or badly damaged, and probably incapable of increasing its growth rate or responding to liberation.

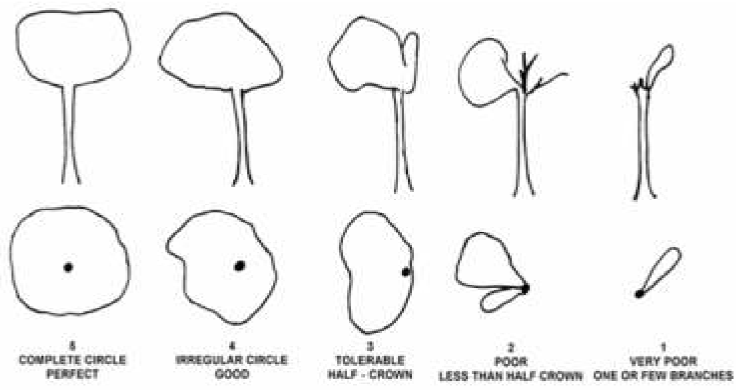

Figure 74. Dawkins crown form classification (in Alder and Synnot 1992)

- Crown porosity (isolated, dominant, co-dominant trees)
  Crown "porosity" to light is defined as the percentage of sky visible from below the crown and is simply assessed using sub-vertical photographs towards the sky. Best time to take good quality photographs is early morning or under heavily overcast skies (no direct sunlight). Low branches can make pictures of the entire crown difficult or impossible, as we can't move back far enough to capture the whole crown. In that case it is recommended to beginners to take a series of

pictures of parts of the crown, in a systematic pattern. Once experienced, selection of a representative part of crown in the field is a more efficient way of doing. In most cases selection of a representative portion of crown (which can be the entire crown once it has been delineated on the photograph but is more commonly restricted to half a crown excluding the tree trunk) will be done by cropping part of the digitised image on the computer.

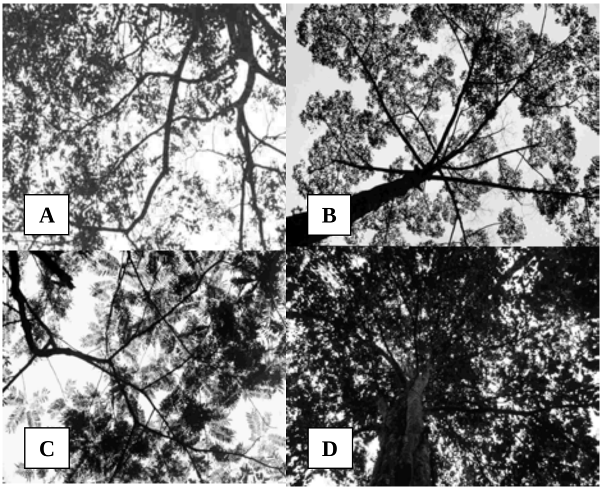

Figure 75. Crown porosity of *Pterospermum javanicum* (A), *Shorea javanica* Koord. et Valeton (B), *Parkia speciosa* Hassk. (C), and *Lansium domesticum* Correa (D).

Once a representative portion of the crown has been selected and cropped the picture is converted into black and white bitmap format in order to assess the percentage of visible sky. Image thresholding (deciding which level of grey defines the limit between black and white i.e. between tree parts and the sky) is the critical step. Most image processing software offer facilities that allow instant comparison between the original image and the classified image which provide some control over the quality of the thresholding step.

Note: *crown porosity cannot be measured on trees growing in the understorey. This may be problematic as there are indications that tree porosity is responsive to tree growth environment and may be significantly lower in shaded trees than trees fully exposed to light.*

6.1.3 Tree growth environment

When relating tree dimensions to its growth environment care should to be taken in making sure that the current environment does reflect the growth environment of the tree (which may have changed over time through self thinning, tree fall creating gaps, differential growth rates in height affecting CP, etc).

Local density and local basal area are recorded by measuring the trees growing in the vicinity of the target tree. A tree is recorded if its dbh is >= 5 cm.

A circular plot with radius rmax around the target tree is defined with:
rmax =max(r1,r2)

Where r1 is defined as the maximum crown width of target tree and r2 equals the distance to the furthest tree in physical contact with target tree.
If rmax=r1 then local density is simply computed as total number of trees divided by plot area (Pi*rmax^2) by and local basal area as the sum of all cross sectional areas of individual trees divided by plot area.
If rmax=r2 then local the furthest tree (which defines the plot radius) is counted as half inside and half outside the plot and hence given a weight of 0.5 both when computing density and basal area.

Note: *in case of regular planting (which for example may be the case for rubber plantation) the elementary plot may be delineated as a rectangle (which is quicker in the field) including all 8 "neighbouring" trees (two on the line and the three trees on each neighbouring planting line). In that case the plot area is simply defined as 9 times average planting distance.*

For all trees within a circular plot, the following three variables are recorded: tree species, tree diameter, whether the tree neighbouring tree crown is in contact with target tree crown is (Boolean).

6.2 Data processing

6.2.1 DBH-Crown diameter

DBH and crown diameter are related by linear regression. Data from the various groups are pooled to establish this relationship. It is useful however to check that groups do not differ significantly (biologically meaningfully rather than statistically). If scaling appears not to be isometric, log-log regression may be used assuming a power relation between crown width and stem diameter.

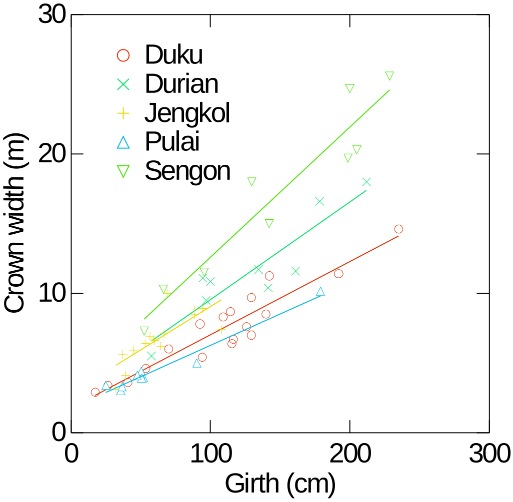

Figure 76. Girth-Crown diameter relations

6.2.2 DBH-Crown surface

Assuming a half-ellipsoid approximation of the crown profile we then compute the approximate crown surface as

```
e = (1-(cr*cr) / (cd*cd))^0.5;
if(cd > cr) {
        crown surface = PI*cd*cd + PI*cr*cr / e*ln((1+e) / (1-e));
} else {
        crown surface = PI*cr*cr + PI*cd*cr / e*arcsin(e);
}
```

where *cd* stands for crown depth (total height height of crown base) and cr is crown radius (half of crown width).
see http://mathforum.org/library/drmath/view/51743.html for derivation of the formula of surface area of an ellipsoid.

Then estimated surface (or volume) is fitted to dbh; a loglinear fit is usually satisfactory (as total leaf area is expected to scale linearly with stem cross sectional area e.g. Morataya et al. 1999).

Again we expect this relationship to vary little between groups (which can be tested by ANCOVA) and data for the various groups should be pooled for this adjustment to increase robustness of parameters estimates.

Note: *multilayer trees (sensu (Horn 1971) which are rare in our data sets) are likely to show a more consistent linear fit between crown volume and dbh rather than crown surface. This may be explored using the estimated volume of crown computed as 1/3*Pi*cwa *cwb*CD (half ellipsoid), where cwa and cwb is crown width measured twice perpendicular (see tree parameter measured on section 6.1.2).*

6.2.3 Estimation procedure of the flexi parameter

Objectives
We are interested in assessing the change in the slope (derivative) of the height-dbh relationship observed in trees of various species when grown either isolated or in dense stands. In the SExI-FS model, this corresponds to the *flexi* parameter (precisely the ratio of the derivatives is equal to *flexi +1*)

Data
We assume we have two tree population samples measured in contrasted conditions (i.e. isolated or in dense stands). We further assume that the “dense stand” sub-population may be considered representative of the most extreme conditions, i.e. we capture most of the species possible range of growth conditions. In case the height-dbh relationship of either of the two subpopulations shows a strong dispersion an envelop curve analysis could be used (e.g. stochastic frontier functions may be used

instead of standard regression; see free software at: http://www.uq.edu.au/economics/cepa/software.htm) but has not used in the present study.

We use the data collected by ICRAF by mid 2004 for 6 species for which sample size seems suitable (*Lansium domesticum, Hevea brasiliensis, Durio zibethinus, Archidendron jiringa, Alstonia angustiloba, Paraserianthes falcataria*).

Methodology

Step 1: graphical analysis and data transformation

Assuming that the dbh-height relationship may be correctly described using the following relationship: height=a*dbh^b, data are first log transformed and plotted using linear smoother. We visually check that the log transformation is fine (graphical analysis of residuals may help pinpoint possible problem such as heteroscedascity or unwished pattern in the residuals).

Step 2: first parameter estimates

For most species it can be seen that the regression lines of the two sub-populations are almost parallel and we therefore choose to analyse data using a GLM where sub-population differ only in terms of their intercept (i.e. assuming homogeneous slope). In one case (*Paraserianthes*) this assumption is clearly not met but this may be due the data set used as a single very dense evene-aged plot was sampled.

From the model above we estimate three parameters for each species (a1, a2 and b).
And the ratio of the derivatives are equal to the ratios of the a1 and a2 parameters if b are identical leading to the estimates for the different species reported in Table 1.

Rerunning the equal model without those two outliers yielded similar estimates for sensi. (Marked with an asterisk in table beside)

Table 1. Estimates of flexi parameter for 6 species used in SExI-FS model

Species	group	Log(a)	a	Sensi + 1
Lansium	isolated	0.582	1.78961408	
	dense plot	0.932	2.53958327	**1.42**
Durio	isolated	0.399	1.49033362	
	dense plot	0.799	2.2233165	**1.49**
Archidendron	isolated	0.84	2.31636698	
	dense plot	1.41	4.0959554	**1.77**
Hevea	isolated	0.963	2.61954333	
	dense plot	1.275	3.57870141	**1.37**
Sengon	isolated	0.853	2.34667633	
	dense plot	1.441	4.22491862	**1.80**
Alstonia	isolated	-0.006	0.99401796	
	dense plot	0.268	1.30734714	**1.32**

Note on crown deformation parameterisation: *crown asymmetry resulting from neighborhood competition is commonly observable and has been measured (Brisson 2001). However we have not yet attempted to directly measure the parameter governing the ability of a crown to adjust to lateral anisotropy of resources due to difficulties involved in standardizing such measures. One favourable situation which may occur with planted species would make use of crown deformation response of trees growing under different planting patterns (i.e. inter-row, and on the row inter-tree distances). Rather, we make the assumption that flexibility in tree height adjustment (ratio of k value in the height-dbh relationship under contrasted vertical gradient) is a good proxy for the ability of a species to adjust its crown expansion under lateral anisotropic distribution of light.*

6.3 Growth Data

Permanent sample plot data are used to derive the following parameters

- Species potential growth function (site specific)
- Species sensitivity to shading
- Species sensitivity to tapping
- Species influential zone (determining BGCI)

6.3.1. Potential growth function

Standard procedures are used to analyse data from Permanent Sample Plot (see for example Alder and Synnot 1992, Vincent et al 2001 for an introduction to such methods). Predictors used in the GLM include size, crown indices (and tapping regime). Rare species (< 10 individuals monitored) are grouped into a miscellaneous grey species for the data analysis purpose. Once factors effect are estimated, potential growth is computed after correcting for CF, CP, Tapping index (and possibly BGCI / Below Ground Crowding Index).
Corrected dbh increment is used to adjust the dbh_inc=f(dbh) using a Chapman Richard function with standard non linear regression procedures.

Using precisely the method described above on PSP sample plot for rubber and comparing the growth rate as a function of size obtained from Sembawa plantings, we can observe that the patterns are not consistent. Essentially, data from PSP provide an estimate of maximum potential growth which is strictly decreasing with tree size whereas data from Sembawa density trial indicate that maximum growth rate may be attained later in case of low density (6x6 planting pattern).

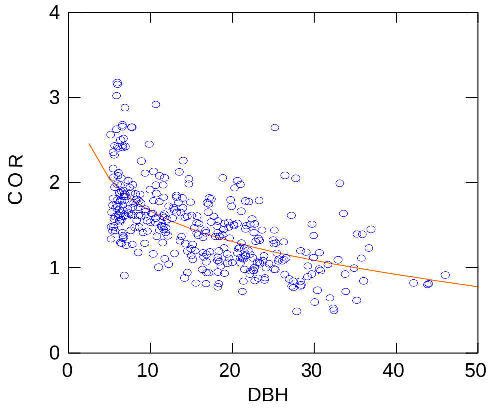

Figure 77. PSP standardised dbh increment data (computed for CF 5, CP 3 and no tapping) in cm per year

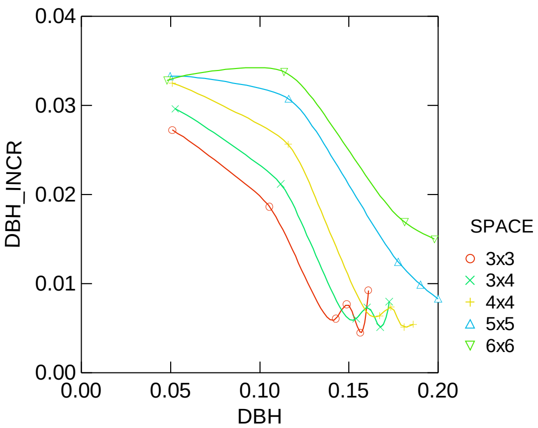

Figure 78.Density trial (annual dbh increment in m per year, plot average values, tapping starts around 0.15 cm dbh)

This strictly decreasing growth rate with size found in analysing the PSP data (instead of the expected typical increase and decrease in growth rate) is probably at least partly due to the fact that the monitoring starts at about the size when the rubber reaches its maximum growth. Early growth (needed in the model if we want to simulate growth starting at diameters less than 0.05 m) cannot be directly estimated from PSP data but need to rely on additional measurements, this was done by using data from other experimental plots where growth of seedling was measured starting from planting.

Why should “maximum potential growth” decrease faster in PSP - even after increments have been corrected for CF, CP and tapping - than what is observed in low density plantation trials? There are at least two possible explanations. The first one is that below ground competition (which we have not corrected for) is stronger in PSP (mature agroforest) than in young plantations where it is minimal during the earlier stages. A similar conclusion, i.e. that below ground competition most probably limits early growth of rubber saplings grown in rubber agroforest was reached after careful comparison of growth of rubber plants under artificial shading and under live canopy (Vincent et al. in prep).

However, such an explanation is not entirely satisfactory as high below ground competition should most likely translate into a sustained lower growth rate over the whole period of early growth and cannot be unequivocally related to a shift in maximum dbh growth rate. Another, possible explanation, is that the difference observed between rubber agroforest and young plantation reflects the fact that dbh increment in young trees growing under strong light gradient may be reduced as a consequence of accelerated height growth which occurs under limited light and which correlatively limits diameter increment. To test this hypothesis, we can test for dbh*CP interaction using the same PSP data as above. It turns out that the interaction between both predictors is statistically highly significant and that smaller trees are indeed more sensitive than larger trees to sub-optimal CP scores.

Note that the above procedure may eventually yield robust estimates only for abundant species. Hence it is preferable whenever possible to develop potential growth curve by repeated measurement of isolated trees (or low density stands).

Experience also indicates that sensitivity to shading is poorly captured in PSP data (often there is no clear species specific response) indicating that additional information should be used to estimate/check Minilum and Optilum parameter values (minimum and optimum light levels for growth). For lesser abundant species, one option is to repeatedly measure purposefully sampled trees. Sample should whenever possible include open grown trees (Crown Position=5). Sample should only include trees with optimal or near optimal crown shape (CF>=4) and cover a range of diameters. Trees should be sampled in similar edapho-climatic environment. If a decent sample of trees is available across a range of CP classes shade response (CP effect on growth) can be meaningfully estimated.

Alternative/complementary options include using scarce published literature and local ecological knowledge about the species of interest. The latter may notably yield useful ranking between species (both in term of growth rate and shade tolerance).

6.3.2. Below Ground Crowding Index (BGCI)

Usually BGCI is correlated to above ground indices (CP and CF) and in species rich PSP it may be difficult to show statistically significant growth reduction which is not yet captured by CP and CF indices. In some particular cases (e.g. limited number of species and expected contrasted competitiveness for below ground resources such as water) it may be possible to actually estimate BGCI from repeated measurements.

What we try to estimate (and which is supposedly different between species) in the present case is the influential zone of each species. In other words we assume equal sensitivity to resource shortage but differential resource capture efficiency represented by a relatively larger or smaller influential zone. Thus, the basic idea is to explore for the different species a range of species specific (and size dependent) influential zones.

The general model to be fitted for each species is:

DBH_Inc=Pot_inc+CP+CF+tapping+BGCI

In the most general case, assuming that only CF is species independent fitting the above model for a particular target species requires estimating 3 (pot inc) + 5 (CP as categorical) + 1 (tapping) + n (lambda, species specific IZ scaling factor)= 8+ n parameters. In addition CF (common to all species) needs to be estimated too.

Although this is certainly feasible it cannot be done using procedures available in standard statistical packages but requires the development of a global optimization algorithm (see Canham et al,. 2004 for such an example) which we have not done yet.

References

Akinnifesi F K, Rowe E C, Livesley, Kwesiga F R, Van Lauwe B and Alegre J C. 2004. Tree root architecture. In: Van Noordwijk M, Cadisch G and Ong C K (eds.) Below-ground interactions in tropical agroecosystems. Concepts and models with multiple plant components. CABI publishing, p 61-82.

Alder D, Synnott T J, 1992. Permanent sample plot techniques for mixed tropical forest. Tropical Forestry Paper 25, Oxford Forestry Institute -Department of Plant Science, Oxford.

Brisson J. 2001. Neighborhood competition and crown asymmetry in Acer saccharum. Can. J. For. Res./Rev. Can. Rech. For. 31, 2151-2159.

Canham C D, LePage P T, Coates K D. 2004. A neighborhood analysis of canopy tree competition: effects of shading versus crowding. Canadian Journal of Forest Research Revue Canadienne De Recherche Forestiere 34(4): 778-787.

Gilbert R, Seavers G P, Jarvis P G, Smith H. 1995. Photomorphogenesis and canopy dynamics. Phytochrome-mediated proximity perception accounts for the growth dynamics of canopies of populus trihocarpa x deltoides 'Beaupré'. Plant, Cell and Environment 18: 475-497.

Grist P, Menz K, Thomas. 1998. Modified BEAM Rubber Agroforestry Models: RRYIELD and RRECON. Canberra, Australia, ACIAR.

Hallé F, Oldeman R A A, Tomlinson P B. 1978. Tropical trees and forests. An architectural analysis. Berlin. Springer-Verlag.

Henriksson J. 2001. Differential shading of branches or whole trees: survival, growth, and reproduction. Oecologia 126(4): 482-486.

Horn H S. 1971. The adaptive geometry of trees. Princeton University Press, Princeton.

Lacointe A, Deleens E, Ameglio T, Saint-Joanis B, Lelarge C, Vandame M, Song G C, Daudet F A. 2004. Testing the branch autonomy theory: a 13C/14C double-labelling experiment on differentially shaded branches. Plant Cell and Environment 27(9): 1159-1168.

Montgomery R A, Chazdon R L. 2001. Forest structure, canopy architecture, and light transmittance in tropical wet forests. Ecology 82(10): 2707-2718.

Morataya R, Galloway G, Berninger F, Kanninen M. 1999. Foliage biomasssapwood area and volume relationships of Tectona grandis L.f. and Gmelina arborea Roxb.: silvicultural implications. Forest Ecology and Management 113(2-3): 231-239.

Press W H, Teukolsky S A, Vetterling W T, Flannery B P. 1992. Numerical recipes in C (2nd ed.): the art of scientific computing. Cambridge University Press. p 994.

Putz F E, Parker G G, Archibald R M. 1984. Mechanical Abrasion and Intercrown Spacing. American Midland Naturalist 112:24-28.

Ritchie G A. 1997. Evidence for red: far red signaling and photomorphogenic growth response in Douglas-fir (Pseudotuga menzii) seedlings. Tree Physiology 17: 161-168.

Rudnicki M, Lieffers V J, Silins U. 2003. Stand structure governs the crown collisions of lodgepole pine. Can. J. For. Res. 33(7): 1238-1244.

Sprugel D G. 2002. When branch autonomy fails: Milton's Law of resource availability and allocation. Tree Physiology 22(15-16): 1119-1124.

Sterck F J. 1999. Crown development in tropical rain forest trees in gaps and understorey. Plant Ecology 143(1): 89-98.

Van Noordwijk M. 1999. Functional branch analysis to derive allometric equations. In: Murdiyarso D, Van Noordwijk M, Suyamto D A. 1999. Modelling global change impacts on the soil environment: Report of Training Workshop 5-13 May 1998. Bogor. IC-SEA Report No. 6, BIOTROP-GCTE/ICSEA. pp 77-80

Vincent G, Azhima F, Joshi L, Healey J R (submitted). Are permanent rubber agroforests an alternative to cyclical rubber cultivation? An agro-ecological perspective. Agroforestry Systems.

Vincent G, Wibawa G, Manurung G. 2000. Inter-tree rubber yield and growth variability. A comparison of plantations and agroforests in Sumatra - Indonesia. Indonesian Rubber Conference and International Rubber Research Development Board Annual Symposium, Bogor, Indonesian Rubb. Res. Inst.

Appendix

This manual is also complement with CD which contains some file as listed below:

- Simulation (*.s)
  A full simulation file included the tree and plot data.

- Simulation data (*.txt)
  Statistical data output is saved on this format

- Simulation setting (*.xml)
  Predefined simulation setting is save on this format

- Tree Species (*.trs)
  Tree species file is save on this file type with XML content format

- Hemiphot (*.hem)
  Hemiphot image is save on this file type with XML content format

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