



Modelling Forest Dynamics Course 2013-2014

ABSTRACT

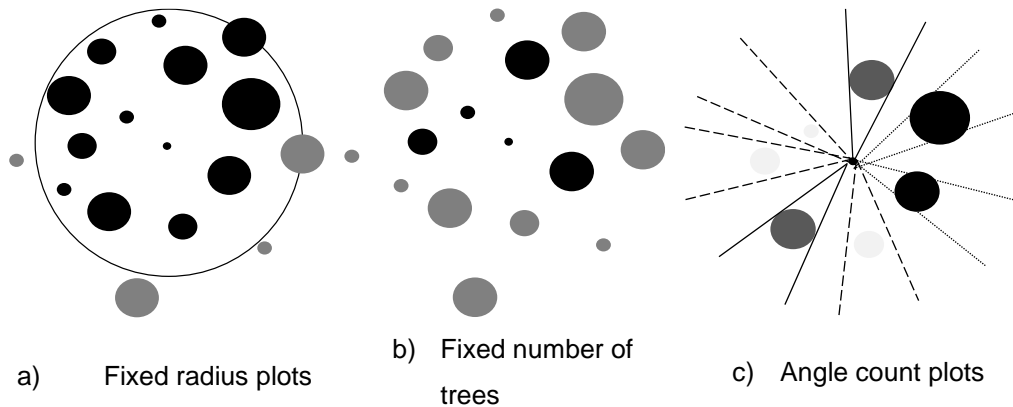
Overview description of the importance of forest inventory for growth modelling. From measuring trees to the application of different types of growth models.

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1 Evaluating Stand Variables Based on Inventory Plots

In the course of forest inventory, the objective of characterizing a stand is obtaining the values for a group of stand variables that are usually reported to the hectare. Due to the big dimensions of forest stands, in practice it is impossible to assess all stand variables through the extensive measurement of the whole stand. Therefore, stand level assessments are usually conducted through sampling. In order to carry out the sampling the definition of the population (individuals) implies one of three methods, where the circles in black represent the trees considered for measurement:

- a) Measurement of trees in plots of fixed radius;
- b) Trees' measurement in plots with a fixed number of trees;
- c) Point Sampling, Bitterlich method (*not covered in this course*).



The first method is the most commonly used because the second usually originates biased estimates of stand variables, although there is the possibility to apply correction factors to minimize the bias. The fixed radius plots' method considers the stand as a population of plots of a given shape and size for which a sample of these plots is characterized. Each of the sampled plots is assessed and dendrometric variables measured or estimated being afterwards reported to the hectare. In general terms stand variables, which are usually obtained as the sum, average or other functions of tree variables can be obtained by three alternative approaches:

- a) **Complete enumeration** – when tree level variables required have been measured in all the trees in the plot.
- b) **Sample tree** - when tree level variables are only measured for a subset of trees in the plot. (For example, total tree height is usually measured only in sample trees).

- c) **Estimates** – when the variable is difficult and/or expensive to measure it can be assessed using a regression fitted between the desired variable and other variables easier to obtain. Development of stand specific regressions require having access to a considerable amount of data from different plots which makes it more difficult to develop being generally obtained doing a bibliographic research.
- d) Before introducing the methodologies applied to assess stand variables in plots a set of plot characteristics such as shape and dimension will be considered.

1.1 The Inventory Plot

1.1.1 Plot Shape and Dimension

The most common plot shapes are the rectangle/square, the circle and the strip. The advantage of one shape when compared to another consists of the ratio perimeter/area, which should be the smallest possible to minimize the number of border trees an extremely important source of error. In theory, the best shape is the one that for the same area presents the biggest ratio. For this reason, the circle is the preferred shape (**Table 1**).

Table 1. Relationship between area and perimeter for different plot shapes and different areas.

Plot shape		Perimeters (m) for the following areas (m ²) :				
		400 (m ²)	500 (m ²)	1000 (m ²)	1256.64 (m ²)	2827.43 (m ²)
Circle		70.90	79.27	112.10	125.66	188.50
Square	<i>lxl</i>	80.00	89.44	126.49	141.80	212.69
Rectangular	<i>2lxl</i>	84.85	94.87	134.16	150.40	225.60
	<i>3lxl</i>	92.38	103.28	146.06	163.73	245.60
	<i>4lxl</i>	100.00	111.80	158.11	177.25	265.87

The issue of plot dimension is related to the fact that variation among plots decreases with the increase of its dimension. Thus, sampling error decreases with plot size. If plots are too small it is possible that having one very big tree in one plot and only small trees in other plot to increase the variance between plots. On the contrary, if the plot is big enough to capture the stand's variability, then variance among plots decreases. That is

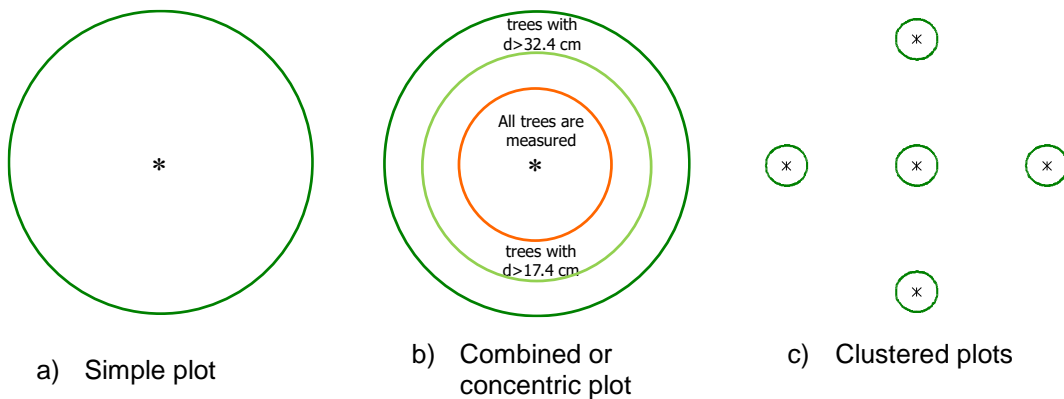
why plot dimension is closely related to stand density and homogeneity. **Table 2** shows the most commonly used plot areas in Portugal for the Portuguese main tree species.

Table 2. Plot areas by tree species.

Species	Area (m ²)	Radius (m)
Eucalyptus	400	11.28
Pine and eucalyptus	500	12.64
Pine and young cork oak	1000	17.84
Dense cork oak	1256.64	20
Sparse cork oak	2827.43	30

1.1.2 Plot Type

Different types of plots can be used in an inventory either for practical reasons or for choosing a sampling scheme that optimizes the ratio costs/precision. There are three types of plots:



In the case of simple plots all trees have their diameters measured. It is also common that only trees above a certain diameter threshold are measured (5 cm for Eucalyptus

and 7.5 cm for other species). Generalizing any Y variable to the hectare is a simple process:

$$\frac{Y}{Y_p} = \frac{10000}{A_p} \Rightarrow Y = \frac{10000}{A_p} Y_p$$

The factor $10000/A_p$, by which the Y variable obtained for a plot with area A_p has to be multiplied in order to obtain a corresponding value reported to the hectare, is called area expansion factor.

In the case of combined plots, the sampling unit is composed of various concentric circles where trees are selected to be measured according to the dimension class they belong to. Smaller trees are measured in the smaller circle and other classes are measured in successively larger plots. This was the type of plot used until 1992 in the Portuguese National Forest Inventory (NFI), but is no longer used. However it is very useful for uneven-aged stands for which the plot area required to ensure a good representativeness of big trees has to be large resulting in the measurement of high numbers of small trees.

Supposing 3 concentric plots corresponding to $d < 12.5$ cm, $12.5 \leq d < 22.5$ cm and $d \geq 22.5$ cm, the generalization of Y to the ha would be;

$$\Rightarrow Y = \frac{10000}{A_{p1}} Y_{p1} + \frac{10000}{A_{p2}} Y_{p2} + \frac{10000}{A_{p3}} Y_{p3}$$

Where A_{pi} is the area for each one of the plots and Y_{pi} the corresponding value for the variable Y. In plot 1 just trees with $d < 12.5$ cm are measured, in plot 2 the measurement focuses trees with d between 12.5 and 22.5 cm and, finally, in plot3 the trees with $d \geq 22.5$ cm are the only measured.

The clustered plots consist of a settlement of simple or combined plots or even sampling points around a central point. After the central plot is located and measured another four plots are measured in the direction of the cardinal points at pre-defined distance from

the centre of the central plot. It is commonly used for assessing natural regeneration in the NFI and the generalization to the hectare is done as follows:

$$Y = \sum_{i=1}^n \frac{10000}{A_{p_i}} Y_{p_i}$$

As all plots present the same area, then:

$$Y = \frac{10000}{A_p} \sum_{i=1}^n Y_{p_i}$$

Where A_p is the area of each plot.

Clustered plots can have a different settlement and number of plots, for instance a series of simple plots measured along the perimeter of a square as is the case in the Finish Forest Inventory.

1.1.3 Delimiting the Plot in the Field

After locating the plot centre, the first operation consist of determining the plot limits as accurately as possible which is essential for a correct determination of per hectare values. The incorrect identification of a tree in a 500 m² plot corresponds to an error of 20 trees per hectare. The methods will depend on the plot shape and the instrument used in the process. In the case of circular plots delimited using a vertex, the transponder has to be placed in the centre of the plot and all the trees located at a horizontal distance lesser than the plot radius marked facing the plot centre. Special care must be devoted to border trees. Border trees are the ones whose inclusion in the plot raises doubts. The procedure to follow must be the one defined in the field manual and in case this

information has been neglected it will be the field crew responsibility to define an inclusion rule and report it along with the measurements. Possible rules are:

- a) Considering as part of the plot all trees whose centre at the height of 1.30 m is located within the plot radius
- b) Considering as part of the plot all trees whose centre at the base of the tree is located within the plot radius
- c) Considering as part of even-numbered plots all trees that touch the border line, whereas for uneven-numbered ones trees should only be considered if totally inside the plot.
- d) Considering as part of the plot every-other tree.

Special care must also be taken in the presence of slope. In such cases, the plot area equal to πR^2 , when horizontally projected decreases to $\pi R^2 \cos\beta$. **Table 3** shows the errors in plot area obtained for slopes varying between 1° and 50° .

Table 3. Percentage of decrease in horizontal projected areas for a range of slopes up to 50° .

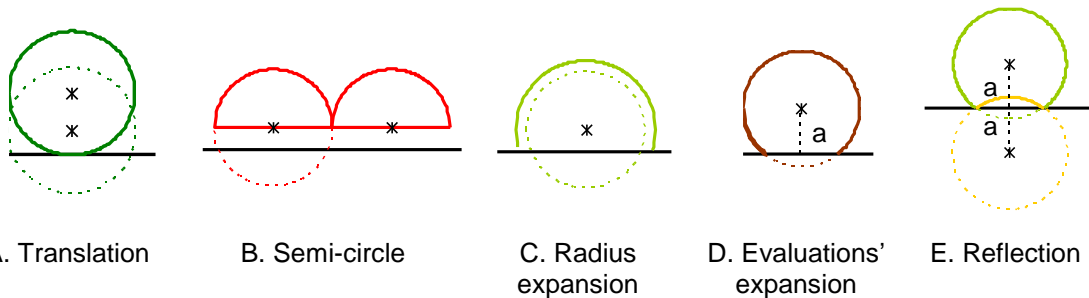
Slope (degrees) β	Slope (%) $100 \tan\beta$	Decrease in projected area (%) $100 (1 - \cos\beta)$
1	1.75	0.02
5	8.75	0.38
7.5	13.17	0.86
10	17.63	1.52
15	26.79	3.41
20	36.40	6.03
30	57.74	13.40
50	119.18	35.72

Nowadays, this problem is less important due to the use of instruments that automatically calculate horizontal distances.

1.1.4 Border Plots

The stand border consists of a strip, variable in size, which limits the stand and where growth conditions are different than the ones inside the stand for different light and wind exposures. As a result of this, because the trees located in the stand border also present different characteristics the border must be properly represented in the sample.

A large number of sample plots are frequently intercepted by the stand border. Several methods have been developed in order to determining the variables' values per area. All the methods consider disregarding plots whose centres are located outside the stand. On the contrary, if the plot centre is part of the stand one of the following methods can be adopted:



Schmid (1969) studied the errors associated to each of these methods and proved that the Reflection method is free from bias, and that both expansion methods are preferable to the Translation and Semi-circle methods. The Evaluations Expansion Method is the one applied by the Portuguese NFI. Field crews are responsible for registering the perpendicular distance from the plot centre to the stand limit represented by a in the figures. The plot area can be subdivided in to two areas, the main one representing the area occupied by the stand ($A_{\text{principal}}$) being assessed and the remaining area occupied

by a different stratum or land use ($A_{\text{remaining}}$) based on the values of a , plot radius (r) and plot area (A_p).

$$A_{\text{remaining}} = r^2 \left(\arccos \left(\frac{a}{r} \right) \right) - a \sqrt{r^2 - a^2}$$

$$A_{\text{principal}} = A_p - A_{\text{remaining}}$$

1.2 The Number of Trees per Hectare

One of the first variables to assess in a plot of a given area is the number of trees in the plot. Knowing the number of trees in a plot of area A_p (N_p), the number of trees per hectare is given by:

$$N = N_p \frac{10000}{A_p} = N_p \text{ EF}$$

For simplicity reasons it is common to use the symbol n when referring to the number of trees in the plot instead of N_p . The value $10000/A_p$ refers to the area Expansion Factor (EF), since it is the value by which the stand variable calculated in a A_p area plot has to be multiplied in order to obtain the corresponding value per hectare.

N refers to the number of living trees in a stand. Natural regeneration is not accounted for, because most of the seedlings are likely to die. On the other hand, there is also the need for setting a threshold for young trees which can no longer be considered regeneration. For these, a DBH threshold is defined above which trees are measured (often 2.5 cm, 5 cm or 7.5 cm).

Other number of trees can be accounted for as described for N , namely: number of dead trees (N_{dead}); number of thinned trees (N_{thin}); number of planted trees (N_{pl}); and ingrowth,

the number of trees that were not accounted for in the previous inventory for being below the threshold (N_{ing}).

1.3 Diameter Distribution, Basal Area and Mean Diameter

1.3.1 Diameter Distribution

The diameter distribution of a stand corresponds to determining the frequency of trees according to different diameter classes. Diameter classes usually have a range of 5 cm, however, the range can be adjusted depending on the species and the trees' dimensions. The first diameter class to be considered has a central value 5, the "5 cm Class", and is represented as [2.5;7.5[, meaning that trees with a diameter of 7.5 cm must be accounted for in the class with a central value of 10, the "10 cm Class" (thus represented as [7.5;12.4]).

In the field the diameter distribution is filled in as tree's diameters are measured in a diameter distribution table:

Plot nr: 2		Diameter Distribution						Diameters' Measurement								
d Class	Main Tree species: Pine					Other:	Main Tree species: Pine						Other:			
2.5-7.4							8.7	26.0								
7.5-12.4							45.7	31.3								
12.5-17.4							21.0	29.3								
17.5-22.4							40.0	28.0								
22.5-27.4							30.0	15.0								
27.5-32.4							37.3	22.5								
32.5-37.4							28.3	29.3								
37.5-42.4							25.3	9.2								
42.5-47.4							31.9									

The first tree to be measured has a diameter of 8.7 (in yellow) being represented by a vertical bar in the first box of class [7.5; 12.4], the "10 cm Class" (in yellow). Each tree measured must be represented by a vertical bar in the corresponding diameter class with the one representing the 5th tree being horizontal and closing the first group of 5 trees (in grey). The 6th tree in this same class is represented in the next box corresponding to the

same class. The procedure is described for the "25 cm Class": the first tree in this class has a diameter of 30.0 cm (in grey) and the 6th, to which corresponds a vertical bar in the next box, of 28.0 cm (in grey). The 1st, 6th, 11th trees in a diameter class are selected as sample trees based on the modified Draudt method.

Afterwards, the diameter distribution is generalized to the hectare and can be represented by a histogram. The diameter distribution is an indicator of stand structure providing precious information about the silvicultural options to take in a given stand. The next table (**Table 4**) shows examples of rules to follow while managing cork oak stands based on the simulations carried out using the SUBER model (Tomé et al., 2004).

Draudt Method and Modified Draudt Method

According to Draudt method, trees are distributed by k diameter classes being the total number of sample trees (m) proportionally distributed to the frequencies by class. The total number of sample trees per class will vary with the number of classes and with the corresponding frequencies. In practice, implementing Draudt method is quite complex since it requires to:

1. Measure the diameter of all trees in the plot;
2. Grouping these trees by diameter classes;
3. Calculating the quadratic mean DBH (dg) of the trees in each class;
4. Locating in the field the m_i sample trees which are closest of each of the dg's;
5. Measuring the height(s) of these trees.

Given the difficulties, several countries adopted a simplification of this method based on the assumption that if the range of diameter classes is small, any tree can be considered a sample tree. In this way, it is possible to select the sample trees while measuring the diameters:

1. Measure the diameter of all trees in the plot;
2. Grouping these trees by diameter classes and selecting the 1st of every five trees in each diameter class (1st, 6th, 11th,...);
3. Measuring the height(s) of these trees.

1.3.2 Stand Basal Area

The basal area of a stand is defined as the sum of all the tree basal areas in it. This variable is not only essential in the calculus and/or estimation of several stand variables,

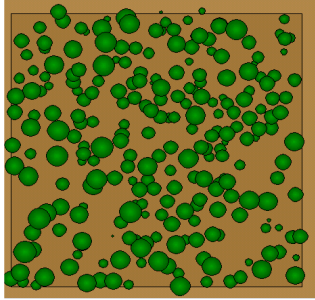
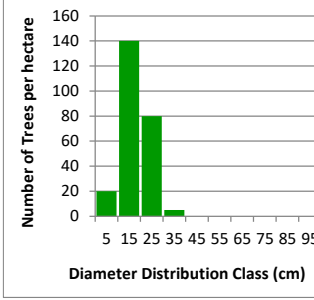
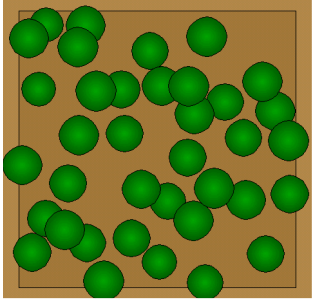
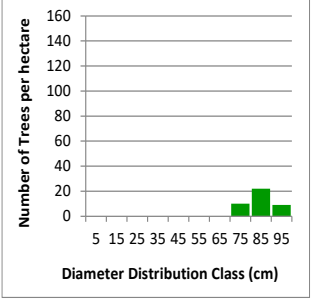
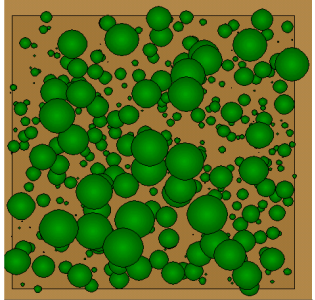
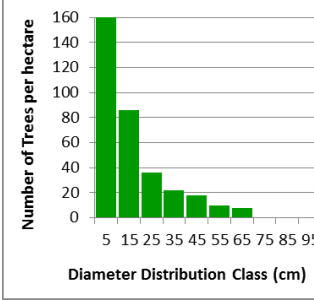
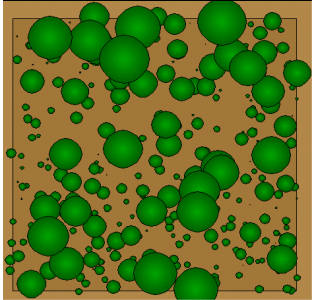
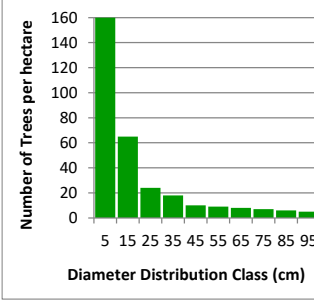
but it is also an important stand density indicator. The basal area (G_p) of a plot with a given A_p area, can be determined as:

$$G_p = \sum_{i=1}^n g_i = \sum_{i=1}^n \frac{\pi \cdot d_i^2}{4} = \frac{\pi}{4} \sum_{i=1}^n d_i^2,$$

Where g_i and d_i are the basal area and diameter of the tree i , respectively; whereas n is the number of trees in the plot. Similarly to what was described for determining the stand density, stand basal area is obtained by

$$G = G_p \frac{10000}{A_p} = G_p EF \quad (\text{m}^2 \text{ ha}^{-1})$$

Table 4. Diameter distribution and stand variables for 4 cork oak stands managed differently.

Even-aged stand - 27 years		Even-aged stand - 153 years	
			
Crown Cover = 49%	Stand Density = 250 trees ha ⁻¹	Crown Cover = 49%	Stand Density = 37 trees ha ⁻¹
Basal Area = 7 m ² ha ⁻¹	Quadratic mean dbh = 19 cm	Basal Area = 20 m ² ha ⁻¹	Quadratic mean dbh = 83 cm
Average crown diameter = 5 m	Virgin Cork weight = 833 kg ha ⁻¹	Average crown diameter = 14 m	Virgin Cork weight = 40 kg ha ⁻¹
Mature Cork weight = 1153 kg ha ⁻¹		Mature Cork weight = 5394 kg ha ⁻¹	
Uneven-aged stand - Structure 1		Uneven-aged stand - Structure 2	
			
Crown Cover = 58%	Stand Density = 181 trees ha ⁻¹	Crown Cover = 58%	Stand Density = 143 trees ha ⁻¹
Basal Area = 12.5 m ² ha ⁻¹	Quadratic mean dbh = 30 cm	Basal Area = 15 m ² ha ⁻¹	Quadratic mean dbh = 36 cm
Average crown diameter = 6 m	Virgin Cork weight = 342 kg ha ⁻¹	Average crown diameter = 7 m	Virgin Cork weight = 274 kg ha ⁻¹
Mature Cork weight = 3076 kg ha ⁻¹		Mature Cork weight = 3760 kg ha ⁻¹	

1.3.2.1 Assessing Stand Basal Area

As previously mentioned, stand variables can be determined using alternative approaches. In the case of basal area, two alternative approaches can be applied: complete enumeration and diameter distribution. The first approach requires having measured the diameters of all trees in the plot so that the corresponding basal areas can be determined and summed to calculate the plot basal area as in the following example:

Property: <i>Fernão Ferro</i>			
Plot: <i>74</i>			
Date: <i>1997</i>			
Tree Number	d (cm)	g (m ²)	
23	11.1	0.0097	With g calculated using the expression: $\pi()/40000*d^2$ (with d representing DBH)
24	11.5	0.0104	
28	13.9	0.0152	
12	14.5	0.0165	
13	14.6	0.0167	
11	17.1	0.0230	
10	18.2	0.0260	
9	19.6	0.0302	
25	20.3	0.0324	
7	21.1	0.0350	
6	21.5	0.0363	
29	21.6	0.0366	
27	21.7	0.0370	
8	22.1	0.0384	
26	22.4	0.0394	
19	22.7	0.0405	
20	22.7	0.0405	
18	23.2	0.0423	
32	23.2	0.0423	
31	23.4	0.0430	
14	23.5	0.0434	
5	24.1	0.0456	
15	24.1	0.0456	
22	24.2	0.0460	
4	25.2	0.0499	
1	25.4	0.0507	
2	25.4	0.0507	
21	25.7	0.0519	
17	26.0	0.0531	
3	26.4	0.0547	
30	27.5	0.0594	
16	30.6	0.0735	
	$G_p =$	1.2356 m ²	With G_p as the sum of g and G as G_p times the expansion factor that in this case is 20 (10000/500)
	$G =$	24.71 m ² ha ⁻¹	

The other approach was widely used in the XX century before the computers' age. Back in those days, calculations took time and therefore it was common to determine stand variables using aggregated data. However, nowadays despite having access to fast computers it is still important to understand this approach because old records will present the calculus in this format being impossible to recalculate stand variables using

the current methodologies. When we can only have access to diameter distributions the basal area (G_p) of a plot with an A_p area is determined as follows:

$$G_p = \sum_{j=1}^k f_j g_j = \sum_{j=1}^k f_j \frac{\pi}{4} \frac{d_j^2}{4} = \frac{\pi}{4} \sum_{j=1}^k f_j d_j^2,$$

Where k stands for the number of diameter classes, f_j represents the frequency in class j and d_j and g_j are, respectively, the central diameter of class j and its corresponding basal area. Look at the example below where using the data from “Fernão Ferro property” basal area was calculated using aggregated data by diameter classes:

Property: Fernão Ferro						
Plot: 74						
Date: 1997						
d Classes	central diameter	f _i (n _p)	n	g _i	G _p	With g _i calculated using the expression: $\pi()/40000*(\text{central diameter})^2$ and G_p calculated as $g_i * (10000/500)$
7.5-12.4	10	2	40	0.007854	0.314159	
12.5-17.4	15	4	80	0.017671	1.413717	
17.5-22.4	20	9	180	0.031416	5.654867	
22.5-27.4	25	15	300	0.049087	14.72622	
27.5-32.4	30	2	40	0.070686	2.827433	
N = 640			G = 24.93639 m ² ha ⁻¹		G results from summing up the G _p values in each diameter class	

1.3.3 Mean Basal Area and Quadratic Mean DBH

The mean basal area results from averaging the basal areas of all the trees in a plot or a stand. It is an important stand variable because (being the volume and biomass linearly related to it) the trees with a basal area close to the average basal area can be considered as the most representative trees of the plot or the stand.

The mean basal area (gm) can be determined either using the plot basal area or the stand basal area:

$$gm = \frac{G_p}{N_p} = \frac{G}{N}$$

To the mean basal area corresponds a diameter: the quadratic mean DBH (dg). This diameter is used to locate the average trees in the plot. Please note that this diameter is different from averaging all tree diameters, presenting a slightly higher value. The

difference between the average diameter and quadratic mean DBH increases with the variability of diameters observed in the plot. The quadratic mean DBH is calculated as:

$$gm = \pi \frac{dg^2}{4} \quad \Rightarrow \quad dg = 100 \sqrt{\left(\frac{4 \text{ gm}}{\pi}\right)} = 100 \sqrt{\frac{4 \text{ G}}{\pi \text{ N}}}$$

It can also be calculated as the quadratic average of DBHs:

$$dg = 100 \sqrt{\frac{\sum_{i=1}^n d_i^2}{n}}$$

Using the same data as in the previous examples, mean basal area and quadratic mean DBH can be calculated:

$$gm = \frac{G}{N} = \frac{24.71}{640} = 0.0386 \text{ m}^2$$

$$dg = 100 \sqrt{\frac{4 \text{ G}}{\pi \text{ N}}} = 100 \sqrt{\frac{4 \times 24.71}{\pi \times 640}} = 22.17 \text{ cm}$$

1.4 Stocking and Stand Density

Despite not being synonyms, these terms are usually used with the same meaning. The stand density is a quantitative measure of woody material per area, whereas the stocking refers to an evaluation of stand density with regard to a given management. In this sense, stands can be classified as under-stocked, fully stocked or over-stocked.

Stocking and stand density assessments are extremely important because the need for thinning as well as the thinning intensity can often be based on these stand variables.

1.4.1 Assessing Stocking

Stocking assessment relies on determining or defining the suitable stand density for a given tree species, in a certain place, being managed with a specific purpose.

Consequently it is a quite subjective and difficult to define concept. According to Bickford (1979):

The stocking that results in maximum yield is the ideal that every forest manager would like to have if he only knew what it was and could recognize it if he saw it.

The terminology under-stocked and over-stocked is still quite common among forest managers.

1.4.2 Assessing Stand Density

1.4.2.1 Basal Area

Basal area is one of the most commonly used stand variables for assessing stand density. Apart from being easily obtained in the course of forest inventory, it is also objective and easy to understand by forest managers. Basal area is a good measure of stand density expressing the need for thinning. The thinning intensity can be defined through the residual basal area, which means the basal area left in the stand after thinning. However, the practical implementation can sometimes be a hard task because the forest manager has to select the trees to be thinned in order to reach the desired residual basal area.

1.4.2.2 Number of Trees per Hectare

The number of trees per hectare is not usually used in natural stands, because stand density does not always relate with this variable. On the other hand, in planted forests it is the most used. It is easy to determine and allows an objective definition of thinning intensity. Once the forest manager has decided to thin, either based on the basal area

or any other measure, he knows the number of trees per hectare to be removed in the thinning, which is much easier than removing trees until a certain basal area is attained.

1.4.2.3 Percent Crown Cover

This is a very useful density measure particularly in stands characterized by low densities. Percent crown cover (%cc) results from expressing the sum of crown areas as a percentage of plot area:

$$\%cc = \frac{\sum \frac{\pi CW^2}{4}}{A_p} 100$$

For example, Natividade (1950) suggests that cork oak stands should always be managed keeping percent crown cover below 58% to secure that sufficient light reaches the trees' crowns. The calculus of the percent crown cover is illustrated bellow for a cork oak permanent plot with $A_p=2827 \text{ m}^2$ where the four crown radius were measured. When the crown radius are not measured a crown diameter equation has to be used.

Property: <i>Herdade do Chaparro</i>								
Permanent Plot: 8								
Date: 1989								
Tree Number	Tree Species	Crown Radius				Mean Crown Radius	Tree Crown Area	
		North	South	East	West			
1	<i>Sb</i>	3	4.4	2.3	4.7	3.6	40.72	
2	<i>Sb</i>	5.2	7.4	4.5	6.2	5.8	106.60	
3	<i>Sb</i>	4.6	6.2	2.7	3.9	4.4	59.45	
4	<i>Sb</i>	1.9	3	3.1	3.3	2.8	25.07	
5	<i>Sb</i>	2	4.2	4.1	5.4	3.9	48.40	
6	<i>Sb</i>	5	4.9	5.6	4.9	5.1	81.71	
7	<i>Sb</i>	2.5	6.5	2.2	4.2	3.9	46.57	
8	<i>Sb</i>	6.6	9.1	8.3	7.8	8.0	198.56	
9	<i>Sb</i>	2.4	4.2	5.1	3.8	3.9	47.17	
10	<i>Sb</i>	2.9	5.5	2.6	3.8	3.7	43.01	
11	<i>Sb</i>	5.4	3.6	2.8	4.3	4.0	50.90	
12	<i>Sb</i>	5.6	5.7	8.1	4.7	6.0	114.04	
13	<i>Sb</i>	3.7	6.1	4.7	2	4.1	53.46	
14	<i>Sb</i>	5.1	7.1	6.7	5.5	6.1	116.90	
15	<i>Sb</i>	6.7	7.1	7.2	6.6	6.9	149.57	
16	<i>Sb</i>	5.1	5.5	4.3	5.4	5.1	80.91	
17	<i>Sb</i>	5.1	4.5	5.7	4.5	5.0	76.98	
18	<i>Sb</i>	6.1	5.9	5.4	5.1	5.6	99.40	
19	<i>Sb</i>	2.9	4.8	4	3.6	3.8	45.96	
20	<i>Sb</i>	7.5	9.6	5.3	7.9	7.6	180.27	
21	<i>Sb</i>	2.6	1.4	1.9	2.4	2.1	13.53	
22	<i>Sb</i>	2	0.3	1.8	0.8	1.2	4.71	
23	<i>Sb</i>	0.8	2.1	2	1.6	1.6	8.30	
24	<i>Pm</i>	3.4	2.9	3.5	3	3.2	32.17	
25	<i>Pm</i>	4.8	3.4	4.3	3.9	4.1	52.81	
26	<i>Pm</i>	1.9	1.7	2.1	1.7	1.9	10.75	
27	<i>Pm</i>	2.6	2.5	2.7	2	2.5	18.86	
28	<i>Pm</i>	1.4	1.7	1.6	1.9	1.7	8.55	
29	<i>Pm</i>	5.3	6.1	5.8	4.6	5.5	93.31	
30	<i>Pm</i>	2.1	2.3	2	2.4	2.2	15.21	
31	<i>Pm</i>	2.2	2.7	2.2	2.4	2.4	17.72	
A _p =		2827 m ²				Total Crown Area		1941.55 m ²
						%CC		68.68 %

The Mean Crown Radius (crd) is obtained by averaging the radius measured in the cardinal directions.

The tree crown area is then determined using the expression:
 $PI() * crd^2$

The Total Crowns Area results from summing up all the Tree Crown Areas

The %CC is then calculated as the ratio between the Total Crowns Area and the plot area (A_p):
 $Total\ Crowns\ Area / A_p * 100$

1.4.2.4 Stand Density Index

Both the basal area and the number of trees per hectare are incomplete measures of stand density. Two stands with the same basal area can have distinct stand densities as long as these stands have a different number of trees per hectare or a different age.

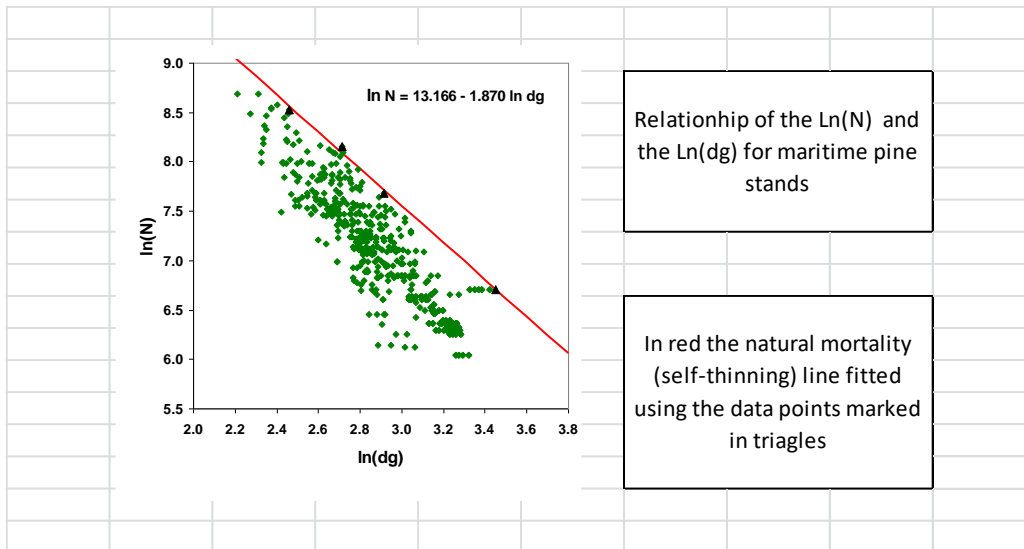
In order to tackle the limitations of the previous measures, other measures were developed combining more than one stand variable. The stand density index (SDI) is based in the two components of basal area: number of trees per hectare and quadratic mean DBH. This index assesses stand density by comparing the stands characteristics with those of a stand with the maximum stand density (under self-thinning). Reineke (1933) has observed that the relationship between the logarithm of the number of trees per hectare and the logarithm of the quadratic mean DBH in maximum stocked stands is usually linear. Moreover, he also observed that for stands with the maximum stock this line presents a slope close to -1.605:

$$\log_{10} N = -1.605 \log_{10} dg + k ,$$

Where N is the number of trees per hectare, dg is the quadratic mean DBH and k is a species specific constant. This line is usually defined as reference curve and it is assumed that in maximum stocked stands the relative growth rate of the number of trees (negative) and the relative growth rate of the quadratic mean DBH (positive) are proportional:

$$-\frac{1}{N} \frac{dN}{dt} = b \frac{1}{dg} \frac{ddg}{dt}$$

This relationship is shown in the graphic below for data from a thinning trial established in Portuguese maritime pine stands. Natural logarithms were used since the slope is not affected by the logarithm base. All trials include some non-thinned control plots. The graphic shows a wide dispersion of data for each dg value indicating that not all the plots have reached the self-thinning line. For the higher values of dg a horizontal evolution is observed indicating that this plot is still far from self-thinning. To estimate the natural mortality line the points marked with triangles are used. The slope obtained is slightly smaller than Reineke's, although it is in line with the value of -1.815 found by Luís et al. (1991) for maritime pine using National Forest Inventory data, or the value of -1.997 obtained by Oliveira (1985) for the mountainous and sub-mountainous regions of Portugal. These results evidenced the need of installing more of these trials in order to obtain more precise information on the natural mortality line.



SDI is based on the difference between the number of trees per ha corresponding to the maximum stock (given by the expression above) and the number of trees per ha of the target stand.

Moreover, SDI assumes that for an under-stocked stand the relationship between $\log N$ and $\log dg$ is parallel but with a lower intercept than the one observed for the fully-stocked stands. The intercept can be obtained by the expression:

$$k = \ln N + 1.870 \ln dg \quad (\text{using the value obtained for the pine stand})$$

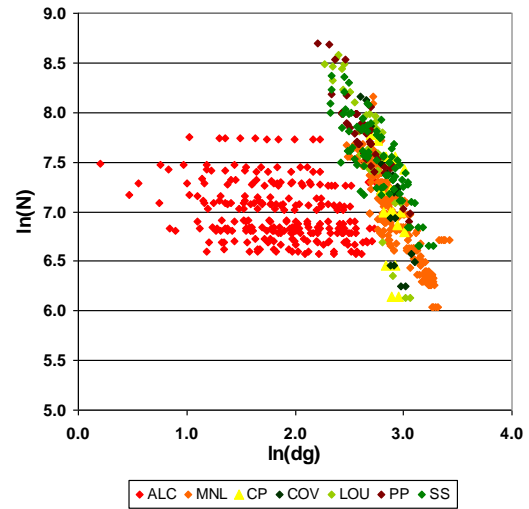
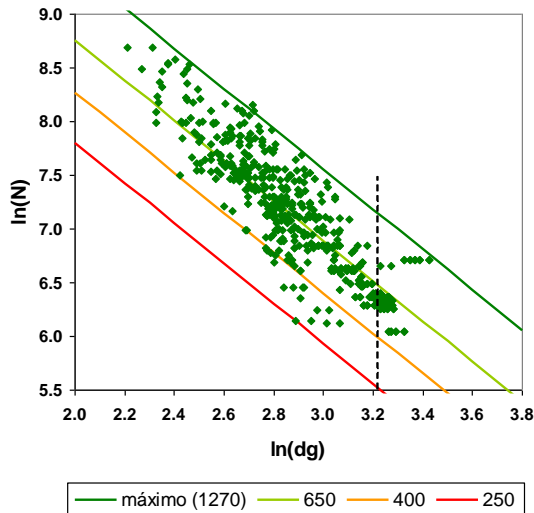
For standardization the calculus of SDI is done based on the number of trees per hectare the stand would have for a $dg=25$ cm. The SDI for any given stand with $dg=25$ is:

$$\ln SDI = -1.870 \ln 25 + k$$

Replacing k by the value obtained for the target stand, the expression for SDI can be obtained:

$$\ln SDI = -1.870 \ln 25 + \ln N + 1.870 \ln dg$$

$$SDI = N \left(\frac{dg}{25} \right)^{1.870}$$



Natural mortality line and the lines corresponding to stands with different SDI values.

In red we have maritime pine under-stocked stands approaching the natural mortality line; the remaining different colours refer to different trials.

For a given dg value, the maximum SDI is obtained for the N corresponding to a fully-stocked stand; if the number of trees in the stand is used in the expression. SDI provides a stand density measure, independent from tree dimension.

The left hand side graphic shows the mortality line fitted for maritime pine using the same data set as before as well as the lines corresponding to stands with different SDI values.

When thinning are not carried out, in the mid-term stands will tend to approach the natural mortality line as shown in the right hand side graphic.

The SDI value for a stand with dg=22.1 cm and N=320, is given by:

$$SDI = N \left(\frac{dg}{25} \right)^{1.87} = 320 \left(\frac{22.1}{25} \right)^{1.87} = 254$$

1.4.2.5 Crown Competition Factor

The crown competition factor (CCF), Krajicek et al. (1961), reflects the relationship between the area available in the stand and the maximum area trees would have access to if they were open-grown (without competition).

It requires knowing the relationship of crown width (cw) and DBH for open-grown trees, which tends to be linear and assumes that the crowns of open-grown trees are circular:

$$cw_i = b_0 + b d_i \qquad ca_i = \pi \frac{cw_i^2}{4}$$

CCF results of the sum of ca_i of all the trees in the plot expressed as a percentage of the plot area (A_p):

$$CCF = \frac{100}{A_p} \sum_{i=1}^n ca_i ,$$

Where A_p is the area of the plot.

If calculated based on the diameter distribution:

$$CCF = \frac{100}{A_p} \sum_{j=1}^k f_j ca_{ij} ,$$

Where k represents the number of diameter classes, f_j the frequency in class j and ca_{ij} the diameter class mid-point.

In Portugal not many studies on the crown dimension of open-grown maritime pine trees have been carried out. Alegria (1994) fitted a model for open-grown pine trees in Oleiros, Castelo Branco and Proença-a-Nova:

$$cw_1 = 0.335229 + 0.171785 d$$

Property: <i>Proença-a-nova</i>				
Date: 1989				
Isolated Trees				
Tree Number	Tree Species	d	Crown width	Crown area
			cw _i	ca _i
1	Pb	11.1	2.24	3.95
2	Pb	11.5	2.31	4.19
3	Pb	13.9	2.72	5.82
4	Pb	14.5	2.83	6.27
5	Pb	14.6	2.84	6.35
6	Pb	17.1	3.27	8.41
7	Pb	18.2	3.46	9.41
8	Pb	19.6	3.70	10.76
9	Pb	20.3	3.82	11.48
10	Pb	21.1	3.96	12.32
11	Pb	21.5	4.03	12.75
12	Pb	21.6	4.05	12.86
13	Pb	21.7	4.06	12.97
14	Pb	22.1	4.13	13.41
15	Pb	22.4	4.18	13.74
16	Pb	22.7	4.23	14.08
17	Pb	22.7	4.23	14.08
18	Pb	23.2	4.32	14.66
19	Pb	23.2	4.32	14.66
20	Pb	23.4	4.35	14.90
A _p =		500 m ²	FCC =	43.42

The crown width (cw_i) is estimated with the equation:
 $cw_i = 0.335229 + 0.171785 d$
 (with d representing DBH)

The tree crown area (ca_i) is then determined using the expression:
 $PI()/4 * cw^2$

The CCF is then calculated as the ratio between the Total Crowns Area and the plot area (A_p):
 $Isolated Crowns Area / A_p * 100$

1.4.2.6 Relative Spacing

The relative spacing (RS) relates the average distance between trees and the height of dominant trees. It is based on the assumption that the relationship between the distances between trees and dominant height expresses stand density:

$$RS = \frac{\text{average distance between trees}}{h_{dom}}$$

Assuming a squared spacing, each tree has an area of:

$$\text{Tree Area} = \frac{10000}{N}$$

Therefore, the average distance between trees will be given by:

$$\text{Average distance between trees} = \sqrt{\frac{10000}{N}}$$

Then the relative spacing index can be written in the following form, commonly designated as Wilson's factor (Wilson, 1946):

$$FW = \frac{\sqrt{10000/N}}{h_{dom}} = \frac{100}{h_{dom} \sqrt{N}}$$

The Wilson's factor has been widely used in the management of maritime pine stands in Portugal, for its easy applicability. Leiria National Forest, the Portuguese forest area with the oldest management plan, has been using this index for determining the need for thinning as well as the thinning intensity. Each stand is inventoried every 5 years and Wilson's factor calculated. If this value is lower than the limit considered then a thinning should be carried out (for several years the value of $F_w=0.25$ was used, lately lower values have been preferred). The thinning intensity is then defined by the difference between the number of trees corresponding to the limit Wilson's factor and the Wilson's factor value found for the target stand. Suppose we are in the presence of a stand with 756 trees per ha and a dominant height of 16 m. The Wilson's factor will be given by:

$$F_w = \frac{100}{16 \sqrt{756}} = 0.227 < 0.25 \quad \Rightarrow \quad \text{thinning required}$$

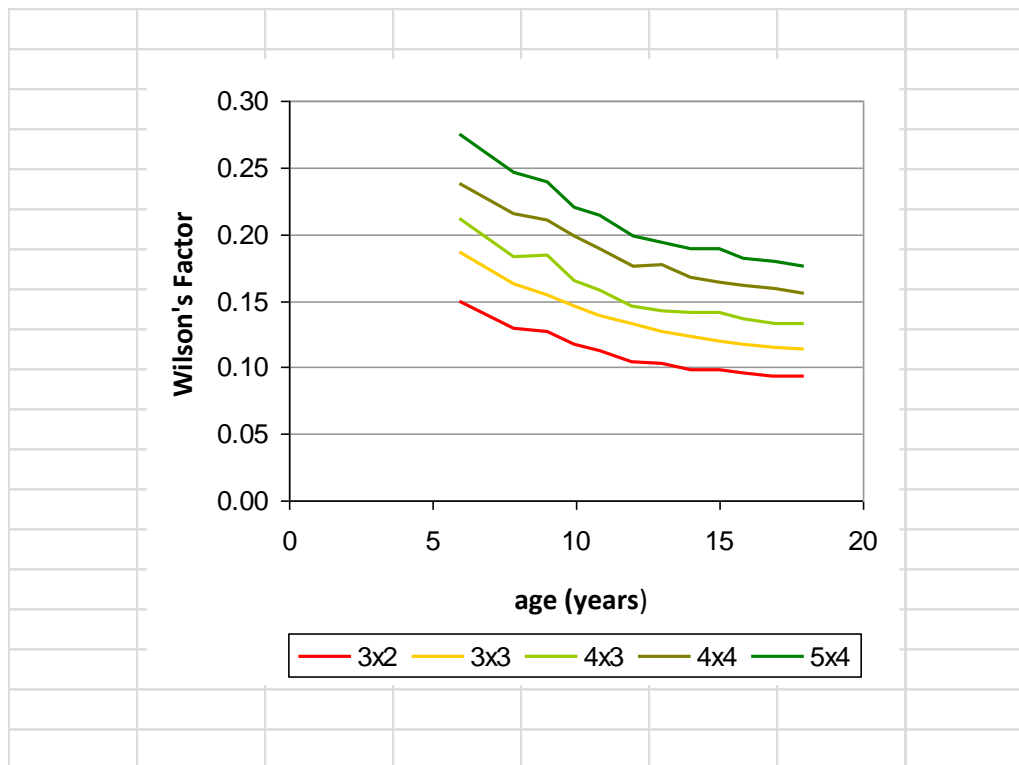
$$N = \frac{100^2}{h_{dom}^2 F_w^2}$$

The number of trees corresponding to a Wilson's factor of 0.25 and a dominant height of 16 m is determined by solving the expression for N:

$$N = \frac{100^2}{(16^2 \cdot 0.25^2)} = 625$$

Thus, the thinning to be carried out will have to remove $(756-625) = 131$ trees per ha.

Regardless of the site quality and initial stand age, all even-aged stand of a given species tend to show the same pattern for Wilson's factor evolution over time.



The graphic shows the evolution of the Wilson's factor (FW) in Eucalyptus stands with different spacings. Initially, FW decreases rapidly the fastest as wider the spacing, but afterward it tends to asymptotically approach a minimum FW.

1.4.2.7 Spacing Coefficient

The spacing coefficient (Cspac) relates the average distance between trees and the mean crown width (cwm):

$$C_{spac} = \frac{\text{Average distance between trees}}{\text{cwm}}$$

This index is not immediately applicable because the tree crown diameters are not commonly measured in forest inventories given the high costs related to these measurements. However, it is a very interesting index for species characterized by wide crowns such as cork oak and umbrella pine. In practical applications, the crown

diameters can be estimated using allometric equations that only use variables measured in the course of forest inventories.

Admitting a regular squared spacing, as assumed for the Wilson's factor, the average distance between trees is equal to the square root of 10000/N. Thus, the spacing coefficient is given by:

$$C_{\text{spac}} = \frac{100}{c_{\text{wm}} \sqrt{N}}$$

There is a close relationship between this index and the percent crown cover (%CC). A C_{spac} of 1.2 corresponds to a %CC value of 58%, defined by Natividade (1950) as the maximum possible value that avoids strong competition between trees. C_{spac} values lower than 1.2 indicates that thinning is required. In order to calculate C_{spac} , all we need to do is calculating the average of the crown diameters (twice the value of the crown radius):

$$C_{\text{spac}} = \frac{100}{8.2 \sqrt{110}} = 2.3$$

In the SUBER model (Tomé et al., 2004), a forest management model available for cork oak stands in Portugal, the need and intensity of a thinning are based on this index.

1.5 Stand Heights

1.5.1 Mean Height of a Stand

For even-aged stands it is valid to admit that the heights of trees in one plot will have close values. Therefore, it makes sense to calculate the mean height as the average of the heights of all trees in the plot:

$$h_m = \frac{\sum_{i=1}^n h_i}{n}$$

According to the European school, it is a standard procedure to define the mean height as the height of the tree with a DBH = to the quadratic mean DBH and it is referred to as h_g . This height can be obtained by two alternative processes

- a) Measuring the height of trees with a diameter closer to the quadratic mean DBH

- b) Estimating the height corresponding to the dg using a height/DBH curve fitted using the plot data

1.5.2 Dominant Height

It is common to define the mean height of the biggest trees in one stand as dominant height. In practice, there is the need to define which trees are the biggest and therefore accounted for the dominant height determination. Kramer (1959) classified the method available for assessing dominant height in two types: mathematical and biological. For the mathematical method, the number of trees considered for calculating h_{dom} is determined by an objective and quantitative rule:

- a) A fixed percentage of the total number of trees, 10 or 20%, selected according to their height or diameter;
- b) A fixed number of trees per hectare, usually 50, 100 or 200, selected according to their height or diameter.

For the biological method, trees are selected based on their social classification being possible to select just the dominant trees or the dominant and codominant trees in the plot.

In Portugal the mean height of the 100 thickest trees (at DBH height) per hectare has been traditionally used to define h_{dom} . This definition cannot be applied in cork oak or umbrella pine stands. In fact, most of these stands have stand densities smaller than 100 trees/ha. In the course of NFI 2005/2007, the mean height of the 25 thickest trees in the stand was used ($h_{dom_{25}}$) for these stands.

Dominant height is an important variable because regardless of the method used to select the dominant trees, this stand variable is most of the times independent of the thinnings carried out being for this reason a good measure of the potential productivity of the stand.

1.5.3 Height/DBH Curves

Height/DBH curves, expressing the relationship between height and DBH for a given stand, have been introduced already when defining the ways to determine tree level variables.

Local height/DBH curves are fitted for a single stand using the DBH as the only independent variable, whereas generic or regional height/DBH curves are applicable to

a region and use stand level variables that express stand density and site quality apart from DBH. Replacing the values of these variables by those of a given stand we obtain a height/DBH curve for the stand. Therefore, a height/DBH curve characterizes a given stand.

The concept of potential productivity of a forest system involves the influence of three types of factors that are determinant of growth: specific potential productivity, site quality and management intensity (Monteiro Alves, 1982).

The site quality of a given tree species refers to the potential present and future productivity of a species in a given site. According to the Society of American Foresters, the term site refers to an area considered for its environment insofar as it determines the type and quality of vegetation that the site can have (Avery e Burkhart, 1983). Site quality assessment is essential for an accurate characterization of a given stand and vital for growth prediction.

1.6 Site Quality

1.6.1 Site Quality Assessment

Avery e Burkhart (1983) grouped the methods for site quality assessment in two classes:

- *Direct assessment*: through the direct measurement of the environmental factors linked to growth;
- *Indirect assessment*: through the measurement of vegetation characteristics that express the impacts of those environmental factors.

Direct Assessment of Site Quality

Despite being theoretically possible to assess site quality through the factors affecting forest productivity (such as nutrient and soil water availability, weather, radiation, topography, etc.) it is extremely difficult to take into account all the factors and their interactions. Therefore it is common to decide for indirect assessment.

Marques (1987, 1991) developed a model to predict site index (defined in section 1.5.5):

$$S = 10.7214 + 0.780177 X_1 + 0.0246574 X_2 + 0.00672025 X_3 - 0.00441198 X_4$$

Where X_1 stands for the mean temperature in autumn ($^{\circ}\text{C}$), X_2 stands for the available potassium (moles m^{-2} in the soil profile), X_3 represents the total soil porosity ($\text{dm}^3 \text{m}^{-2}$ in the soil profile) and X_4 the percentage of fine sand ($\text{dm}^3 \text{m}^{-2}$ in the soil profile). A low R-square value (0.544) was obtained in the fit. However, site index estimates in young

stands, age classes 5 and 10, have proven to be more precise than those obtained by indirect methods.

Indirect Assessment of Site Quality

Indicator plants, stand volume (mean annual increment for the age corresponding to the maximum growth) can be used in the indirect assessment.

Indicator plants

Sometimes, it is possible to relate the presence of some shrubs or herbaceous plants to site quality. The classification of site index based on indicator plants was developed by Cajander and his followers in Finland (Spurr, 1952; Vuokila, 1965). Never the less, this approach has disadvantages pointed out by Avery and Burkhart (1983) and Clutter et al. (1983):

- It only allows qualitative site quality assessment;
- Shrubs and herbaceous plants are often extremely sensitive to external factor such as fire or grazing;
- In most cases, indicator plants can only reflect the fertility of upper soil horizons, being the deeper ones vital for determining stand growth;
- Such an evaluation requires deep knowledge on ecology and systematics which makes its widespread application difficult.

Marques (1987, 1991) studied the relationship between site quality and the presence of indicator plants for maritime pine stands in the Tâmega valley, and the results have proven poorer than those obtained using site index curves.

Stand volume

Stand volume was sometimes used to evaluate site index in natural and un-thinned artificial stands or even in thinned stands where no more than 1/3 of the total volume had been removed (Assman, 1961, 1970). After heavy thinning became common, standing volume per hectare can suffer substantial reductions preventing this variable from being used with this purpose.

Stand height

The method traditionally used to define the quality of a site is certainly determining site index based on dominant height growth. In fact, dominant height is quite sensitive to differences in site quality, while at the same time seems to be little affected by stand density (please note that tree height is affected by stand density, just the height of the

largest trees is not) and its composition. In Portugal, dominant height is defined as the mean height of the thickest trees in the stand in a proportion of one tree per 100 m². The use of the thickest trees intends to avoid the sensitivity to the type of thinning carried out.

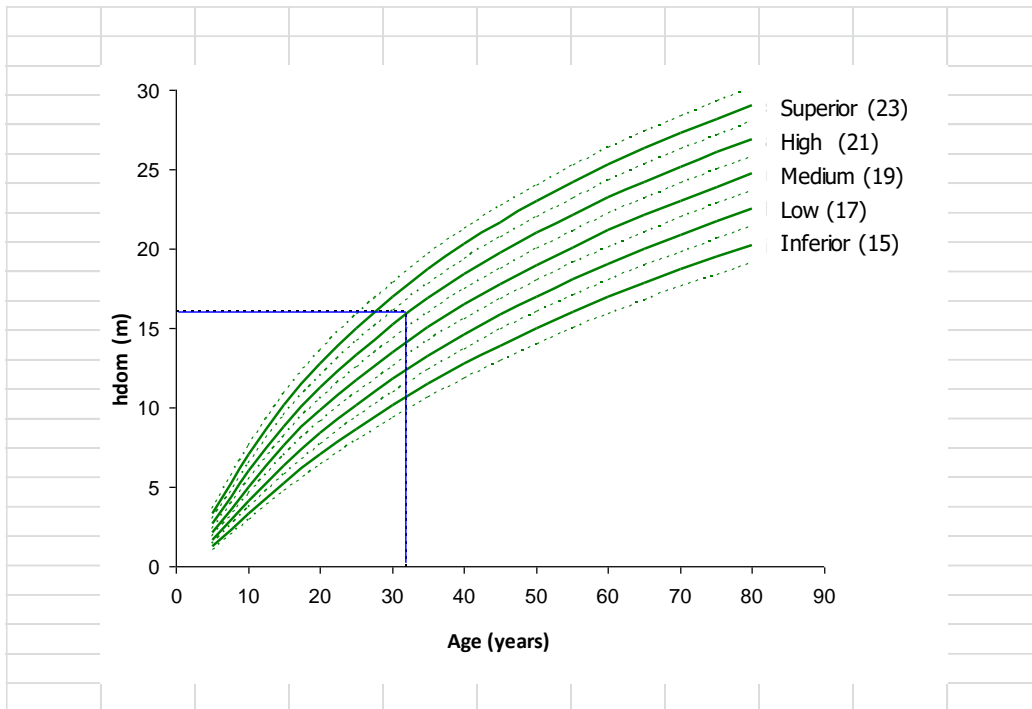
1.6.2 Site Index

Site index (S) can be defined as the dominant height a stand has, had or will have at a certain standard age. The standard age is species-specific and is defined as an age close to the stand rotation age. It is common to group the values that site index might take for a certain region in classes, the site index classes.

In practice, once the age of a stand and its dominant height are known for a given instant in time, three methods can be used to estimate site quality: a set of site index curves (graphical assessment); a dominant height growth equation and a site index prediction equation.

1.6.3 Site Index Curves

These curves represent the evolution of dominant height over age and are simultaneously represented in a graphic. The set of curves in the graphic represents the range of site indices that can be found for the region under study. Usually, 5 site index classes are represented: inferior, low, medium, high and superior; as for the curves fitted for maritime pine in Leiria National Forest by Falcão (1992). Considering a standard age of 50 years, the site indices corresponding to each of the classes are: 15, 17, 19, 21 and 23. Suppose a 32 years stand was measured presenting a height of 16 m. To which site index class does this stand correspond? The answer is to a high site index class (marked in blue in the graphic below).



1.6.4 Using Dominant Height Growth Functions to Estimate Site Index

Dominant height growth functions can be used to estimate the dominant height that corresponds to a given standard age and thus to estimate site index. Two types of dominant height growth functions can be used:

a) Growth functions with S as an independent variable:

One example of this type of function is the growth function that originates Oliveira (1985) site index curves for the mountainous and sub-mountainous regions of Portugal. In this situation, site index (S) is determined by solving the equation for S.

b) Growth functions formulated as difference equation functions, meaning that dominant height in instant 2 (h_{dom_2}) is estimated based on dominant height in instant 1 (h_{dom_1}) and on the age in both instants (t_2 and t_1).

Consider a stand with 22 years and a dominant height of 16 m. Determine its site index for a standard age of 40 years	
Oliveira (1985)	$h_{dom} = S e^{-14.2234 \left(\frac{1}{t} - \frac{1}{40} \right)}$
1) solve the equation for S	
$S = h_{dom} e^{14.2234 \left(\frac{1}{t} - \frac{1}{40} \right)}$	
2) Calculate site index	
$S = 16 e^{14.2234 \left(\frac{1}{22} - \frac{1}{40} \right)}$	S = 16.3 m

This type of functions can be found in the GLOBULUS model (Tomé et al., 2001) where a collection of regionalized dominant height growth functions formulated as difference equations can be used to estimate site index for eucalyptus stands in Portugal. Difference equations, if correctly developed, should be invertible, which means that the function when solved for h_{dom_1} gets the same expression simply shifting the indices 1 with 2. Take the growth function for planted stands in the Coastal Central area of Portugal as an example:

$$h_{dom_2} = 61.1371 \left(\frac{h_{dom_1}}{61.1371} \right)^{\left(\frac{t_1}{t_2} \right)^{0.4805}} \quad h_{dom_1} = 61.1371 \left(\frac{h_{dom_2}}{61.1371} \right)^{\left(\frac{t_2}{t_1} \right)^{0.4805}}$$

To estimate site index using this type of equations simply assume t_2 (or t_1 , depending whether the stand age is lower or higher than the standard age) is equal to the standard age.

1) Consider a stand with 4 years and a dominant height of 8.2 m.
If the age of the stand is lower than the standard age:
hdom ₁ = 8.2 t ₁ = 4
hdom ₂ = ? (S) t ₂ = 10
$hdom_2 = 61.1371 \left(\frac{hdom_1}{61.1371} \right)^{\left(\frac{t_1}{t_2} \right)^{0.4805}} \quad S = 61.1371 \left(\frac{hdom_1}{61.1371} \right)^{\left(\frac{t_1}{10} \right)^{0.4805}}$
S = 16.8 m
2) Consider a stand with 14 years and a dominant height of 24.1 m.
If the age of the stand is lower than the standard age:
hdom ₁ = ? (S) t ₁ = 10
hdom ₂ = 24.1 t ₂ = 14
$hdom_1 = 61.1371 \left(\frac{hdom_2}{61.1371} \right)^{\left(\frac{t_2}{t_1} \right)^{0.4805}} \quad S = 61.1371 \left(\frac{hdom_2}{61.1371} \right)^{\left(\frac{t_2}{10} \right)^{0.4805}}$
S = 20.5 m

For a better idea on the variety of functions available for estimating site index, **Table 5** shows some dominant height growth functions for the main Portuguese tree species.

1.6.5 Using Site Index Prediction Equations

The previous methods are based on functions fitted to estimate dominant height growth for any age (not for the standard age in particular). However, some authors have preferred to develop functions specifically for estimating site index.

Marques (1987, 1991) developed for the Tâmega Valley region separate equations (despite using the same data set) for estimating site index and dominant height growth:

$$S = 17.38 f_1(t) e^{f_2(t)} + f_1(t) hdom$$

$$f_1(t) = 0.865685 - 0.00804747 t + 0.000994305 t^2 - 0.0000187066 t^3$$

$$f_2(t) = 4.04764 - 8.75819 t^{-0.560870}$$

The problem with this lays on the compatibility between site index and dominant height functions being taken into account. The two functions are defined as compatible if the site index estimates obtained for the same age with both of them is the same.

Table 5. Some dominant height growth functions available for Portugal.

Region and reference	Expression	tp ¹
Maritime pine		
Mountainous and sub-mountainous regions Oliveira (1985)	$h_{dom} = S_{40} e^{-14.2234 \left(\frac{1}{t} - \frac{1}{40} \right)}$	40
Tâmega Valley Marques (1987)	$h_{dom} = e^{4.04764 \frac{8.75819}{t^{0.56087}} + 1.19874 \left(1 - e^{-0.081 t} \right)^{2.99578}} (lq - 17.38)$	35
Páscoa (1987)	$h_{dom} = S_{50} 10^{0.380999 - 2.694076 t^{-1/2}}$	50
Leiria National Forest Falcão (1992)	$h_{dom} = 103.7 \left(\frac{S_{50}}{103.7} \right)^{\left(\frac{50}{t} \right)^{0.3593}}$	50 (qq)
Portugal (PAMAF 8165) Tomé et al. (2001)	$h_{dom_2} = 69 \left(\frac{h_{dom_1}}{69} \right)^{\left(\frac{t_1}{t_2} \right)^{0.4582}}$	qq
Eucalyptus		
Soporcel Litoral Stand Amaro et al. (1990)	$h_{dom_2} = 35.7 \left(\frac{1 - \frac{\ln(1 - e^{-0.0917 t_2})}{t_2}}{\ln(1 - e^{-0.0917 t_1})} \right) h_{dom_1} \frac{\ln(1 - e^{-0.0917 t_2})}{\ln(1 - e^{-0.0917 t_1})}$	10 qq
Centre Coastal Portugal 1st rotation ² Tomé et al. (2001)	$h_{dom_2} = 61.1371 \left(\frac{h_{dom_1}}{61.1371} \right)^{\left(\frac{t_1}{t_2} \right)^{0.4805}}$	10 qq
Cork oak		
Spain (Catalunia and Huelva) Gonzalez et al. (2005)	$h_{dom_2} = 16.2954 \cdot \left\{ 1 - \left[1 - \left(\frac{h_{dom_1}}{16.2954} \right)^{1-0.3282} \right] \frac{t_2}{t_1} \right\}^{\frac{1}{1-0.3282}}$	80 qq

1 tp indicates the standard age

2 for other regions and rotations see the original publication

qq indicates the function can be used for any standard age, although authors recommend the suggested age

1.7 Volume

As mentioned for tree volume, stand volume also refers to over bark volume including the stump. The volume of the plot or stand is obtained. Depending on the volume considered for the trees (for example, if the over bark volume without stump was determined for each tree, the corresponding plot/stand volume will also be over bark volume without stump). Stand volume can be determined using alternative approaches. In the case of volume, several alternative approaches can be applied: direct and indirect, based on complete enumeration or diameter distribution.

Direct assessment of volume

In theory it is possible to calculate the cubic volume of each of the trees in a plot using direct assessment. However, in practice this is rarely done because the gain in precision is not counterbalanced for the time and resources consumption. The exception could be the measurement of some permanent plots at the time of harvesting.

1.7.1 Estimation of Volume using Equations

1.7.1.1 Stand Volume Equations

A volume equation is a mathematical expression (fitted by regression) that allows obtaining stand volume based on the values of other stand variables. Volume is usually determined as a function of stand basal area ($\text{m}^2 \text{ha}^{-1}$) and of a stand height, usually dominant height. **Table 6** presents some examples of stand volume equations available in Portugal.

Table 6. Stand volume equations for the main tree species in Portugal.

Region and reference	Expression
Maritime pine	
Leiria Nacional Forest Azevedo Gomes (1952)	$V = 55.745 + 0.3873 G \text{ hdom}$ $V \text{ (m}^3 \text{ ha}^{-1}) \quad G \text{ (m}^2 \text{ ha}^{-1}) \quad \text{hdom (m)}$
Tâmega Valley (Moreira e Fonseca, 2002)	$V = 0.2768 G + 0.4376 G \text{ h}_{\text{dom}}$ $V \text{ (m}^3 \text{ ha}^{-1}) \quad G \text{ (m}^2 \text{ ha}^{-1}) \quad \text{hdom (m)}$ (principal stand before thinning)
Eucalyptus	
Centre Coastal Portugal 1st rotation ¹ Tomé et al. (2001)	$V = \left(0.4886 - 0.1348 \frac{100}{S \sqrt{Npl}} \right) t^{0.0655} \text{hdom}^{0.8839} G^{1.0263}$ $V \text{ (m}^3 \text{ ha}^{-1}) \quad G \text{ (m}^2 \text{ ha}^{-1}) \quad \text{hdom (m)}$

1 for other regions and rotations see original publication

Consider a stand with a basal area of 24.7 m ² ha ⁻¹ and a dominant height of 22 m.			
Determine stand volume			
Leiria Nacional Forest Azevedo Gomes (1952)	$V = \beta_0 + \beta_1 G \text{ hdom}$ $V \text{ (m}^3 \text{ ha}^{-1}) \quad G \text{ (m}^2 \text{ ha}^{-1}) \quad \text{hdom (m)}$	b0 = 55.745 b1 = 0.3873	
G = 24.7 hdom = 22	V =	266.20 m ³ ha ⁻¹	

A forest technician must always use an appropriate stand volume equation. In order to achieve this he can either fit his own stand volume equation in case the stand area and the wood market value justify doing so or he can pick an existing equation from bibliography.

1.7.1.2 Using Tree Volume Equations

There are three methods based on tree volume equations: complete enumeration of diameters and heights; using sample trees and local height/DBH curves and using generic height/DBH curves.

Using complete enumeration of diameters and heights

Once the most appropriate tree volume equation has been selected, tree volumes are estimated, summed up and reported to the hectare.

Tree Number	d (cm)	height (m)	g (m ² ha ⁻¹)	volume estimate	
Property: <i>Fernão Ferro</i>					
Plot: 74					
Date: 1997					
16	30.6	14.2	0.0735	0.48138	With g calculated using the expression: $\pi()/40000*d^2$ (with d representing DBH)
30	27.5	19.2	0.0594	0.52460	
3	26.4	14.9	0.0547	0.37855	
17	26.0	14.5	0.0531	0.35797	With v calculated using the expression: $0.01177+0.000035319*d^2*h$ (with d representing DBH)
21	25.7	15.2	0.0519	0.36635	
1	25.4	13.4	0.0507	0.31604	
2	25.4	12.9	0.0507	0.30464	
4	25.2	13.3	0.0499	0.31030	
22	24.2	13.1	0.0460	0.28246	
5	24.1	13.1	0.0456	0.27976	
15	24.1	13.1	0.0456	0.27976	
14	23.5	12.8	0.0434	0.26186	
31	23.4	12.9	0.0430	0.26120	
18	23.2	12.8	0.0423	0.25603	With G _p as the sum of g and G as G _p times the expansion factor that in this case is 20 (10000/500)
32	23.2	14.5	0.0423	0.28742	
19	22.7	13.4	0.0405	0.25516	
20	22.7	13.4	0.0405	0.25516	
26	22.4	13.3	0.0394	0.24740	
8	22.1	13.4	0.0384	0.24288	With V _p as the sum of v and V as V _p times the expansion factor that in this case is 20 (10000/500)
27	21.7	13.5	0.0370	0.23646	
29	21.6	18.5	0.0366	0.31662	
6	21.5	13.5	0.0363	0.23144	
7	21.1	13.3	0.0350	0.22157	
25	20.3	13.1	0.0324	0.20255	
9	19.6	16.9	0.0302	0.24107	
10	18.2	12.4	0.0260	0.15707	
11	17.1	11.1	0.0230	0.12642	
13	14.6	9.4	0.0167	0.08254	
12	14.5	9.4	0.0165	0.08157	
28	13.9	9.4	0.0152	0.07592	
24	11.5	10.5	0.0104	0.06081	
23	11.1	8.6	0.0097	0.04938	
G _p =	1.2356	m ²	V _p =	8.0323	m ³
G =	24.71	m ² ha ⁻¹	V =	160.65	m ³ ha ⁻¹

Using Sample Trees Combined with Height/DBH Curves

If the plot is big enough (1000 m² or more) a local height/DBH curve can be fitted to the data plot data. However, if the plot area is small, but the plot is in a homogeneous stand

for which several plots have been measured it is possible to fit a local height/DBH curve using the data from all the plots.

Tree Number	d (cm)	height (m)	g (m ² ha ⁻¹)	height estimate	volume estimate
16	30.6	14.20	0.0735	14.20	0.48138
30	27.5	19.2	0.0594	19.20	0.52460
3	26.4	14.90	0.0547	14.90	0.37855
17	26.0	14.50	0.0531	14.50	0.35797
21	25.7	15.2	0.0519	15.20	0.36635
1	25.4		0.0507	13.60	0.32173
2	25.4		0.0507	13.60	0.32173
4	25.2		0.0499	13.56	0.31591
22	24.2		0.0460	13.34	0.28764
5	24.1		0.0456	13.31	0.28489
15	24.1		0.0456	13.31	0.28489
14	23.5		0.0434	13.17	0.26869
31	23.4		0.0430	13.15	0.26604
18	23.2		0.0423	13.10	0.26078
32	23.2	14.5	0.0423	14.50	0.28742
19	22.7		0.0405	12.97	0.24788
20	22.7		0.0405	12.97	0.24788
26	22.4		0.0394	12.90	0.24031
8	22.1		0.0384	12.82	0.23287
27	21.7		0.0370	12.71	0.22315
29	21.6	17.7	0.0366	17.70	0.30344
6	21.5		0.0363	12.65	0.21838
7	21.1		0.0350	12.54	0.20899
25	20.3		0.0324	12.31	0.19090
9	19.6	16.1	0.0302	16.10	0.23022
10	18.2		0.0260	11.62	0.14771
11	17.1		0.0230	11.21	0.12756
13	14.6	9.40	0.0167	9.40	0.08254
12	14.5		0.0165	10.08	0.08665
28	13.9		0.0152	9.78	0.07854
24	11.5	10.5	0.0104	10.50	0.06081
23	11.1		0.0097	8.14	0.04720

Property: *Fernão Ferro*

Plot: 74

Date: 1997

With g calculated using the expression: $\pi()/40000*d^2$
(with d representing DBH)

With h estimated using the expression: $EXP(3.2545-0.0895*\ln(hdom)-10.1175/d)$

With v calculated using the expression:
 $0.01177+0.000035319*d^2*h$
(with d representing DBH)

With G_p as the sum of g and G as G_p times the expansion factor that in this case is 20 (10000/500)

With V_p as the sum of v and V as V_p times the expansion factor that in this case is 20 (10000/500)

hdom=	$G_p =$	1.2356 m ²	$V_p =$	7.9836 m ³
15.60	$G =$	24.71 m ² ha ⁻¹	$V =$	159.67 m ³ ha ⁻¹

On the other hand, if the plot area is small and the plot is the only representative of the stand a generic height/DBH curve can be used (either by fitting an equation to the measured data either by searching the literature). This alternative does not require that all trees are measured; only those necessary to the application of the height/DBH curve such as dominant trees (needed to obtain dominant height).

Afterward, trees' heights are estimated and volume determined as for the complete enumeration.

Using the Diameter Distribution

Volume can be determined using data aggregated in k diameter classes. In this case, the volume calculus is based on the diameter class mid-point (or central diameter - vc_j) and on the average of the heights measured under each diameter class (hm_j) when choosing not to use height/DBH curves.

$$V = \sum_{j=1}^k n_j vc_j \quad \text{with} \quad vc_j = f(dc_j, hm_j)$$

Where vc_j is the volume corresponding to the mid-point diameter in class j determined using a volume equation function of dc_j and hm_j .

However, if only the dominant trees were measured, a height/DBH curve needs to be used as shown below.

Property: Fernão Ferro							
Plot: 74							
Date: 1997							
d Classes	central diameter	fj (n_p)	n	hmj (m)	vcj	Vcj	With mean h calculated using the expression: $EXP(3.2545-0.0895*LN(hdom)-10.1175/"central diameter")$; vcj calculated with $0.01177+0.000035319*"central diameter"^2*"mean h"$ and Vcj as the product of vcj * n
7.5-12.4	10	2	40	7.37	0.037786	1.511433	
12.5-17.4	15	4	80	10.32	0.093784	7.50269	
17.5-22.4	20	9	180	12.22	0.184352	33.18343	
22.5-27.4	25	15	300	13.52	0.310141	93.04221	
27.5-32.4	30	2	40	14.46	0.471404	18.85615	
hdom =	15.6		N = 640		V =	154.0959 m ² ha ⁻¹	V results from summing up the Vcj values in each diameter class

Some Considerations when using Volume Equations

Any situation that affects the tree or stand level volume estimates, namely defects at diameter at breast height and/or the top of the trees will affect the precision of the estimates depending on how severe and frequent they are. Volume equations provide estimates for healthy normal average trees, therefore the correction of abnormalities must be carried out carefully otherwise it might lead to severe errors either by over or under estimating volume. Moreover, when the inventory objective is other than commercial the correction of abnormalities can be disregarded.

As long as a local height/DBH curve fitted using a dataset of trees representative of the population, or a generic height/DBH curve well adapted to the site is used, it is possible to obtain volume estimates with errors below 10%, or even less (Azevedo Gomes, 1952).

1.8 Leaf Area Index

The Leaf Area Index (LAI) results from the sum of the leaf area of all trees in the stand (adimensional measure). This stand variable is not easy to determine. Three alternative approaches can be used: using sample trees, estimation using allometric equations or through indirect assessment of intercepted light. The second approach requires the use of an allometric equation to estimate LAI for each tree. The problem in this approach relates to the fact that sometimes the independent variables used in these allometric equations have not been measured for all trees (total height and height to the base of the crown) and requires fitting new allometric equations using the measurements conducted in that stand or simply estimating the independent variables so that the allometric equation can be used (for example, if total tree height is missing, estimate it using a height/DBH curve). Finally, the third approach is based on the close relation between LAI and light intercepted. A device, named ceptometer, can be used to measure intercepted light in all possible situations: above crown, undercover in transition areas and in open areas. However, the details on approaches one and three are not covered by this course.

1.9 Stand biomass

Stand biomass (usually represented by W) is defined as the sum of biomass of all the trees in the stand reported to the hectare. Similarly to tree biomass, stand biomass has several components that need to be assessed separately. It is common to distinguish between aboveground and belowground biomass. Aboveground biomass (W_a) comprises the biomasses of wood (W_w), bark (W_b), branches (W_{br}), leaves/needles (W_l), flowers and fruits (W_f). Belowground biomass (W_r) can be differentiated in main root, coarse roots and fine roots. Stand biomass can be determined by the following approaches: using sample trees and estimation either using tree or stand level biomass equations.

1.9.1 Using Sample Trees

The method is similar to what has been described for volume and can also present the same troubles described for LAI concerning the availability of some of the independent variables. Given the difficulties of correctly assessing root biomass, this variable is not determined for all sample trees, even for aboveground biomass it is common to adjust the number of sample trees to minimize the number of trees selected for destructive sampling.

1.9.2 Using Tree and stand Biomass Equations

When estimating biomass using tree level equations it is possible that some of the independent variables such as the height of the base of the crown are not available. This problem will have to be solved as described for LAI. On the other hand, if stand level biomass equations are available, as it happens for eucalyptus (**Table 7**) biomass estimates per hectare can be directly obtained.

1.10 Estimating carbon stocks

Carbon stock estimation has become more important over the years. Usually refers to trees, but can also be estimated for the understory vegetation, litter-fall and soil. Except for the soil carbon stock, all others are assessed based on biomass and multiplied by the carbon content, which is close to 0.5 for all tree components.

Table 7. Stand level biomass equations for eucalyptus in GLOBULUS 3.0 model (Tomé et al., 2007)

Eucalyptus					
Wi	Expression				
Ww	$Ww = a_w G^{b_w} h_{dom}^{c_w}$ $a_w = 0.0967$ $b_w = 1.0547 - 0.0018 \times rot - 0.0065 \times \left(\frac{N}{1000}\right) - 0.5198 \times \left(\frac{S}{1000}\right) - 1.2105 \times \left(\frac{t}{1000}\right)$ $c_w = 1.1886$				
Wb	$Wb = a_b G^{b_b} h_{dom}^{c_b}$ $a_b = 0.03636$ $b_b = 1.1691 - 0.0083 \times rot - 0.0459 \times \left(\frac{N}{1000}\right) + 3.2289 \times \left(\frac{S}{1000}\right) + 2.0880 \times \left(\frac{t}{1000}\right)$ $c_b = 0.6710$				
Wl	$Wl = a_l G^{b_l} h_{dom}^{c_l}$ $a_l = 1.0440$ $b_l = 1.0971 - 0.0112 \times \left(\frac{N}{1000}\right) - 1.2207 \times \left(\frac{S}{1000}\right) - 6.2807 \times \left(\frac{t}{1000}\right)$ $c_l = -0.3129$				
Wbr	$Wbr = a_{br} G^{b_{br}} h_{dom}^{c_{br}}$ $a_{br} = 0.3972$ $b_{br} = 1.0005 - 0.0192 \times \left(\frac{N}{1000}\right) + 3.3170 \times \left(\frac{S}{1000}\right) - 1.2747 \times \left(\frac{t}{1000}\right)$ $c_{br} = -0.0160$				
Wa	$Wa = Ww + Wb + Wl + Wbr$	Wr	$Wr = 0,2487 Wa$	Wt	$W = Wa + Wr$

Unit: all biomass is in Mg ha⁻¹, G in m² ha⁻¹, N in ha⁻¹ and t in years.

2 Development and Structure of Empirical Growth and Yield Models

2.1 Elements of Empirical Growth and Yield Models

Despite the expression growth model can also cover the classical growth and yield tables, nowadays a growth model refers to a set of equations that, when combined, allow simulating the growth and yield of a forest under a wide variety of environmental and/or silvicultural conditions.

A growth model comprises a set of state variables, at tree or stand level, whose evolution over time consists of the output of the model. Additionally, the distribution of some of

these variables by dimension classes or their corresponding special distribution can also be considered. The evolution of each variable is simulated based on a well-defined methodology usually consisting of two types of mathematical equations:

1. Growth Function

A growth function allows estimating the evolution of a tree/stand variable over time depending or not on the evolution of other variables. Therefore, growth functions are characterised by being dynamic.

2. Prediction Equation

A prediction equation, on the contrary, allows estimating the value of a tree/stand variable for a given moment in time as a function of other variables. Therefore, prediction equations are defined as static.

In a growth model, the variables whose growth is directly simulated, based on a growth function are considered principal/driving variables. On the other hand, if the evolution of variables over time is indirectly simulated using a prediction equation that is based on the consecutive values of principal variables, then these are considered to be derived variables.

Principal/driving variables can be dependent or independent, according to whether the growth function used to simulate its evolution relies on other simulated variables or not. These definitions are important because the simulation of an independent driving variable is only affected by errors inherent to its growth function, whereas the simulation of dependent driving variables also includes the errors inherent to the simulation of all other variables that are part of the growth function. Similarly, the simulation of derived variables includes the errors of: the prediction equation combined with the errors of the principal/driving variables included in the prediction equation.

Additionally, growth models also include a set of external/control variables that affect the evolution of stand dynamics. These can be of two types: environmental, such as site index or environmental factors; and silvicultural, such as the spacing or the thinning intensity.

Growth functions and prediction equations that allow simulating the evolution of a stand over time can contain parameters that vary according to the region or site. The true structure of a model involves establishing the relationship between all the state variables (driving plus derived variables). Finally, the set of growth functions and prediction

equations should be implemented into a computer programme to permit users to simulate different management alternatives in a user-friendly way.

To summarize, a growth and yield model integrates:

1. A set of state variables influenced by a set of environmental and silvicultural control variables;
2. A set of mathematical equations (growth functions and prediction equations);
3. The parameters assigned to the equations;
4. The logical structure required to properly establish the relationships between the different equations;
5. The computer programme to integrate all this in a user-friendly way.

2.1.1 The Different Modules of a Management Oriented Growth and Yield Model

Any management oriented growth and yield model has four components:

Initialization module – This module is responsible for initializing the principal variables directly by inventory data or indirectly through the simulation as a function of age or the value of control variables

Growth module - This module is responsible for updating the values of the principal variables over time based on the growth functions integrated in the model.

Prediction module - This module is responsible for updating the values of the derived variables over time using in the prediction equations the updated values of the principal variables that resulted from the previous module.

Management module - This module is responsible for simulating silvicultural operations by modifying the values of the principal and derived variables determined in the previous modules.

The differences between different types of models consist on the definition of the state variables, how the evolution of growth is simulated, how management is implemented and on the possible existence of additional modules. However, the main structure of growth models maintains.

It is important to stress that dominant height is a vital principal variable either in stand or tree level growth models. However, basal area despite being very important in terms of management represents a principal variable for stand level models and a derived

variable in tree level models being calculated as the sum of all the updated sectional areas of each tree.

2.1.2 Developing an Empirical Growth and Yield Model

Developing a growth and yield model is a complex process that comprises the following different phases:

1. Data collection
2. Model selection
3. Defining the model structure
4. Selecting the growth functions and prediction equations and their corresponding parameterization
5. Model evaluation/validation
6. Implementation of the model into a computer programme.

The data collection phase has a huge impact on the quality of the model. The performance of the model depends greatly on the quality of the data used to develop it. The second phase consists of selecting the type of model to build: stand level model with or without diameter distribution or tree level model distance dependent or independent. After this has been decided, it is time to define the structure of the model by choosing the state and control variables that will integrate the model as well as the relationship between them. Concerning the state variables, it has to be defined which will be directly projected by the model – the principal variables – and which will be estimated based on the projected values of the principal variables – the derived variables. However, for many variables the selection of the type of model regulates whether a variable can be defined as principal or derived. Dominant height growth, and consequently site index, is simulated as an independent principal variable (see section 5.1.3). Environmental control variables are often replaced by site index; however the model can also reflect specific soil-climate conditions. On the other hand, the inclusion of silvicultural control variables depends on the availability of data capable of reflecting the effect of these treatments on the growth of trees and stands. Careful analysis of the available data will allow determining which silvicultural treatments the model will be able to simulate. Once the variables have been selected the relationships between them will have to be established and this represents the model conception.

A wide variety of growth functions can be used to simulate tree and stand growth, direct or indirectly. The choice for one of them is usually based on the theory of regression – linear or non-linear - which provides us a set of tools to assist us in the process of electing the best function. Parameterization consists of assigning the most suitable values to the parameters included in the growth functions, prediction equations or any other equations part of the model. Parameterization is achieved through fitting the functions and equations to the dataset using linear, non-linear and logistic regression techniques or, less often, other statistical tools. With all the parameters defined and before using the model, it is necessary to assess the credibility of our simulations. The assessment of models can be carried out by comparing the simulations with real data (a set of independent data not used in the parameterization process) or sometimes with the results of another model previously developed and validated. It is also necessary to ensure that the model behaves according to forest biology and ecology theories. The final phase consists of implementing the model into a computer programme that will facilitate the use of the tool without a deep knowledge of its structure. The user will only have to provide to the programme the characteristics of the stand he intends to simulate and the management options he would like to compare. The model output will show the evolution of a stand over time under the management options defined as input indicating the quantity, and sometimes the quality, of the products expected as well as the time when these products will be available. Sometimes, the user is given the chance to interactively define his management options step by step based on the simulation results obtained so far.

Finally, it is important to stress that these phases are not necessarily sequential. Model development is an interactive process during which results are constantly evaluated allowing going back in any decision if results prove unsatisfying in order to obtain the best model possible.

2.1.3 Growth Functions

Two types of functions deriving from two opposing philosophies have been used to model growth: empirical growth functions and analytical or functional growth functions.

For the empirical growth functions the relationship between the dependent variable – the one we want to model – and the independent variables is established according to some mathematical function – e.g. linear, parabolic, without trying to identify the causes or explaining the phenomenon. Opposing, analytical or functional growth functions are conceived in terms of the mechanism of the system, usually having an underlying hypothesis associated with the cause or function of the phenomenon described by the response variable. The distinction between the two is not sharp and most modelling applications contain both empiricism and mechanism in varying mixtures

If a mathematical growth model is based on logical prepositions regarding the biology of growth, then the parameter estimates obtained from a given dataset can be interpreted according to the model formulation, which allows to improve the knowledge on the functional relationships –cause/effect) – between variables

The functions used for modelling biological growth, either empirical or biologically derived, must present a shape that concurs with the biological growth principles:

- i) The curve is limited by yield 0 at the start ($t=0$ or $t=t_0$) and by a maximum yield at an advanced age (existence of asymptote)
- ii) The relative growth rate (variation of the x variable per unit of time and unit of x) presents a maximum at a very early stage, decreasing afterwards; in most cases, the maximum occurs very early so that we can use decreasing functions to model relative growth rate;
- iii) The slope of the curve increases in the initial stage and decreases after a certain point in time (existence of an inflexion point)

Theoretical growth functions have commonly been developed in their growth form – either absolute or relative growth – and the respective yield form has been obtained by integration. Generally, this approach allows interpretation of the function parameters and helps to impose restrictions on the values that the parameters can take to be biologically consistent. Theoretical growth functions are grouped according to their functional form in: Lundqvist-Korf type, Richards type, Hossfeld IV type.

2.1.3.1 Empirical Growth Functions

Several empirical functions have been used as growth functions mainly in the differential form. Despite several empirical functions are commonly used (**Table 8**) none of them exhibits all biological principles; therefore the restrictions imposed to the parameters reflect the most convenient shape for modelling growth.

2.1.3.2 Analytical or functional growth functions

Biologically based growth functions are usually obtained by differential form through the definition of a hypothesis regarding the maximum or relative growth rate whereas the production is obtained by integration. It is then possible to define the meaning of the parameters of these functions. **Table 2** summarizes the main characteristics of some of these functions where parameter A represents the production superior asymptote, parameter k is related to the slope of the curve (growth rate) and parameter c reflects the initial dimension of the individual/population.

Table 1. Some empirical growth functions used for modelling forest growth

Author or designation	Mathematical Expression			Characteristics		
	Integral form (production)	Differential form (growth)	Parameter restrictions	Intercept value	Inflection point	Asymptote
Hyperbole	$Y = \beta_0 + \beta_1 \frac{1}{t}$	$\frac{dY}{dt} = -\beta_1 \frac{1}{t^2}$	$\beta_1 < 0$	$t \rightarrow 0; Y \rightarrow -\infty$	lacking	$t \rightarrow \infty; Y = \beta_0$
-	$Y = \beta_0 + \beta_1 \frac{1}{t} + \beta_2 t$	$\frac{dY}{dt} = \beta_2 - \beta_1 \frac{1}{t^2}$	$\beta_1 < 0; \beta_2 > 0$	$t \rightarrow 0; Y \rightarrow -\infty$	lacking	$t \rightarrow \infty; Y \rightarrow \infty$
Semi- Logarithmic	$Y = \beta_0 + \beta_1 \log t$	$\frac{dY}{dt} = \beta_1 - \frac{1}{t}$	$\beta_1 > 0$	$t \rightarrow 0; Y \rightarrow -\infty$	lacking	$t \rightarrow \infty; Y \rightarrow \infty$
Logarithmic 1	$Y = \beta_0 + \beta_1 t^{\beta_2}$	$\frac{dY}{dt} = \frac{\beta_2}{t} (Y - \beta_0)$	$\beta_1, \beta_2 > 0; \beta_2 < 1$ $\beta_1, \beta_2 < 0$	$t = 0; Y = \beta_0$ $t \rightarrow 0; Y \rightarrow -\infty$	lacking	$t \rightarrow \infty; Y \rightarrow \infty$ $t \rightarrow \infty; Y \rightarrow \beta_0$
Logarithmic 2	$Y = (\beta_0 + \beta_1 t)^{\beta_2}$	$\frac{dY}{dt} = \frac{\beta_0 \beta_2 Y}{\beta_0 + \beta_1 t}$	$\beta_1, \beta_2 > 0; \beta_2 < 1$	$t = 0; Y = \beta_0^{\beta_2}$	lacking	$t \rightarrow \infty; Y \rightarrow \infty$
Exponential	$Y = \beta_0 + \beta_1 e^{\beta_2 t}$	$\frac{dY}{dt} = \beta_2 (\beta_0 - Y)$	$\beta_1, \beta_2 < 0$	$t = 0; Y = \beta_0 + \beta_1$	lacking	$t \rightarrow \infty; Y \rightarrow \beta_0$
Freese	$Y = \beta_0 t^{\beta_1} + \beta_2 t$ $\beta_0 > 0$	$\frac{dY}{dt} = Y \left(\log \beta_2 + \frac{\beta_1}{t} \right)$	$\beta_1 > 0; \log \beta_2 < 0$ $\beta_1 > 0; \log \beta_2 > 0$ $\beta_1 > 0; \log \beta_2 > 0$	$t = 0; Y = 0$ $t = 0; Y = 0$ $t = 0; Y = 0$	$t = \frac{-\beta_1 \pm \sqrt{\beta_1}}{\log \beta_2}$ lacking $t = \frac{-\beta_1 \pm \sqrt{\beta_1}}{\log \beta_2}$	$t \rightarrow \infty; Y \rightarrow -\infty$ $t \rightarrow \infty; Y \rightarrow \infty$ $t \rightarrow \infty; Y \rightarrow \infty$
Hossfeld	$Y = \frac{t^2}{\beta_0 + \beta_0 + \beta_2 t^2}$	$\frac{dY}{dt} = Y^2 \left(\frac{2\beta_0 + \beta_1 t}{t^3} \right)$	$\beta_0 > 0; \beta_1 < 0$ $\beta_0 > 0; \beta_1 > 0$	$t = 0; Y = 0$ $t = 0; Y = 0$	$\beta_1 \beta_2 t^3 + 3\beta_0 \beta_2 t^2 - \beta_0^2 = 0$	$t \rightarrow \infty; Y \rightarrow \frac{1}{\beta_2}$
Korsun (logarithmic parabole)	$Y = \beta_0 t^{\beta_1 + \beta_2 \log t}$ $\beta_0 > 0$	$\frac{dY}{dt} = \frac{Y}{t} (\beta_1 + 2\beta_2 \log t)$	$\beta_1 > 0; \beta_2 < 0$	$t \rightarrow 0; Y \rightarrow 0$	$z^2 - z + 2\beta_2 = 0$ $z = \beta_1 + 2\beta_2 \log t$	$t \rightarrow \infty; Y \rightarrow 0$

Table 2. Biologically based growth functions.

Author or designation	Mathematical Expression			Characteristics		
	Integral form (production)	Diferencial form (growth)	Parameter restrictions	Intercept value	Inflection point	Assímptota
Schumacher	$Y = A e^{-\frac{k}{t}}$	$\frac{dY}{dt} = Y \frac{k}{t^2}$	$k > 0$	$t \rightarrow 0; Y \rightarrow 0$	$t = \frac{k}{2}; Y = \frac{A}{e^2}$	$t \rightarrow \infty; Y \rightarrow A$
Johnson-Schumacher	$Y = A e^{-\frac{k}{t+a}}$	$\frac{dY}{dt} = Y \frac{k}{(t+a)^2}$	$k > 0$	$t \rightarrow 0; Y \rightarrow A e^{\frac{k}{a}}$	$t = \frac{k}{2} - a; Y = \frac{A}{e^2}$	$t \rightarrow \infty; Y \rightarrow A$
Lundqvist-Korf	$Y = A e^{-\frac{k}{t^m}}$	$\frac{dY}{dt} = mY \frac{k}{t^{m+1}}$	$k > 0; n > 0$	$t \rightarrow 0; Y \rightarrow 0$	$t = \left(\frac{mk}{m+1}\right)^{\frac{1}{m}}; Y = A e^{-\frac{m+1}{n}}$	$t \rightarrow \infty; Y \rightarrow A$
Monomolecular	$Y = A (1 - ce^{-kt})$	$\frac{dY}{dt} = k(A - Y)$	$k > 0$	$t = 0; Y = A(1 - c)$	lacking	$t \rightarrow \infty; Y \rightarrow A$
Logistic	$Y = \frac{A}{(1 + ce^{-kt})}$	$\frac{dY}{dt} = \frac{k}{A}(AY - Y^2)$	$k > 0$	$t = 0; Y = \frac{A}{1+c}$ $t \rightarrow -\infty; Y \rightarrow 0$	$t = \frac{1}{k} \log c; Y = \frac{A}{2}$	$t \rightarrow \infty; Y \rightarrow A$
Pearl-Reed	$Y = \frac{A}{1 + ce^{-(a_1t + a_2t^2 + a_3t^3)}}$	$\frac{dY}{dt} = \frac{1}{A}(AY - Y^2)f(t)$	$a_1, a_3 > 0$ $c > 0$	$t = 0; Y = \frac{A}{1+c}$ $t \rightarrow -\infty; Y \rightarrow 0$	inflection $Y = \frac{A}{x}$	$t \rightarrow \infty; Y \rightarrow A$
Gompertz	$Y = A e^{-ce^{-kt}}$	$\frac{dY}{dt} = k Y \ln \frac{A}{Y}$	$k > 0$ $c > 0$	$t = 0; Y = A e^{-c}$ $t \rightarrow -\infty; Y = 0$	$t = \frac{\log c}{k}; Y = \frac{A}{e}$	$t \rightarrow \infty; Y \rightarrow A$
Richards	$Y = A \left(1 - ce^{-kt}\right)^{-\frac{1}{1-m}}$	$\frac{dY}{dt} = \frac{kY}{1-m} \left[\left(\frac{A}{Y}\right)^{1-m} - 1\right]$	$k > 0$	$t = 0;$ $Y = A (1 - c)^{\frac{1}{1-m}}$	$t = \frac{\log\left(\frac{c}{1-m}\right)}{k}; Y = Am^{\frac{1}{1-m}}$	$t \rightarrow \infty; Y \rightarrow A$
McDill-Amateis	$Y = \frac{A}{1 - (1 - A/Y_0) (t_0/t)^a}$	$\frac{dY}{dt} = a \frac{Y}{t} \left(1 - \frac{Y}{A}\right)$	$a > 0$ $A > Y_0 > 0$	$t \rightarrow 0; Y \rightarrow 0$	$Y = \frac{A}{2} \left(1 - \frac{1}{a}\right)$	$t \rightarrow \infty; Y \rightarrow A$

2.1.4 Expressing growth functions' parameters as a function of stand variables

Several authors have tried to overcome the difficulties originated from trying to model altogether datasets from different stands by expressing the coefficients of growth functions as a function of stand variables. This process was suggested by Schumacher

with the objective of introducing the influence of other variables, such as site index and density, into his model.

For the logarithmic form of Schumacher's function:

$$\ln Y = a - k \frac{1}{t}, \quad \text{with } a = \ln A$$

One can consider, for example, parameter a as a linear function of site index, therefore obtaining:

$$\ln Y = \beta_0 + \beta_1 CQ - k \frac{1}{t}.$$

Another typical example are the site index curves obtained by multiple regression found in GLOBULUS model (Tomé *et al.*, 2000, 2001) which are based on a set of growth functions, some of which formulated as difference equations, whose parameters are expressed as a function of one or several stand variables: site index, stand density, age, rotation, etc. As an example, consider the basal area initialization in GLOBULUS model:

$$G = Ag e^{-(kg_1 + kg_2) \left(\frac{1}{t}\right)^{mg}}$$

$$kg_1 = kg_0 + (kgQ + kgQr \cdot rot) \frac{1}{lqe} + kgr \cdot rot$$

$$kg_2 = (kgn + kgnr \cdot rot) \frac{1}{\sqrt{Npl}}$$

$$Ag = AgQ \cdot lqe$$

$$mg_1 = mg_0 + mgQ \cdot \log(lqe) + (mgr + mQr \cdot \log(lqe)) \cdot rot$$

$$mg_2 = mgn + mgnr \cdot rot$$

where: G_i is basal area in instante t_i ; N_i is stand density in instant t_i ; Npl is the density at planting; lqe is the site index, rot is the indicative variable for rotation (=0 in planted stands and =1 in coppices); AgQ , $ng0$, ngQ , ngr , ngn , $ngnr$, $kg0$, kgQ , $kgQr$, kgr ; kgn and $kgnr$ are parameters..

A usual way to incorporate stand variables other than time in growth functions has been using multiple regression shifting therefore to empirical models. A typical example are the tree level diameter increment functions (Harrison *et al.*, 1986; Walsh, 1986).

2.1.5 Growth Functions and Difference Equations

Tree growth follows some type of sigmoidal function that shows three stages along the life span of the tree. The length of each of the three stages of growth – exponential, linear

and senescence – depends on the variable considered as well as on the species and environment. Modelling of sigmoidal functions is usually achieved with the so-called theoretical growth curves, such as the Lundqvist (Stage 1963, Korf 1939), Richard or Hossfeld functions.

Those functions are mathematical equations that predict the variable under consideration as a function of age depicting the three stages of growth through the existence of an asymptote and of an inflection point. Theoretical growth functions are

usually developed on the basis of recognized biological relationships and, therefore, their parameters can be interpreted from a biological standpoint.

The Lundqvist function is obtained based on the hypothesis that relative growth rate varies inversely with a potential function of age, a relationship that agrees with biological concepts of tree and even-aged stands development. The yield form is:

$$Y = A e^{-k \frac{1}{t^n}},$$

Where k defines the rate of decrease of the relative growth rate and n is a shape parameter, Y is a tree or stand variable, t is age and A is an asymptote. The use of theoretical growth functions in tree and stand growth models guarantees an appropriate behaviour of the growth models and it is therefore an advantage over the use of empirical functions when used for extrapolation.

One very successful way of modelling tree and stand growth is through the use of growth functions expressed as difference equations. A difference equation represents a family of growth functions with all the parameters common except one, the “free” parameter. It predicts one variable at t_2 (Y_2) as a function of t_2 , the initial measurement age (t_1) and the value of the variable at the initial measurement age (Y_1).

Let us look at the example of dominant height.

The difference equation method is based on the development of a difference equation based on the growth functions selected for fitting in order to express dominant height in instant t_2 (h_{dom_2}) as a function of dominant height in instant t_1 (h_{dom_1}) and on the ages t_1 and t_2 . In order to achieve this one of the parameters will have to be considered the “free parameter” and the growth function will have to be solved for this parameter. Let's exemplify with the k parameter:

$$Y = A e^{-k \frac{1}{t^n}} \Leftrightarrow \frac{Y}{A} = e^{-k \frac{1}{t^n}} \Leftrightarrow \ln\left(\frac{Y}{A}\right) = -k \frac{1}{t^n} \Leftrightarrow -t^n \ln\left(\frac{Y}{A}\right) = k$$

k is the same for the instants t_1 and t_2 , therefore one can write:

$$-t_1^n \ln\left(\frac{Y_1}{A}\right) = -t_2^n \ln\left(\frac{Y_2}{A}\right) \Leftrightarrow \left(\frac{t_1}{t_2}\right)^n \ln\left(\frac{Y_1}{A}\right) = \ln\left(\frac{Y_2}{A}\right) \Leftrightarrow \ln\left(\frac{Y_1}{A}\right)^{\left(\frac{t_1}{t_2}\right)^n} = \ln\left(\frac{Y_2}{A}\right)$$

$$A \left(\frac{Y_1}{A}\right)^{\left(\frac{t_1}{t_2}\right)^n} = Y_2$$

Replacing Y by dominant height we get:

$$hdom_2 = A \left(\frac{hdom_1}{A} \right)^{\left(\frac{t_1}{t_2} \right)^n} \Leftrightarrow hdom_1 = A \left(\frac{hdom_2}{A} \right)^{\left(\frac{t_2}{t_1} \right)^n}$$

The use of this methodology relies on the existence of at least two consecutive measurements.

Because site index (S) is the height of a stand at a standard age (defined according to the species and/or site) it can be calculated using these expressions:

$$S = A \left(\frac{hdom}{A} \right)^{\left(\frac{t}{t_p} \right)^n} \Leftrightarrow hdom = A \left(\frac{S}{A} \right)^{\left(\frac{t_p}{t} \right)^n}$$

GLOBULUS 3.0 model

BRIEF DESCRIPTION & EQUATIONS

SUSANA BARREIRO

Globulus 3.0 Model

Background Introduction

Since the 90's, several empirical growth models have been developed to simulate *E. globulus* growth in the country ([Amaro 1998](#), [Amaro 2003](#), [Tomé et al. 2001a](#), [Tomé et al. 2001b](#), [Soares and Tomé 2003](#), [Barreiro and Tomé 2004](#), [Tomé et al. 2006](#)). At present, the third version of Globulus, referred to as Globulus 3.0 ([Tomé et al. 2006](#)), is the most commonly used model.

The GLOBULUS model ([Tomé et al. 2006](#), [Tomé et al. 2001](#)) is a stand level growth and yield model developed for pure even-aged stands. It integrates all the information available on eucalyptus growth and yield in Portugal and represents the combined efforts between industry and universities, which have been involved in several co-operative research projects over the past decades.

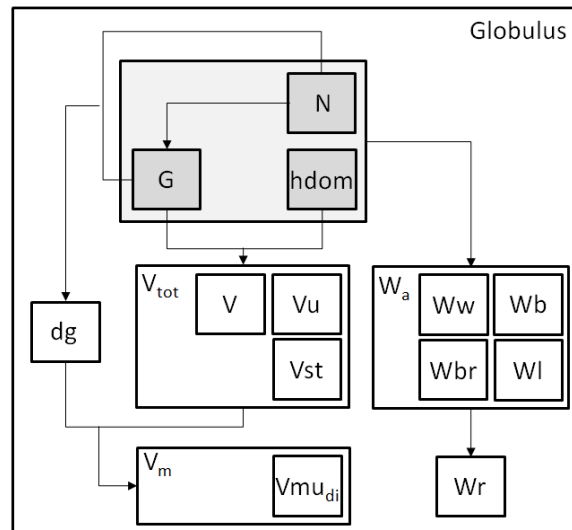
Model Description

GLOBULUS 3.0 includes two types of variables and two main modules. The variables that define the state of the stand over time (state variables) can be divided into principal variables in case they are directly projected with growth functions or derived variables when their values are predicted from allometric or other equations that relate them to the principal variables and other previously predicted derived variables (**Figure 1**). On the other hand, the external variables control the development of the state variables and can be of three different sub-types: environmental, related to the management regime or intrinsic to the stand. The model includes a sub-model for each one of the state variables. Each sub-model for principal variables includes a

growth function formulated as a difference equation that projects the variable over time. On the other hand, derived variables are predicted as a function of principal variables as well as of control variables and previously predicted derived variables.

The present version of this model has some of the parameters expressed as a function of climatic and site variables: the number of days with rain, the altitude, the total precipitation, the number of days with frost and the temperature.

The model has two modules, the initialization and the projection module. The initialization module predicts each principal variable as a function of the control variables that characterize the stand and is used to estimate the values of the principal variables in stands younger than 3 years that are not measured in the NFI (just visited and characterized). This module is essential to allow initializing a new stand either by planting or coppice. The projection module consists of a system of compatible functions for each principal variable as a function of its starting value and control variables. All the functions



Where: N , stand density; h_{dom} , dominant height; G , stand basal area; dg , quadratic mean diameter at breast height; V_u , volume under-bark with stump; V_b , volume of bark; V_{st} , volume of stump; V_{ust} , volume under-bark without stump; W_a , aboveground biomass; W_w , biomass of stem wood; W_b , biomass of stem bark; W_{br} , biomass of branches; W_l , biomass of leaves and W_r , biomass of roots.

Figure 1. Schematic view of the principal (in grey boxes) and derived (in white boxes) variables in Globulus 3.0.

of the growth module are growth functions formulated as first order non-linear difference equations.

The greatest achievements in relation to previous versions is that: (i) it allows simulating the transition between rotations, by simulating growth for coppice stands before the thinning of the shoots usually occurring during the third year after the final harvest, and (ii) it includes improved biomass equations. Stand level compatible aboveground biomass and biomass per tree component equations were developed (Oliveira 2008) based on tree level biomass estimates obtained using a system of compatible equations to estimate tree aboveground biomass and biomass per tree component (António et al. 2007).

Difference equations estimate stand variables in an instant (t_2) based on the values of stand variables and control variables in the previous instant (t_1). This approach was used for modeling dominant height and basal area stand growth. If the objective is to simulate the growth of a stand for which no measurements have been made or of a stand after harvesting (coppice) it is necessary to estimate the initial conditions. In order to ensure the compatibility between the initialization and projection modules, the growth function from which the difference equation is derived needs to be used as the prediction equation used in the initialization module. Thus, the initialization and projection functions were developed using Lundqvist and Lundqvist-k functions, respectively. Parameters were estimated by non-linear least squares using the PROC MODEL procedure of the SAS statistical software (SAS Institute Inc. 2011). The results of the fitting of dominant height and basal area can be found in **Tables 1** and **2**.

Table 1. Site Index and dominant height projection functions.

Site Index and Dominant height			
$(1) SI = A \left(\frac{hdom}{A} \right)^{\left(\frac{t}{tp} \right)^n} \quad (2) hdom_2 = A \left(\frac{hdom_1}{A} \right)^{\left(\frac{t_1}{t_2} \right)^n} \quad A = a_0 + a_1 DR$			
model	a_0	a_1	n
(1) and (2)	29.0669	0.2880	0.4890

Where SI is the site index; hdom is the stand dominant height; t is the stand age; tp is a standard age (tp=10 for eucalyptus); DR is the number of days with rain (see the list of Symbols) and the indices 1 and 2 represent the instants in time.

Table 2. Basal area: initialization function (1) and growth projection function (2).

Basal Area	
(1) $G = A_G e^{-k_G \left(\frac{1}{t}\right) (n_{Gp} + n_{GN})}$	(2) $G_2 = A_G \left(\frac{G_1}{A_G}\right) \left(\frac{t_1 n_{GN1}}{t_2 n_{GN2}}\right) \left(\frac{t_1}{t_2}\right)^{n_{Gp}}$
$A_G = (a_{G0} + a_{G1} DR)$	$K_G = k_{G0} + k_{G1} SI + k_{G2} \frac{100}{SI \sqrt{Npl}} + k_{G3} rot$
$n_{Gp} = n_{G0} + \frac{n_{G1}}{\left(1 - \left(\frac{cota}{2000}\right)\right)} + n_{G2} rot$	$n_{GNi} = n_{G3} \frac{N_i}{1000}$

model	a _{G0}	a _{G1}	k _{G0}	k _{G1}	k _{G2}	k _{G3}	n _{G0}	n _{G1}	n _{G2}	n _{G3}
(1)	80.1683	0.2354	8.8294	-0.1876	3.3759	0.1180	0.4493	-0.0441	-0.0164	0.0655
(2)	80.1683	0.2354	-	-	-	-	0.4493	-0.0441	-0.0164	0.0655

Where G is the stand basal area; t is the stand age; DR is the number of days with rain (see the list of Symbols); SI is the site index; Cota is the stand altitude; NPL is the number of trees at planting; rot is the stand rotation (0 for planted and 1 for coppice stands) and the indices 1 and 2 represent the instants in time.

Apart from projecting the number of trees in the stand, the mortality model can be used to initialize planted stands assuming that $N_1=Npl$ is the density at planting and $t_1=0$ (**Table 3**, equation (1)). Whilst for coppices, it can be used to project the number of sprouts as soon as ingrowth ceases by assuming $N_1=N_0$ (the number of shoots after ingrowth) and $t_1=t_0$ (age at which ingrowth ceases, assumed to be 3 years). To initialize the number of stools, the number of living trees by the time the planted stand was harvested is considered and discounted of the percentage of death occurring in the transition between rotations (**Table 3**, equation (3)).

Table 3. Planted stand’s density of trees initialization function (1), planted stand’s density of trees growth projection function as well as for coppices older than 3 years (2), coppice stand’s density of living stools initialization function (3), coppice stand’s density of living stools prediction function (4), Coppice stand’s density of spouts for stands under 3 years of age (5) and Coppice stand’s density of spouts for stands at 3 years of age (6). The number of sprouts for t>3 years is given by equation (2).

Density and/or Mortality

Planted Stands:

$$(1) N = N_{pl} e^{-am t}$$

$$(2) N_2 = N_1 e^{-am (t_2 - t_1)} \quad (\text{projection of planted and coppice stands after shoots selection})$$

Coppice Stands:

$$(3) N_{stools} = N_{harv} (1 - \text{death}\%) \quad (\text{number of stools initialization})$$

$$(4) N_{stools_2} = N_{stools_1} e^{-am (t_2 - t_1)} \quad (\text{number of stools projection})$$

$$(5) N_{sprouts_{t \leq 2}} = N_{stools} (b_0 + b_1 t) \quad (\text{number of sprouts before shoots selection})$$

$$(6) N_{sprouts_{t=3}} = \frac{N_{stools}}{1 - e^{-\left(am_2 \frac{N_{stools}}{1000} + am_3 \frac{1}{SI} \right)}} \quad (\text{number of sprouts at shoots selection})$$

If there is any kind of sprouts selection rule, model (6) won't be needed. Usually it is user defined and the default value =1.6

$$am = am_0 + am_1 \text{rot} + am_2 \frac{N_{pl}}{1000} + am_3 \frac{1}{SI}$$

model	am ₀	am ₁	am ₂	am ₃	b ₀	b ₁	b ₂	b ₃
(1)	0.0104	-0.0025	0.0023	-	-	-	-	-
(2)	0.0104	-0.0025	0.0023	-	-	-	-	-
(4)	0.0147	-0.0025	-	-	-	-	-	-
(5)	-	-	-	-	4.26831	285.963	0.048092	712.382043
(6)	-	-	0.4050	13.6400	-	-	-	-

Where N is the stand density; NPL is the number of trees at planting; t is the stand age; N_{stools} is the number of stools; N_{sprouts} is the number of sprouts/trees; SI is the site index; rot is the stand rotation (0 for planted and 1 for coppice stands); death% is the percentage of death occurring in the transition between rotations and the indices 1 and 2 represent the instants in time.

After the principal variables have been initialized and projected, the derived variables such as volumes (**Tables 4 and 5**) and biomasses (**Table 6**) are calculated.

Table 4. Volume initialization function (1) and Volume projection function (2),

Volume Total							
(1)	$V_i = K_v t^a h_{dom}^b G^c$	$kv = kv_0 + kv_1 rot + \left(\frac{kv_2}{1 - \left(\frac{cota}{2000} \right)} \right) + kv_3 \frac{100}{SI \sqrt{N_0}}$					
(2)	$V_{i_2} = V_{i_1} \left(\frac{t_2}{t_1} \right)^a \left(\frac{h_{dom_2}}{h_{dom_1}} \right)^b \left(\frac{G_2}{G_1} \right)^c$						
model	a	b	c	kv0	kv1	kv2	kv3
(1) Vu	-0.0510	0.9982	1.0151	0.3504	0.0011	0.0049	0.0908
(2) Vu	-0.0511	0.9982	1.0151	-	-	-	-
(1) Vb	-0.0548	0.7142	1.0513	0.1502	-	0.0014	0.1336
(2) Vb	-0.0548	0.7142	1.0513	-	-	-	-
(1) V_st	-0.0821	0.3440	0.9914	0.0567	-0.0002	-	0.0104
(2) V_st	-0.0821	0.3440	0.9914	-	-	-	-

Where V_i represents the following stand volumes: V_u is the under-bark volume with stump, V_b is the volume of bark, V_{st} volume of stump; h_{dom} is the stand dominant height; G is the stand basal area; SI is the site index; $Cota$ is the stand altitude; rot is the stand rotation (0 for planted and 1 for coppice stands); NPL is the number of trees at planting; N_0 represents NPL for planted stands and $N_{sprouts}$ by age of 3 years for coppice stands.

Table 5. Merchantable volume above stump without bark up to a predefined top diameter prediction function.

Merchantable Volume							
$V_{umdi} = (V_u - V_{st}) e^{a \left(\frac{di}{d_{gdom}} \right)^b}$							
$a = a_0 + a_1 rot + a_2 \left(\frac{Npl}{1000} \right) + a_3 \left(\frac{100}{SI \sqrt{N_0}} \right) + \left(\frac{a_4}{1 - \left(\frac{cota}{2000} \right)} \right)$ $b = b_0 + b_1 rot$							
model	a0	a1	a2	a3	a4	b0	b1

V umdi	-1.1075	-0.3436	0.0741	1.2604	0.2660	3.1854	0.5513
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Where Vumdi is the merchantable volume under bark without stump up to a top diameter di; Vu is the under bark volume with stump; Vst volume of stump; dgdom is the quadratic mean diameter at breast height of the dominant trees; rot is the stand rotation (0 for planted and 1 for coppice stands); NPL is the number of trees at planting; SI is the site index; Cota is the stand altitude; N0 represents Npl for planted stands and Nsprouts by age of 3 years for coppice stands.

Table 6. Biomass prediction functions.

Biomass							
$W_i = a G^b hdom^c$		$b = b_0 + b_1 rot + b_2 \left(\frac{N}{1000}\right) + b_3 \left(\frac{SI}{1000}\right) + b_4 \left(\frac{t}{1000}\right)$					
$W_a = W_w + W_b + W_l + W_{br}$		$W_r = a W_a$		$W_t = W_a + W_r$			
model	a	b ₀	b ₁	b ₂	b ₃	b ₄	c
W _w	0.0967	1.0547	-0.0018	-0.0065	-0.5198	-1.2105	1.1886
W _b	0.03636	1.1691	-0.0083	-0.0459	3.2289	2.0880	0.6710
W _l	1.0440	1.0971	-	-0.0112	-1.2207	-6.2807	-0.3129
W _{br}	0.3972	1.0005	-	-0.0192	3.3170	-1.2747	-0.0160
W _r	0.2487	-	-	-	-	-	-

Where Wi represents the following biomass components: Ww is the biomass of wood, Wb is the biomass of bark, Wbr is the biomass of branches and Wl is the biomass of leaves; Wa is the total aboveground biomass; Wr is the biomass of roots; hdom is the stand dominant height; G is the stand basal area; SI is the site index; rot is the stand rotation (0 for planted and 1 for coppice stands); N is the stand density and t is the stand age.

Literature Cited

- Amaro, A., 2003. SOP model. The SOP Model: the Parameter Estimation Alternatives. In: Amaro, A., Reed, D., Soares, P. (Eds.), *Modelling Forest Systems*. CABI Publishing, USA.
- Amaro, A., Reed, D., Tomé, M., Themido, I., 1998. Modeling Dominant Height Growth: Eucalyptus Plantations in Portugal. *Forest Science*, **44** (1): 37-46
- Barreiro, S., Tomé, M., Tomé J., 2004. Modeling Growth of Unknown Age Even-aged Eucalyptus Stands. In: Hasenauer, H. & Makela, A. *Modeling forest production. Scientific tools – data needs and sources. Validation and application. Proceedings of the International Conference, 19-22 April, Wien, Austria. Department of Forest and Soil Sciences. Boku. (Poster)*
- SAS Institute Inc., 2011. *SAS/STAT 9.3 User's Guide*. SAS Institute Inc, Cary, NC
- Soares P., Tomé, M., 2003. GLOBTREE: an Individual Tree Growth Model for Eucalyptus globulus in Portugal. In: Amaro, A., Reed, D., Soares, P. (Eds.), *Modelling Forest Systems*. CAB International, pp. 97-110.
- Tomé, M., Soares P., Oliveira, T., 2006. O modelo GLOBULUS 3.0. Dados e equações. Publicações GIMREF RC2/2006. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Centro de Estudos Florestais, Lisboa.
- Tomé, M., Borges, J.G., Falcão, A., 2001a. The use of Management-Oriented Growth and Yield Models to Assess and Model Forest Wood Sustainability. A case study for Eucalyptus Plantations in Portugal. In: Carnus, J.M., Denwar, R., Loustau, D., Tomé, M., Orazio, C. (Eds.), *Models for Sustainable Management of Temperate Plantation Forests*, European Forest Institute, Joensuu, pp. 81-94.
- Tomé, M., Ribeiro, F., Soares, P., 2001b. O modelo Globulus 2.1. Departamento de Eng^a. Florestal. Instituto Superior de Agronomia. Universidade Técnica de Lisboa. Lisboa. Portugal.

List of Symbols

- DR** – weight average of the central values of the classes of the number of days with precipitation ≥ 0.1 mm found in each square of the grid (cm);
- SI** – Site Index, which is the stand's dominant height at the age of 10 years (m);
- t** – Stand age (years);
- t₁** – Stand age at instant 1 (years);
- t₂** – Stand age at instant 2 (years);
- t_p** – Standard age, which for eucalyptus corresponds to 10 years (years);
- hdom** – Stand dominant height (m);
- hdom₁** – Stand dominant height at instant 1 (m);
- hdom₂** – Stand dominant height at instant t₂ (m);
- N** – Stand density (ha⁻¹);
- N₁** – Stand density at instant 1 (ha⁻¹);
- N₂** – Stand density at instant 2 (ha⁻¹);
- N_{pl}** – Stand density at plantation (ha⁻¹);
- N_{stools}** – Number of stools after the first harvest (ha⁻¹);
- N_{sprouts t=2}** – Number of sprouts before sprouts selection (ha⁻¹);
- N_{sprouts t=3}** – Number of sprouts after sprouts selection (ha⁻¹);
- N_{harv}** – Number of trees by the end of the 1st rotation (ha⁻¹);
- Death%** - Percentage of stools that die in the transition between rotations
- rot** – dummy variable with 0 representing planted stands and 1 representing coppice stands;
- cota** - weight average of the central values of the classes of altitude found in each square of the grid (m);
- G** – Stand basal area (m² ha⁻¹);
- G₁** – Stand basal area at instant 1 (m² ha⁻¹);
- G₂** – Stand basal area at instant 2 (m² ha⁻¹);
- V_u** – Stand volume under-bark with stump (m³ ha⁻¹);
- V_b** – Stand volume of bark (including the bark of stump?!) (m³ ha⁻¹);
- V_{st}** – Stand volume of stump (m³ ha⁻¹);
- V_{umdi}** – Stand mercantile volume without stump and bark up to a top diameter of di (m³ ha⁻¹);
- di** – top diameter with bark (cm);
- dgdom** – Stand quadratic mean d.b.h of the dominant trees (cm² ha⁻¹);
- W_i** – Stand biomass per component, where i represents: w, b, l, br or r (Mg ha⁻¹);
- W_w** – Stand wood biomass (Mg ha⁻¹);
- W_b** - Stand bark biomass (Mg ha⁻¹);
- W_l** – Stand leaves biomass (Mg ha⁻¹);
- W_{br}** - Stand branches biomass (Mg ha⁻¹);
- W_r** - Stand roots biomass (Mg ha⁻¹);
- W_a** – Stand aboveground biomass (Mg ha⁻¹);
- W_r** - Stand belowground (roots) biomass (Mg ha⁻¹);
- W_t** - Stand total biomass (Mg ha⁻¹);

GLOBULUS 2.1 model

BRIEF DESCRIPTION & EQUATIONS

SUSANA BARREIRO

Globulus 2.1 Model

Background Introduction

GLOBULUS 2.1 represents a perfected version of GLOBULUS 2.0 model. GLOBULUS is a whole stand model developed for even-aged eucalyptus plantations in Portugal. The 2.1 version was developed under the scope of a PRAXIS project reference PRAXIS/3/3.2/PAPPEL/2323/95 (LCA – from eucalypt to paper). When compared to previous versions, the GLOBULUS 2.1 model has the following improvements:

- relies on a homogeneous classification of the country based on climatic regions (Ribeiro e Tomé, 2000)
- developed using a reasonable data coverage for all the considered homogenous regions except for 1sr rotation data in the North Litoral region.
- an analysis to assess the need for parameterizing the different regions and rotations was carried out.
- a methodology to obtain initialization and prediction compatible basal area models (dbh>5 cm) was developed.
- a methodology to obtain initialization and prediction compatible stand volume models (over- and under-bark) were developed, also compatible with the basal area and dominant height models.
- merchantable (over- and under-bark) volume models were also developed considering top diameters from 5 to 10 cm
- the productivity variability of eucalyptus stands for each particular region and for Portugal as a whole was analyzed according to 5 site index classes: very high, high, medium, low, very low.
- a methodology was developed that enables the number of trees at planting as well as the number of trees after shoots selection in the basal area prediction model to be replaced by the number of living trees at any given stand age. This will allow correcting the basal area predictions in stands with high mortality.
- an improved mortality model including site index, stand density and region as predictive variables was developed.
- a system of equations for total stand biomass and stand biomass by tree component was developed.
- based on the biomass estimates and on the chemical composition data published by Pereira et al. (1988), carbon and other macronutrients' estimates (N, P, K e Ca) estimates by biomass component are available.

Model Description

GLOBULUS 2.1 comprises a range of state and control variables (**Table 1**). One of the control variables is the climatic region that reflects different growth for different soil and climatic conditions. To enable the model to take this into account, the country was ranked into eight homogeneous regions. **Figure 1** represents the regions resulting from the ranking of the municipalities into edapho-climatic homogeneous regions.

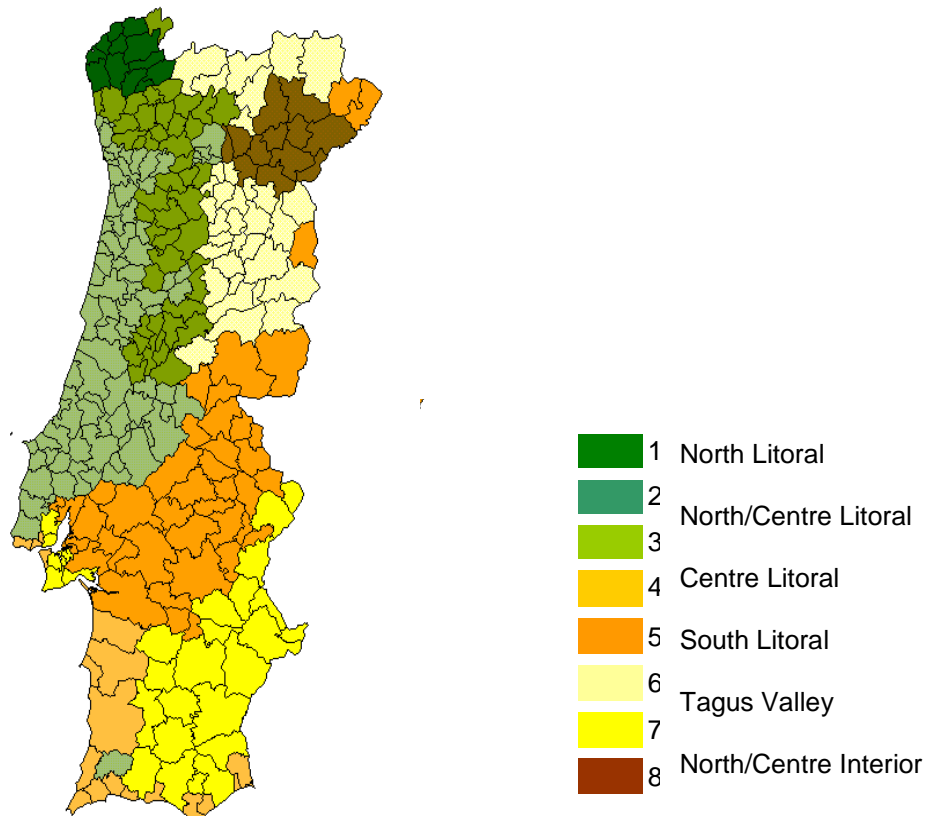


Figure 1. Map containing the distribution of the 8 edapho-climatic homogeneous regions.

The model has an initialization and a prediction module. The prediction module is built by a set of growth functions (e.g. dominant height, basal area) formulated as difference equations that predict the value of a particular state variable in instant t_2 (principal variables) as a function of the values of state variables in instant t_1 as well as of control variables. Additionally, the model integrates a range of other equations that allow estimating the values of secondary variables based on the values of other variables in the same instant in time (e.g. merchantable volume, biomass).

The prediction of growth for a stand that has forest inventory data available only requires the prediction module to be used. On the other hand, growth simulation of stands that have been harvested or of new plantations require the use of the initialization module to set the initial conditions based on the control variables. The models can be found in **Tables 2 to 10**.

Table 1. GLOBULUS 2.1 model variables.

Control Variables	State variables	
	Principal variables	Secondary variables
Environmental: - Site index (standard age=10)	Dominant height	Merchantable volumes (with and without bark, top diameters from 5 - 10 cm)
Climatic region	Stand density (ha ⁻¹)	Total aboveground biomass
Cultural: - Number of trees at planting (1 st rotation) - Number of sprouts after shoots selection (coppice rotations) - Stand age	Stand basal area	Root biomass
Stand: - Stand rotation (0-planted, 1-coppice) - Stand age	Stand total volume (with and without bark)	Biomass by tree component: wood, bark, branches and leaves Carbon stock by tree component: wood, bark, branches, leaves and roots Nutrients (N, P, K, Ca) by tree component: wood, bark, branches, leaves and roots

Table 2. Site Index and dominant height functions.



$$hdom_2 = A_h \left(\frac{hdom_1}{A_h} \right)^{\left(\frac{t_1}{t_2} \right)^{n_h}}$$

	Region	1NL	2NC	3CL	4SL	5VT	6NI	7SI	8VD
A_h	Planted	61.1372							
	Coppice								
n_h	Planted	0.5225	0.4805	0.4407	0.4780	0.4805	0.3955		
	Coppice	0.4384	0.3964	0.2826	0.3199	0.3964	0.2374		

Table 3. Stand density functions.

Initialization: $N = N_{pl} e^{-a_m(t)}$ (planted stands) $N = N_0 e^{-a_m(t-3)}$ (coppice stands)

$$a_m = a_{m0} + a_{mnp} \frac{N_{pl}}{1000} + a_{mQ} \frac{SI}{10}$$

Prediction: $N_2 = N_1 e^{-a_m(t_2-t_1)}$

	Region	1NL	2NC	3CL	4SL	5VT	6NI	7SI	8VD
a_{m0}	Planted	0.0211				0.0242	0.0211	0.0401	0.0242
	Coppice	0.0052				0.0083	0.0052	0.0090	0.0083
a_{mnp}	Planted	0.0013							
	Coppice								
a_{mQ}	Planted	-0.0064							
	Coppice	-0.0014							

Table 4. Stand basal area initialization and prediction functions.

Initialization: $G = A_g e^{-k_g \left(\frac{1}{t}\right)^{n_g}}$ $k_g = k_{g0} + k_{gQ} \frac{1}{SI} + k_{gnp} \frac{N_{pl}}{1000} + k_{gf} Fe$

Prediction: $G_2 = A_g \left(\frac{G_1}{A_g}\right)^{\frac{t_1^{n_g1}}{t_2^{n_g2}}}$ $A_g = A_{gQ} lqe^2$ $n_{gi} = n_{g0} + n_{gQ} \ln(SI) + n_{gn} \frac{N_i}{1000}$

	Region	1NL	2NC	3CL	4SL	5VT	6NI	7SI	8VD
A_{gQ}	Planted	0.1586							
	Coppice								
n_{g0}	Planted	3.7350	3.6354	3.6091	3.5676	3.6893	3.4571	3.5676	
	Coppice	2.8638	2.7642	2.6990	2.6575	2.8181	2.5470	2.6575	
n_{gQ}	Planted	-1.0288							
	Coppice	-0.7316							
n_{gn}	Planted	0.1024							
	Coppice	0.0216							
k_{g0}	Planted	-4.4826	-5.5311	-6.1201	-6.2433	-4.7560	-7.7941	-6.9326	
	Coppice	0.7582	-0.2903	-0.8793	-1.0025	0.4848	-2.5533	-1.6918	
k_{gQ}	Planted	177.9							
	Coppice	72.3							
k_{gnp}	Planted	0.5408							
	Coppice	0.0134							
k_{gf}	Planted	16.015							
	Coppice	14.1898							

Table 5. Total volume with stump with and without bark initialization and prediction functions.

Initialization: $V = k_v t^{a_v} hdom^{b_v} G^{c_v}$ $k_v = k_{v0} + k_{vf} F_e$

Prediction: $V_2 = V_1 \left(\frac{t_2}{t_1} \right)^{a_v} \left(\frac{hdom_2}{hdom_1} \right)^{b_v} \left(\frac{G_2}{G_1} \right)^{c_v}$

Total volume with stump and bark

Region		1NL	2NC	3CL	4SL	5VT	6NI	7SI	8VD
a_{vc}	Planted	0.0655							
	Coppice								
b_{vc}	Planted	0.8830							
	Coppice								
c_{vc}	Planted	1.0263							
	Coppice								
k_{v0c}	Planted	0.5007		0.4886		0.5007		0.4886	
	Coppice	0.5355		0.5272		0.5355		0.5272	
k_{vfc}	Planted	-0.1348		-		-0.1348		-	
	Coppice	-0.3828		-0.2480		-0.3828		-0.2480	

Total volume with stump without bark

Region		1NL	2NC	3CL	4SL	5VT	6NI	7SI	8VD
a_{vs}	Planted	0.0592							
	Coppice								
b_{vs}	Planted	0.9349							
	Coppice								
c_{vs}	Planted	1.0077							
	Coppice								
k_{v0s}	Planted	0.3886		0.3724		0.3886		0.3724	
	Coppice	0.4218		0.4108		0.4218		0.4108	
k_{vfs}	Planted	-0.1497		-		-0.1497		-	
	Coppice	-0.3616		-0.2119		-0.3616		-0.2119	

Table 6. Merchantable volume with and without bark equations.

$$V_d = V e^{a_{vm} \left(\frac{d_d}{d_g} \right)^{b_{vm}}} \quad a_{vm} = a_{vm0} + a_{vmnp} \frac{N_{pl}}{1000} + a_{vmf} Fe$$

Merchantable volume with bark

	Region	1NL	2NC	3CL	4SL	5VT	6NI	7SI	8VD
a_{vm0c}	Planted	-1.0904							
	Coppice	-1.2881							
a_{vmnps}	Planted	0.0729							
	Coppice	0.09267		0.0729			0.0927	0.0729	
a_{vmfc}	Planted	0.3851							
	Coppice	1.0378							
b_{vmc}	Planted	3.3716							
	Coppice	3.3716							

Merchantable volume without bark

	Region	1NL	2NC	3CL	4SL	5VT	6NI	7SI	8VD
a_{vm0s}	Planted	-1.0625							
	Coppice	-1.2531							
a_{vmnps}	Planted	0.0654							
	Coppice	0.0850		0.0654			0.0850	0.0654	
a_{vmfs}	Planted	0.3841							
	Coppice	1.0247							
b_{vms}	Planted	3.3288							
	Coppice	3.3288							

Table 7. Total aboveground biomass equations.

$$W_t = \alpha_w G^{\beta_w} h d o m^{\gamma_w} \quad \alpha_w = \alpha_{w0} + \alpha_{wQ} \frac{Iq_e}{10} \quad \beta_w = \beta_{w0} + \beta_{wn} \frac{N}{1000} + \beta_{wt} t$$

Region	1NL	2NC	3CL	4SL	5VT	6NI	7SI	8VD
α_{w0}	0.0095							
α_{wQ}	-0.0025							
β_{w0}	1.1392							
β_{wn}	-0.0424							
β_{wt}	-0.0115							
γ_w	2.4043							

Table 8. Stem and canopy biomass equations.

$$W_{tronco} = W_t P_{tronco} = W_t (\alpha_{wt} G^{\beta_{wt}} hdom^{\gamma_{wt}}) \quad \beta_{wt} = \beta_{wt0} + \beta_{wtn} \frac{N}{1000} + \beta_{wtt} t + \beta_{wtQ} \frac{lqe}{10}$$

$$W_{copa} = W_t - W_{tronco}$$

Region	1NL	2NC	3CL	4SL	5VT	6NI	7SI	8VD
α_{wt}				0.2019				
β_{wt0}				0.1613				
β_{wtn}				0.0046				
β_{wtt}				-0.0037				
β_{wtQ}				-0.0355				
γ_{wt}				0.4301				

Table 9. Biomass equations by tree component.

$$W_{casca} = W_{tronco} (a_{c0} + a_{ct} t + a_{ct2} \frac{t^2}{10}) \quad W_{lenho} = W_{tronco} (1 - P_{casca})$$

$$W_{folhas} = W_{copa} (a_{f0} + a_{ft} t + a_{ft2} \frac{t^2}{10}) \quad W_{ramos} = W_{copa} - W_{folhas}$$

Region	1NL	2NC	3CL	4SL	5VT	6NI	7SI	8VD
a_{c0}				0.1946				
a_{ct}				-0.0094				
a_{ct2}				0.0026				
a_{f0}				0.7304				
a_{ft}				-0.0154				
a_{ft2}				0.0021				

The biomass and nutrient estimates' module in GLOBULUS 2.1 is still quite simple. The conversion factors for roots are the same applied for wood.

Table 10. Conversion factors used in the GLOBULUS 2.1 model for converting the biomass by tree component into carbon and macronutrients.

Components	Carbon	Nutrients (% kg/kg)			
	%	N	P	K	Ca
Wood	49.0	0.0753	0.0221	0.0682	0.1086
Bark	46.8	0.1862	0.0137	0.1271	0.6651
Leaves	49.2	1.1363	0.0548	0.5285	0.5280
Branches	47.4	0.2763	0.0117	0.3593	0.6896
Roots	49.0	0.0753	0.0221	0.0683	0.1086

List of Symbols

SI or IQE – Site Index, which is the stand’s dominant height at the age of 10 years (m);

t – Stand age (years);

t₁ – Stand age at instant 1 (years);

t₂ – Stand age at instant 2 (years);

t_p – Standard age, which for eucalyptus corresponds to 10 years (years);

h_{dom} – Stand dominant height (m);

h_{dom1} – Stand dominant height at instant 1 (m);

h_{dom2} – Stand dominant height at instant t₂ (m);

N – Stand density (ha⁻¹);

N₁ – Stand density at instant 1 (ha⁻¹);

N₂ – Stand density at instant 2 (ha⁻¹);

N_{pl} – Stand density at plantation (ha⁻¹);

rot – dummy variable with 0 representing planted stands and 1 representing coppice stands;

G – Stand basal area (m² ha⁻¹);

G₁ – Stand basal area at instant t₁ (m² ha⁻¹);

G₂ – Stand basal area at instant t₂ (m² ha⁻¹);

V – Stand volume with stump (m³ ha⁻¹);

V₁ – Stand volume with stump at instant t₁ (m³ ha⁻¹);

V₂ – Stand volume with stump at instant t₂ (m³ ha⁻¹);

V_d – Stand mercantile volume without stump and bark up to a top diameter of d_i (m³ ha⁻¹);

d_d – top diameter with bark (cm);

dg – Stand quadratic mean d.b.h (cm² ha⁻¹);

W_{lenho} – Stand wood biomass (Mg ha⁻¹);

W_{casca} – Stand bark biomass (Mg ha⁻¹);

W_{folhas} – Stand leaves biomass (Mg ha⁻¹);

W_{ramos} – Stand branches biomass (Mg ha⁻¹);

W_r – Stand roots biomass (Mg ha⁻¹);

W_t – Stand aboveground biomass (Mg ha⁻¹);

W_{tronco} – Stand stem biomass (Mg ha⁻¹);

W_{copa} – Stand canopy biomass (Mg ha⁻¹);

GYMMA Model

BRIEF DESCRIPTION & EQUATIONS

SUSANA BARREIRO

GYMMA Model

Background Introduction

Eucalyptus globulus Labill. planted forest is of crucial importance for the Portuguese economy being the main source for high quality raw material for the pulp and paper industries. Portugal has a long experience in developing empirical growth models for eucalyptus even-aged stands for which the planting date is known. Age is one of the most important variables in growth and yield modelling of even-aged stands. However, plantation date is often unknown for Portuguese eucalyptus stands and stand age is especially hard to assess for fast growing species with no well defined tree rings like is the case of Eucalyptus. In order to solve the problem of unknown stand age, GYMMA model Growth and Yield Model Missing Age, was developed and is at present being applied to project uneven-aged stands ([Barreiro et al. 2004](#)). Additionally, a set of biomass functions per component was included to complement the model ([Oliviera xxxx](#)).

Model Description

Tree or stand growth modelling is usually achieved with so-called theoretical growth curves, such as the Lundqvist growth function; one of the most commonly used in growth and yield modelling. A methodology to formulate growth functions as age independent difference equations was applied to the Lundqvist function in order to model dominant height and basal area, the driving variables. By formulating growth functions as age independent difference equations the problem of modelling growth of trees or stands when age is not available is solved (Tomé et al. 2006, Barreiro and Tomé 2010).

Dominant height and basal area models were fitted with the procedure PROC MODEL of the SAS statistical software (SAS Institute Inc. 1993), whereas for the mortality and volume models linear regression was used through the procedure PROC REG of the same software.

The growth and prediction functions that make up the GYMMA model are presented in **Tables 1 to 6**.

Table 1. GYMMA model projection function for dominant height.

Dominant height					
$(1) \text{ hdom}_2 = A e^{\frac{-k}{\left(\left(\frac{-k}{\ln(\text{hdom}_1/A)} \right)^{\frac{1}{n}+1} \right)^n}}$ $k = k_0 + k_1 G + k_2 \text{ hdom}$					
model	a	K ₀	K ₁	K ₂	n
(1)	84.2463	3.0839	-0.1142	0.1202	0.4057

Where G is the stand's basal area; hdom is the stand's dominant height and If $k \leq 2.5$ then $k=2.5$ else if $k \geq 5.5$ then $k=5.5$.

Table 2. GYMMA model projection function for stand basal area.

Basal Area

$$(1) G_2 = A e^{\frac{-k}{\left(\left(\frac{-k}{\ln(G_1/A)}\right)^{\frac{1}{n}} + 1\right)^n}}$$

$$k = k_0 + k_1 \text{ hdom} + k_2 \frac{N_{(d>5)}}{1000}$$

$$A = a_0 \text{ hdom}$$

model	a ₀	K ₀	K ₁	K ₂	n
(1)	63.9939	9.8573	0.4420	-2.2890	0.4141

Where G is the stand's basal area; hdom is the stand's dominant height; N_(d>5) is the number of trees with DBH greater than 5 cm and if k≤9.0 then k=9.0 else if k≥20 then K=20.

Table 3. GYMMA model Mortality functions.

Alternative Projection/Prediction Functions for Mortality

$$(1) N_2 = N_1 e^{a_0}$$

$$(2) N_{(d>5)} = a_0 + a_1 N + a_2 G$$

$$(3) N_{(d>5)} = \frac{N}{\left(1 + e^{-\left(a_0 + a_1 \text{ hdom}\right)}\right)^{a_2}}$$

model	a ₀	a ₁	a ₂
(1)	-0.00988	-	-
(2)	-10.5204	0.8549	6.0069
(3)	-1.5163	0.1075	0.1667

Where N is the number of trees; N_(d>5) is the number of trees with diameter at breast height greater than 5 cm, hdom is the stand's dominant height and G is the stand's basal area. Note that models 2 and 3 are alternative models.

Table 4. GYMMA model prediction functions for stand total volume.

Total Volume				
$V_i = A \text{ hdom}^b G^c$		$A = a_0 + a_1 \text{ rot}$		
model	a_0	a_1	b	c
V	0.5207	-	0.9933	0.9285
Vu	0.3625	-	0.9885	0.9879
V_st	0.4602	0.0012	0.9796	0.9750
Vu_st	0.3202	0.0023	0.9756	1.0343

Where V_i represents the following stand volumes: V is the stand over bark volume with stump, Vu is the stand under bark volume with stump, V_st is the stand over bark volume without stump and Vu_st is the stand under bark volume without stump; G is the stand basal area; hdom is the dominant height and rot is the stand rotation (0 for planted and 1 for coppice stands).

Table 5. GYMMA model prediction functions for merchantable stand volume.

Merchantable Volume		
(1)	$V_{mdi} = V_st e^{a \left(\frac{di}{dg}\right)^b}$	(2)
(2)	$V_{mudi} = Vu_st e^{a \left(\frac{di}{dg}\right)^b}$	
model	a	b
(1)	-1.0033	3.8608
(2)	-1.0173	3.8929

Where V_{mdi} is the merchantable volume over bark without stump up to a top diameter di ; V_{mudi} is the merchantable volume under bark without stump up to a top diameter di ; V_st is the stand over bark volume without stump; Vu_st is the stand under bark volume without stump and dg is the quadratic mean diameter at breast height.

Table 6. GYMMA model biomass prediction functions.

Biomass

$$W_i = a \text{ hdom}^b G^c$$

$$a = a_0 + a_1 \text{ rot}$$

$$W_a = W_w + W_b + W_l + W_{br}$$

$$b = b_0 + b_1 \frac{N}{1000}$$

$$W_r = a_0 W_a$$

$$c = c_0 + c_1 \text{ rot} + c_2 \frac{N}{1000}$$

model	a0	a1	b0	b1	c0	c1	c2
W_w	0.1108	-0.0002	1.1569	- 0.0085	1.0195	-	-
W_b	0.0262	-	0.8500	- 0.0564	1.1964	-0.0080	-
W_{br}	0.3015	-	0.1263	-	0.9963	-0.0030	-0.0126
W_l	1.4570	-	-0.4065	-	0.9870	-	-0.0080
W_r	0.2487	-	-	-	-	-	-

Where W_w is the biomass of wood; W_b , is the biomass of bark; W_{br} is the biomass of branches; W_l is the biomass of leaves; W_r is the biomass biomass of roots; W_a is the total aboveground biomass; rot is the stand rotation (0 for planted and 1 for coppice stands) and **N is the stand density**.

Final Remarks

The performance of GYMMA model was compared with Globulus 2.1 model for the driving variables (dominant height and basal area) and the derived variables (total volume and merchantable volume). Graphical analyses were used to accomplish validation through the relationship of observed stand variables over predicted stand variables for each of the models mentioned and the model performed reasonably well.

However, GYMMA will neither allow to determine the exploitable age nor to estimate a site index value for a given stand, because this is an age dependent variable, which is an important drawback for the model.

Literature Cited

Barreiro, S., Tomé, M., 2010, Developing a dominant height growth model for Eucalyptus globulus Labill. in Portugal based on age-independent difference equations. (...)

Barreiro, S., Tomé, M., Tomé J., 2004. Modeling Growth of Unknown Age Even-aged Eucalyptus Stands. In: Hasenauer, H. & Makela, A. Modeling forest production. Scientific tools – data needs and sources. Validation and application. Proceedings of the International Conference, 19-22 April, Wien, Austria. Department of Forest and Soil Sciences. Boku. (Poster)

SAS Institute Inc.,1993. SAS/STAT 9.3 User's Guide. SAS Institute Inc, Cary, NC

Oliveira, T. XXXX

Tomé, J., Tomé, M., Barreiro, S., Paulo, J.A., 2006. Modelling tree and stand growth with growth functions formulated as age independent difference equations. Can. J. For. Res. 36, 7, pp 1621.

PBRAVO Model

BRIEF DESCRIPTION, EQUATIONS & SOFTWARE

SUSANA BARREIRO

PBRAVO Model

Background Introduction

Eucalyptus globulus Labill. planted forest is of crucial importance for the Portuguese economy being the main source for high quality raw material for the pulp and paper industries. Portugal has a long experience in developing empirical growth models for eucalyptus even-aged stands for which the planting date is known. Age is one of the most important variables in growth and yield modelling of even-aged stands. However, plantation date is often unknown for Portuguese eucalyptus stands and stand age is especially hard to assess for fast growing species with no well defined tree rings like is the case of Eucalyptus. In order to solve the problem of unknown stand age, GYMMA model Growth and Yield Model Missing Age, was developed and is at present being applied to project uneven-aged stands ([Barreiro et al. 2004](#)). Additionally, a set of biomass functions per component was included to complement the model ([Oliviera xxxx](#)).

Model Description

In whole stand models, such as the GLOBULUS 3.1 model, state variables are all defined at stand level: (e.g. dominant height (hdom), number of trees per ha (N), basal area (G)). In turn, diameter distribution models apart from some stand level variables (e.g. stand density) often require other variables that are needed for the simulation of diameter distribution. These models are based on a particular probability distribution function, and the PBRAVO diameter distribution model is based on the Weibull probability distribution function (eq 1):

$$F(x) = 1 - e^{-\left(\frac{x-a}{b}\right)^c} \quad (\text{Eq. 1})$$

Where x corresponds to the upper limit of the diameter class, and a , b and c are the Weibull parameters estimated with the following equations:

$$a = 0.9 d_{\min} \quad b = \frac{(x_p - a)}{\left[-\ln(1 - P_{95})\right]^{1/c}} = \frac{(P_{95} - a)}{\left[2.99573\right]^{1/c}}$$

Where d_{\min} represents the minimum diameter of the stand/plot and P_{95} the percentile 95. After a and b are estimated, the c parameter is estimated by resolution using numerical methods following the non-linear equation.

$$a^2 + 2a(x_p - a) \frac{\Gamma\left(1 + \frac{1}{c}\right)}{-\ln(1 - p)^{1/c}} + (x_p - a)^2 \frac{\Gamma\left(1 + \frac{2}{c}\right)}{-\ln(1 - p)^{2/c}} - E(x^2) = 0$$

The Weibull function has the inconvenience of having one of its parameters difficult to estimate (c). Thus, for practical applications the parameter is either provided or the user is recommended to use the PBRAVO software developed by (Pascoa xxx). The model was programmed in *fortran* and a user friendly interface was developed. Before moving to a description of the interface let us look at an example of how these type of models work in the following example.

Knowing the values of the 3 Weibull parameters and the stand density (N), the accumulated probabilities of trees that occur under each dbh class can be estimated. Suppose a=2.6, b=9.0, c=3.2 and N=878.

classe d	dcentral (cm)	dsup (cm)	Weibull P(d<=dsup)
[2.5, 7.5]	5	7.5	0.137
]7.5, 12.5]	10	12.5	0.751
]12.5, 17.5]	15	17.5	0.994
]17.5, 22.5]	20	22.5	1.000
]22.5, 27.5]	25	27.5	1.000
]27.5, 32.5]	30	32.5	1.000
]32.5, 37.5]	35	37.5	1.000

Weibull function to estimates the accumulated frequency of trees per dbh class

$$F(12.5) = 1 - e^{-\left(\frac{12.5-2.6}{9.0}\right)^{3.2}}$$

Nacum is obtained by multiplying the accumulated probabilities by N=878. The number of trees in each dbh class is obtained subtracting the Nacum between consecutive dbh classes and the corresponding G by dbh class is obtained as shown.

dcentral (cm)	Weibull P(d<=dsup)	Nacum (ha ⁻¹)	N (ha ⁻¹)	G (m ² ha ⁻¹)
5	0.137	120	120	0.2
10	0.751	659	539	4.2
15	0.994	873	214	3.8
20	1.000	878	5	0.2
25	1.000	878	0	0.0
30	1.000	878	0	0.0
35	1.000	878	0	0.0
Stand			878	8.4

$$\Rightarrow = \left(\frac{\pi}{4} (10/100)^2\right) 539$$

The next step is predicting the height and volume of the average tree of each dbh class, volume per dbh class is obtained by multiplying the average tree volume by the number of trees.

dcentral (cm)	N (ha ⁻¹)	h (m)	v (árvore)	V (m ³ ha ⁻¹)
5.0	120	1.4	0.003848	0.5
10.0	539	4.6	0.021739	11.7
15.0	214	6.8	0.060050	12.8
20.0	5	8.4	0.119334	0.6
25.0	0	0.0	0.000000	0.0
30.0	0	0.0	0.000000	0.0
35.0	0	0.0	0.000000	0.0
878				25.6

Stand volume is estimated by summing up these values

$$\Rightarrow = (0.021739) 539$$

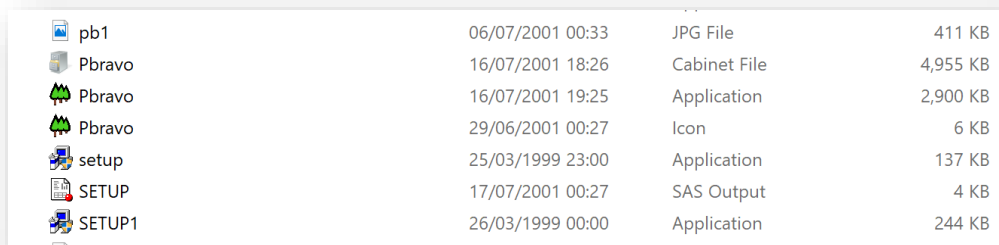
The growth and prediction functions that make up the PBRAVO model are presented in **Table 1**.

Table 1. PBRAVO model functions by module.

	Initialization Module	Projection/prediction Module	
G	$G = 0.000984 h_{dom}^{2.103402} N^{0.797707} e^{-\frac{8.702327}{t}}$	$G_2 = G_1 e^{\left(\frac{h_1}{t_2} - \left(\frac{h_1}{t_1}\right)^4\right) (4.178774 + 0.039053 h_{dom})}$	
P 95%	$P_{95} = 2.754927 h_{dom}^{1.445365} N^{-0.161445}$	$P_{95} = 154.155144 \left(\frac{G_1^{1/2}}{N_1}\right)^{1/2} e^{-0.009172(t_2-t_1) - \left(\frac{h_1}{t_2}\right) (2.919335 - 0.034485 h_{dom})}$	
d _{min}	$d_{min} = 12.302998 h_{dom}^{1.617991} N^{-0.687786}$	$d_{min_2} = 44.995291 \left(\frac{G_1^{1/2}}{N_1}\right)^{1/2} e^{0.062039(t_2-t_1) - \left(\frac{h_1}{t_2}\right) (-6.721703 - 0.039053 h_{dom})}$	
N	$N = Npl^{(1-0.00400588 t)}$	$N = 1324.485 G^{-0.23156} h_{dom}^{-0.382656} e^{5.407995 t^{-1}}$	
Calculus Module			
h _{dom} & S	$h_{dom} = S 10^{\left(0.380999 - 2.694076 t^{-1/2}\right)}$		$S = h_{dom} 10^{\left(-0.380999 + 2.694076 t^{-1/2}\right)}$
Height DBH curve	$h = 1.891036 h_{dom}^{0.890695} G^{-0.146749} N^{0.075548} e^{\left(\frac{2.000723}{t} - \frac{11.96184}{d}\right)}$		
Total volume	$v = 0.336 g h^2 e^{\left(\frac{0.94}{d} - \frac{d+3.79}{h}\right)}$	Merchantable volume	$di = d \sqrt{1.0080 e^{\left(\frac{0.94}{h} - \frac{3.79}{d}\right)} \left(1 - 2\frac{hi}{h} + \frac{hi^2}{h^2}\right)}$
Thinning Module			
Residual d _{min}	1st thinning $d_{min_{res}} = 0.438034 + 1.047001 d_{min}$	Following thinnings	$d_{min_{res}} = 0.684456 + 1.07904 d_{min}$
Residual P 95%	1st thinning $P_{95_{res}} = 0.121887 + 1.000760 P_{95}$	Following thinnings	$P_{95_{res}} = 1.22143 + 0.981559 P_{95}$
Residual N	1st thinning $N_{res} = N \left[1 - \left(1 - \frac{G_{res}}{G}\right)^{0.896268}\right]^{0.882856}$	Following thinnings	$N_{res} = N \left[1 - \left(1 - \frac{G_{res}}{G}\right)^{0.715054}\right]^{0.820574}$

Using the PBRAVO model

Copy the folder PBRAVO from the memory stick, go to PBRAVO\PBRAVO-FPFP, then click on the setup (NOT on the SETUP1). After installing the setup, click on the PBRAVO application (**Figure 1**).



File Name	Date	Type	Size
pb1	06/07/2001 00:33	JPG File	411 KB
Pbravo	16/07/2001 18:26	Cabinet File	4,955 KB
Pbravo	16/07/2001 19:25	Application	2,900 KB
Pbravo	29/06/2001 00:27	Icon	6 KB
setup	25/03/1999 23:00	Application	137 KB
SETUP	17/07/2001 00:27	SAS Output	4 KB
SETUP1	26/03/1999 00:00	Application	244 KB

Figure 1. Location of the PBRAVO application within the folder.

Once installed, the PBRAVO model shows a very simple interface (**Figure 2**) with 4 buttons: 1) the Model Options (Opções do Modelo); 2) the Run (simulação); 3) The Help; and 4) the Exit (Sair).

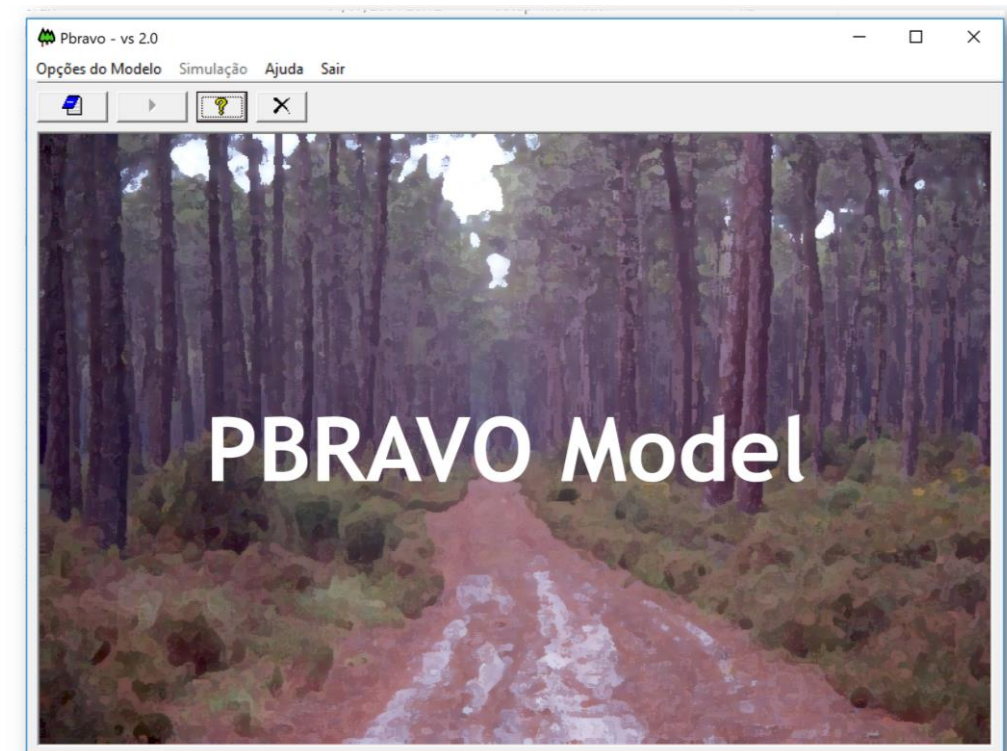


Figure 2. PBRAVO interface.

By Clicking on the Model Options button, a new window shows (**Figure 3**). Here the user is asked to provide some details about the simulation, such as:

- the current year, which should be consistent with the stand's age;
- whether to simulate underbark or overbark volume (since the bark of maritime pine trees represents 20-30% of stem volume);
- some details about the assortment dimensions (**Figure 4**).

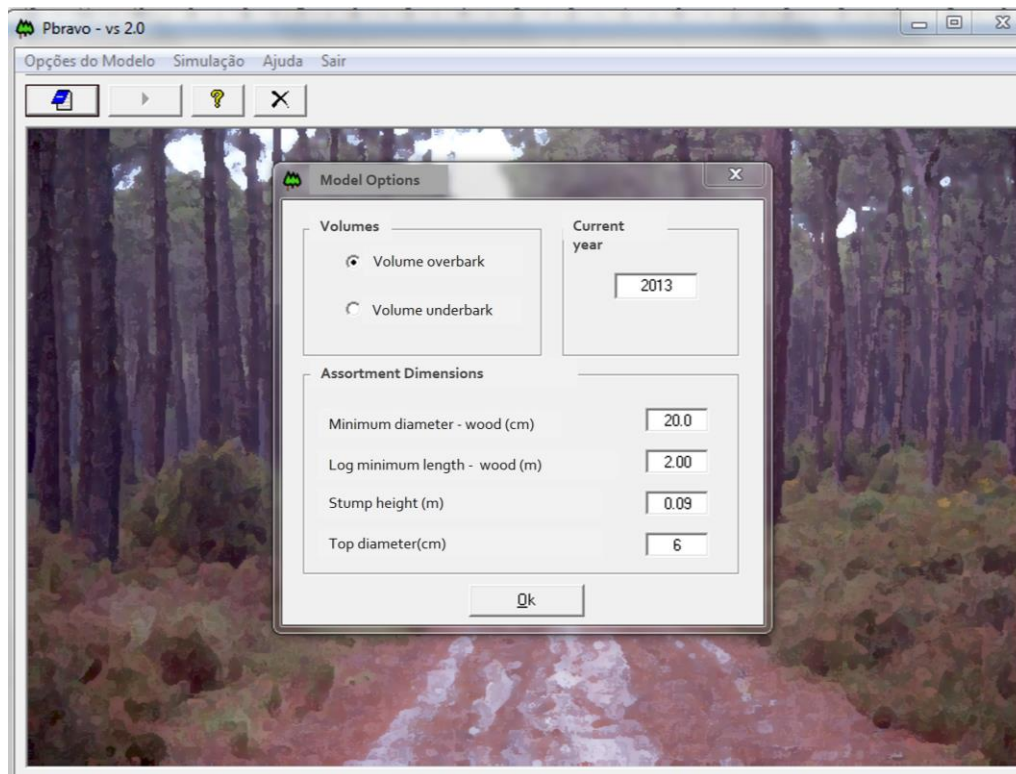


Figure 3. PBRAVO model options window 1.

For the example on the right, the inputs should be:

- Minimum diameter of wood (cm) = 20 cm
- Log minimum length (m) = 2 m
- Stump height (m) = 9 cm
- Top diameter (cm) = 6 cm

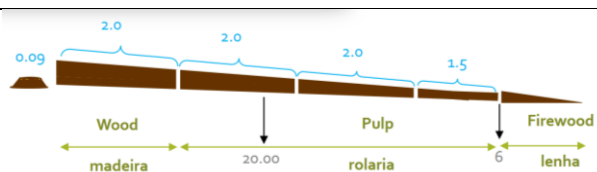


Figure 4. Example of the assortment dimensions requested by PBRAVO model.

Moving to the next step, the user will be asked to decide whether he wants to run the model for one of the 3 situations (**Figure 5**):

- stands that have the dominant height (hdom) measured, and then fill the hdom value;
- stands with no information on dominant height, and in this case the site index class is required;
- unthinned stands, ie young stands. Please note that, projections are not so good for old stands that have never been thinned.

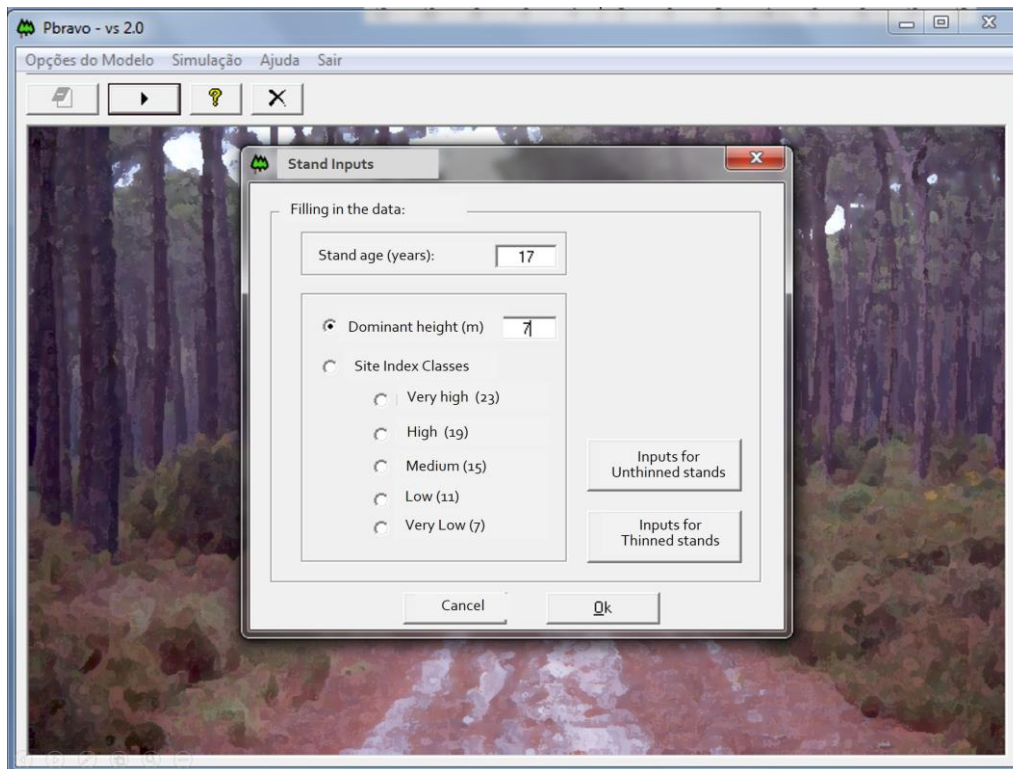


Figure 5. Example of a 17 year old stand with dominant height measured.

For young stands, the user has to provide either the number of standing trees (ha^{-1}) or the number of trees planted (ha^{-1}). In the latest case, a mortality model is applied to express the death of trees due to competition in early stages of stand development. The model runs in 5-year time-steps, stopping at each step allowing the user to (re-)define the management for the next 5-years period. For older stands (already thinned), the user has to provide either the number of trees by diameter class or the required stand variables so that the Weibull parameters (a , b , c) can be obtained (**Figure 6**). Before filling in the information the user has to remember to check which of the 2 options he prefers.

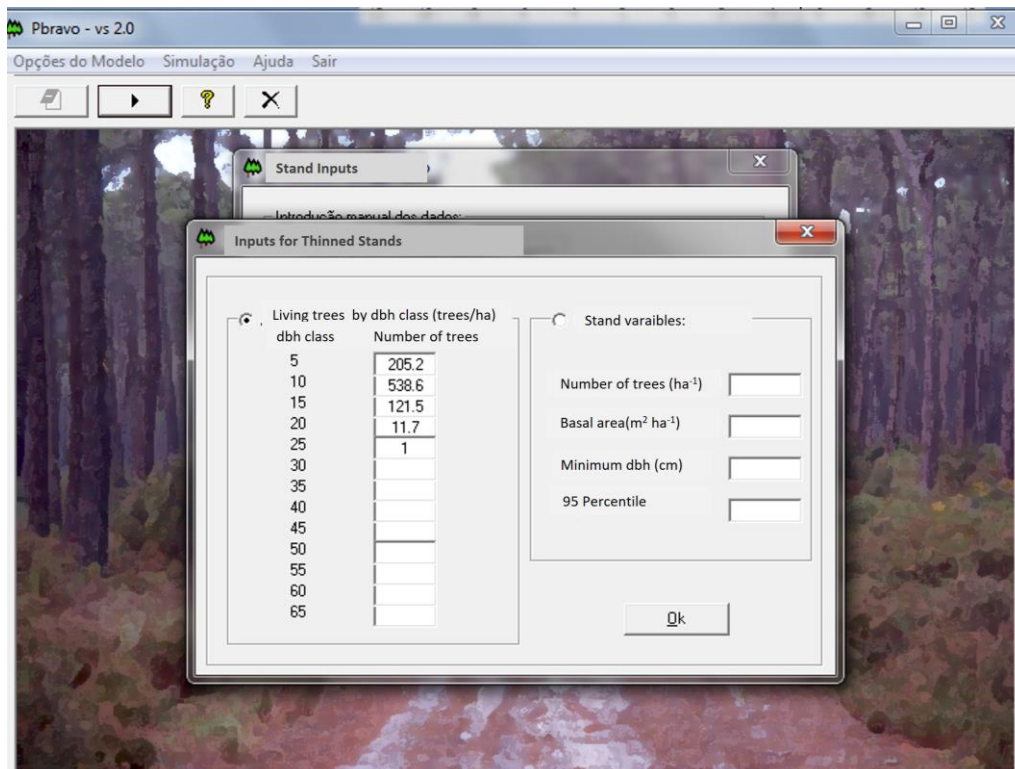


Figure 6. Example of a simulation run for which it was chosen to provide the number of trees by diameter class instead of the stand variables.

Making a bridge to what has been previously explained; the dbh class value represents the midpoint of the diameter class. In case the stand has trees with dbh values greater than 67.5 cm these should be grouped under the 65 class. Likewise, dbh class 5 includes not only the trees with dbh [2.5, 7.5[but also those with dbh < 2.5 cm.

After the stand has been described, by clicking the OK button a new window showing a summary table with the estimated diameter distributions is displayed (**Figure 6**). Among the information provided, the user will see the values of the Weibull parameters and the volume by assortments for each dbh class. To move forward the user will have to choose whether to carry out a thinning or not. If he chooses not to thin, then growth is projected by diameter class for a 5 years period and an updated table is displayed (**Figure 7**).

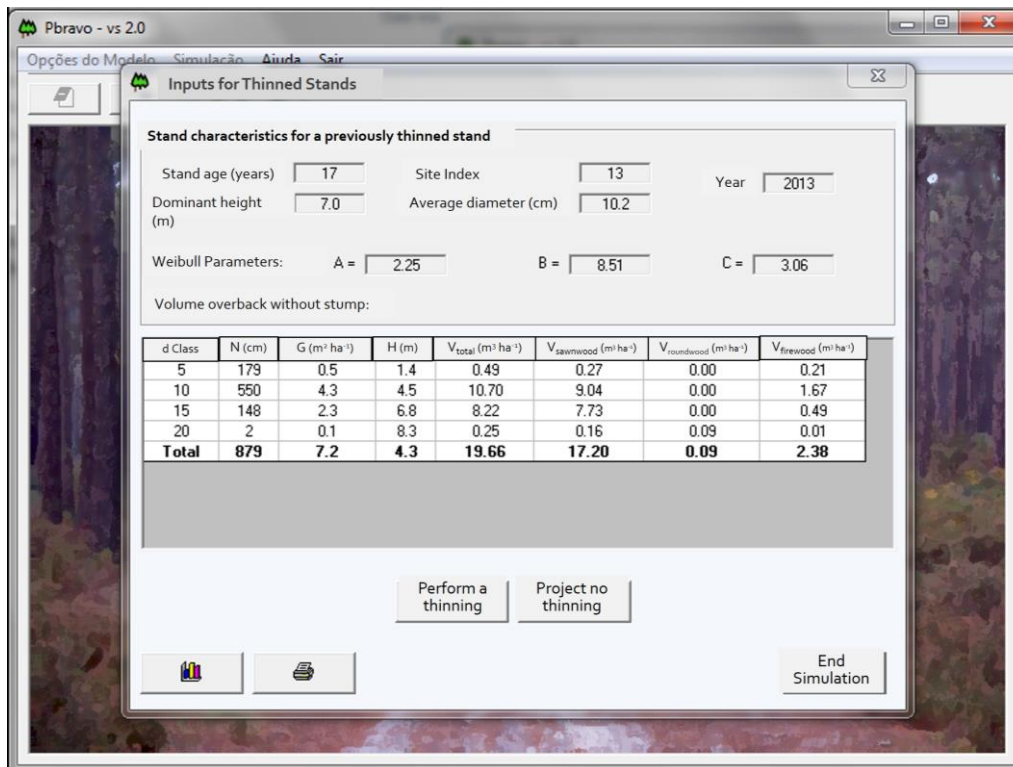


Figure 6. Example of a summary table characterizing the stand at the beginning of simulation (following the examples in previous figures).

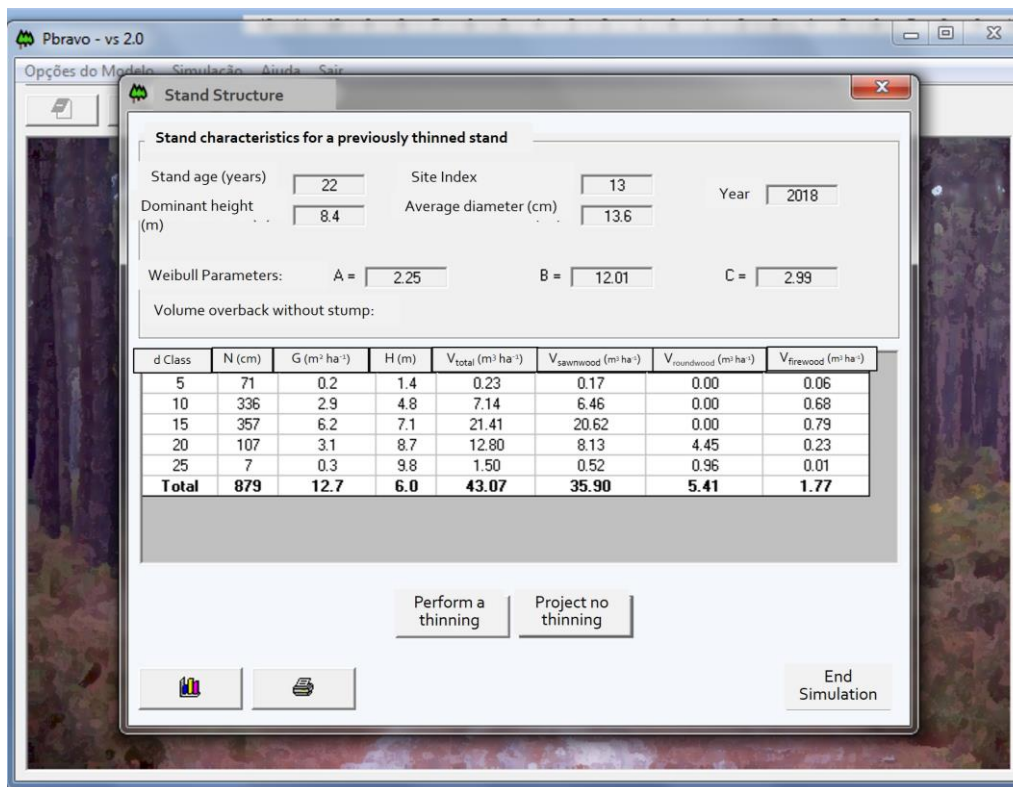


Figure 7. Example of the summary table characterizing the stand after the first 5-years simulation run.

On the other hand, if the user chooses to thin, he has to click on “Project thinning” so that a new window requesting the thinning details is displayed (**Figure 8**). In this window the user has to choose whether to thin by removing a percentage of trees or defining the residual basal area (the standing basal area).

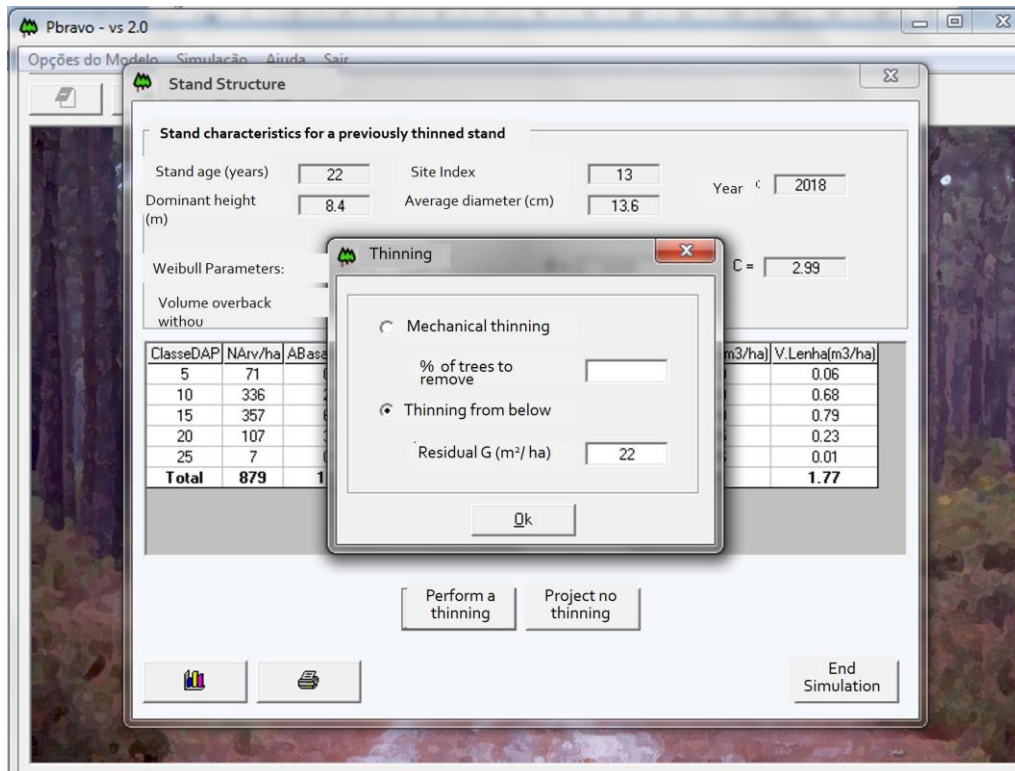


Figure 8. Example of the thinning details window assuming a thinning from below leaving a basal area of $22 \text{ m}^2\text{ha}^{-1}$.

If the user decides to perform a thinning leaving a residual basal area greater than the stand basal area, a message is displayed (**Figure 9**). Please note that the stand basal area was $12.7 \text{ m}^2\text{ha}^{-1}$ (**Figure 7**) and when the thinning was defined a residual basal area of $22 \text{ m}^2\text{ha}^{-1}$ (**Figure 8**). In such situation, the user is left with the option to project growth without thinning until the stand basal area is greater than the predefined value or decreasing the residual basal area. However the user should be aware that the PBRABO model was programmed with a restriction that only allows thinning to take place if the amount of basal area removed is above a certain threshold to avoid that the thinned wood would pay off the for the thinning costs. For this reason, even after reaching a basal area of $23.6 \text{ m}^2\text{ha}^{-1}$, a warning message is still displayed for a residual basal area of $22 \text{ m}^2\text{ha}^{-1}$ (**Figure 10**). Whenever a thinning takes place two tables are displayed characterizing the stand before and after thinning. At any point of the simulation the user can click on the graphs button on the lower left part of the window and a smaller window opens displaying a summary of stand characteristics and a graphic comparing the situation before and after thinning (**Figure 11**). Alternatively, the user can choose to print the results.

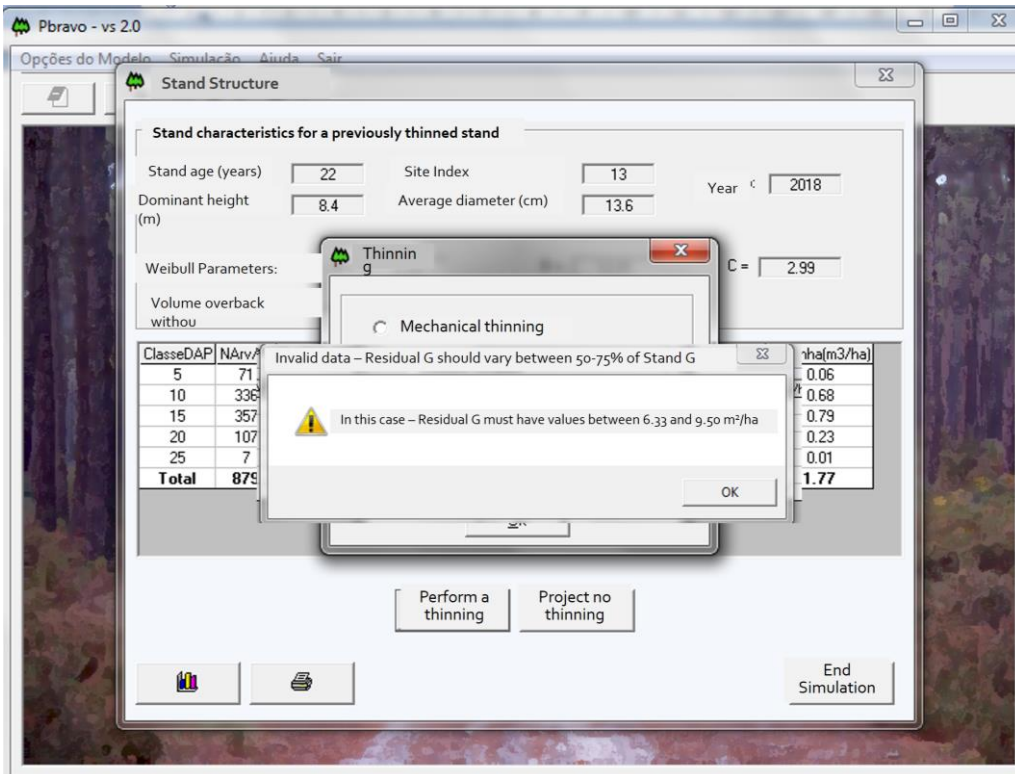


Figure 9. Warning message stating the interval of residual basal area values that would allow a thinning to take place for this stand.

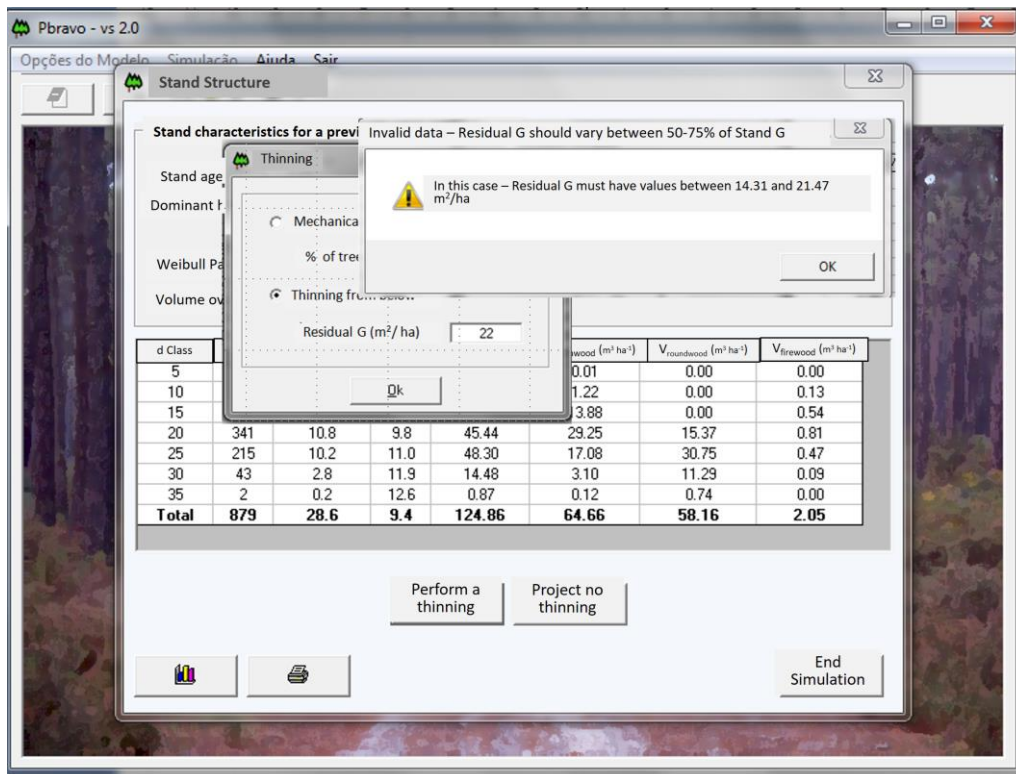


Figure 10. Warning message stating the interval of residual basal area values that would allow a thinning to take for this stand even when the stand has a basal area greater than the residual basal area.

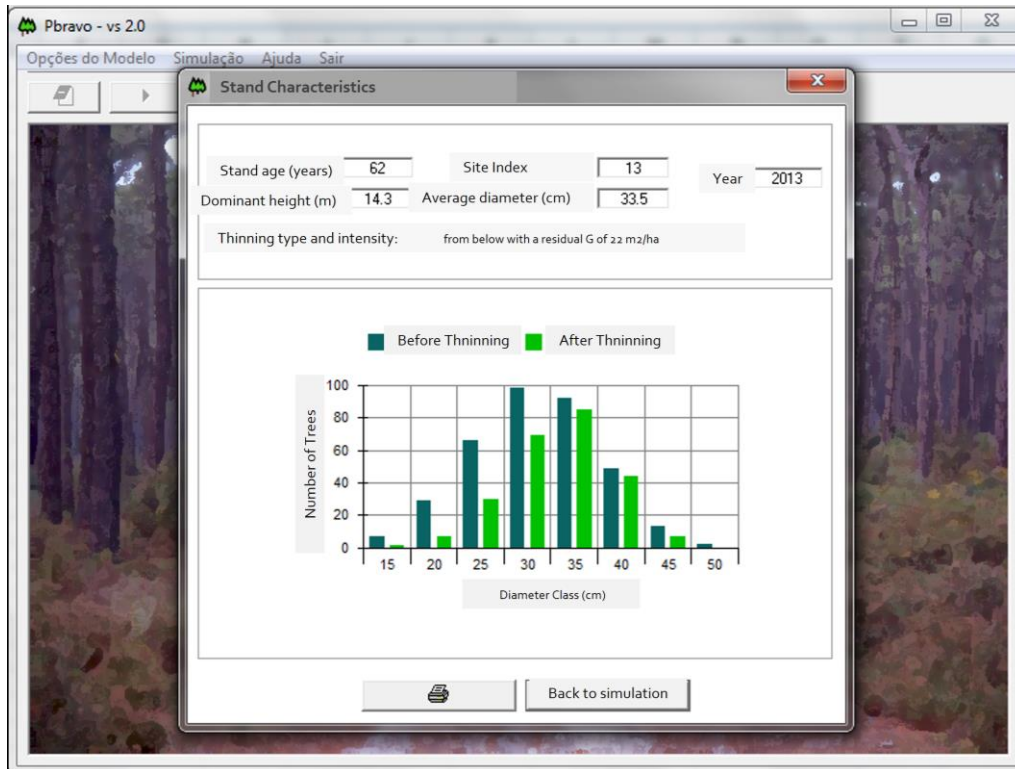


Figure 11. Graphical display of stand characteristics comparing the before and after thinning situations.

When the simulation is terminated, the user can click on the “End Simulation” button on the lower right and the last window is displayed. At this stage, the user can choose to visualize results in graphical or tabular form, save the simulation results in a text file, print the simulation outputs or carry put another simulation (**Figure 12**).

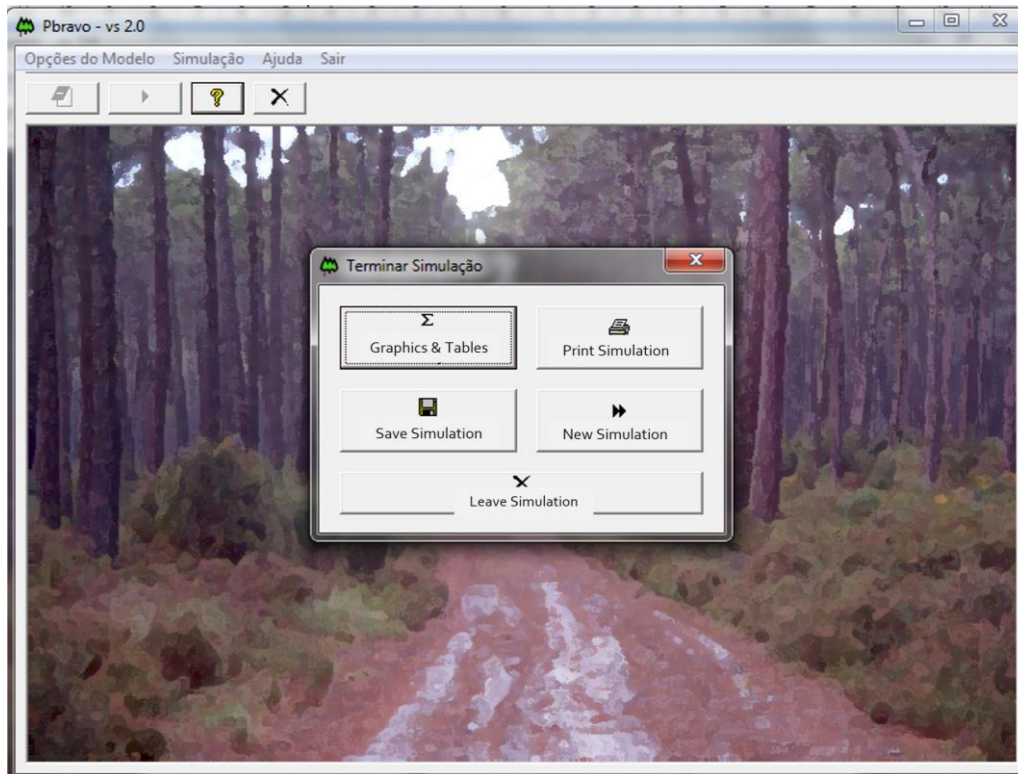
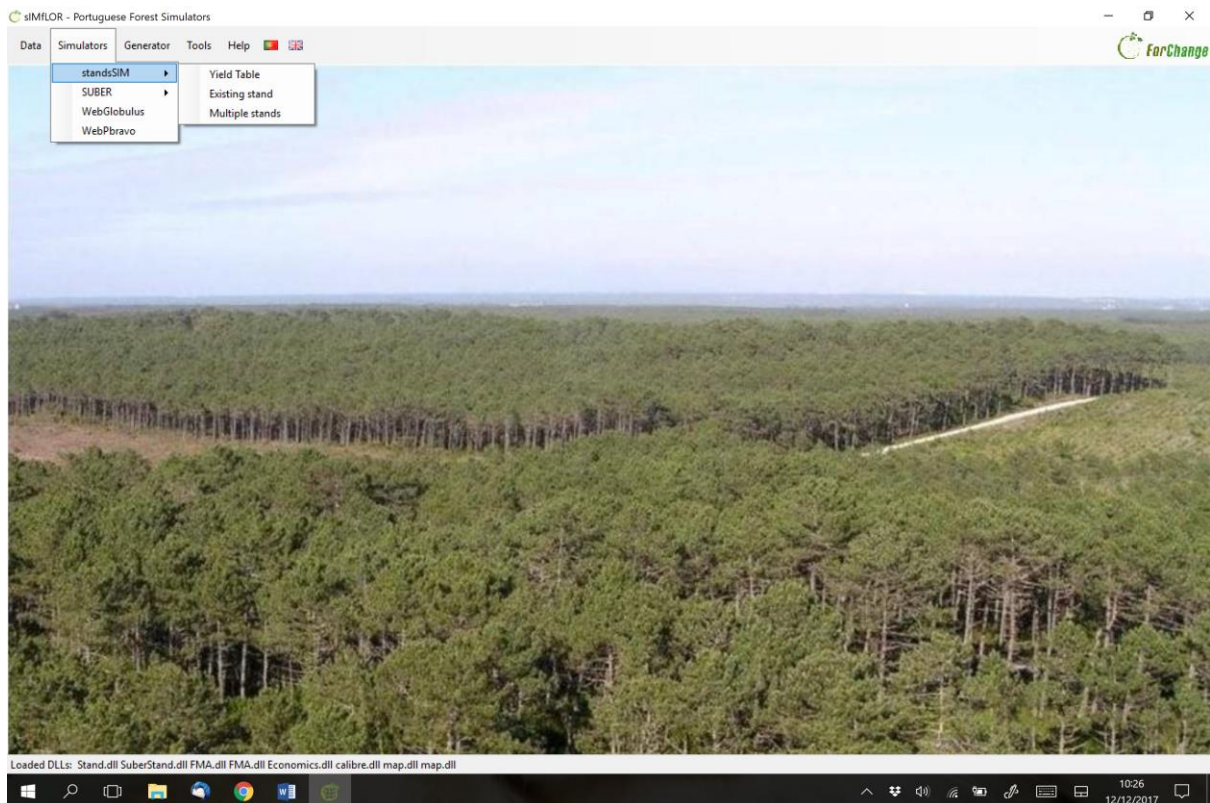


Figure 1. Interface giving the user the option to run a new simulation, visualising, printing or saving results.

StandsSIM.md Simulator Handbook

Forest Models course
2017-2018

Susana Barreiro and Margarida Tomé



Work-in-progress
December 2017

Lisbon, Portugal

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StandsSIM.md handbook organization

The objective of StandsSIM.md handbook is to present a description of the version of the **StandsSIM.md** currently integrated in the **sIMfLOR** platform illustrating its potential for simulating and assessing forest management alternatives.

The handbook is organized in 5 chapters. The first chapter provides a brief description of the **sIMfLOR** simulators platform, after which a brief description of models and simulators is provided. The third chapter describes **StandsSIM.md** structure and functioning and it is followed by a chapter where the inputs needed to run the simulations are described making a link between the csv input files and the information provided through the interface. The last chapter presents a compilation of solved hands-on-examples with print screens to illustrate the process for simulations runs for Yield Tables, Existing Stands and Multiple stands including a section where the consistency between different inputs is addressed. Finally, two appendices containing the list of variables and in the input and output files their descriptions are presented.

sIMfLOR download and installation instructions

sIMflor is freely available on the FCTools website. The user must register to have access to the download. The sIMfLOR_2017 zipped folder should be saved and unzipped in a location other than the *desktop* or the *downloads* folder. Make sure you don't leave blank spaces in the name of the folder where you save sIMfLOR_2017. Please note that sometimes the applications *graphs.exe* and *Graphs_DD.exe* (within STANDsSIM folder) have to be unzipped in a next step. The latest JAVA version is advisable; otherwise, the graphs functionality will not be available.

The software has no specific requirements, but the user must set the regional settings to English and make sure the *decimal symbol* is set to "." (not ",") and the *list separator* is set to "," (not to ";"). In case the tool still does not run, it might be possible that you opened one of the input csv files in excel and saved it. Open all the inputs that you visited using Notepad to make sure you don't have any ";". If you do, within Word go to: Home \ Editing \ Replace \ Find What: ";" \ Replace with "," \ Replace All.

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The development of **simfLOR**, the simulators and partly the growth and yield models has been developed under the scope of several national and European research projects:

EFORWOOD: Tools for Sustainability Impact Assessment of the Forestry-Wood Chain (FP6-2004-518128-2);

MOTIVE: Models for Adaptive Forest Management (FP7-ENV-2008-1-226544);

AFORE: Forest biorefineries: Added-value from chemicals and polymers by new integrated separation, fractionation and upgrading Technologies (CP-IP 228589-2);

SIMWOOD: Sustainable Innovative Mobilisation of Wood – Regional forest governance dialogues fostering conscious forest ownership and sustainable wood mobilisation in Europe (EU FP7-KBBE-2013.1.2-07);

StarTree: Multipurpose trees and non-wood forest products: a challenge and opportunity (FP7-ENV-2012-311919);

Agforward: AGroFORestry that Will Advance Rural Development (FP7-KBBE-2013-7-613520).

SADRI: Models and Decision Support Systems for Addressing Risk and Uncertainty in Forest Planning (SADRI) - PTDC/AGR-FOR/4526/2012 - funded by the Portuguese Science Foundation (FCT);

ForEAdapt: Knowledge exchange between Europe and America on forest growth models and optimization for adaptive forestry. Funded by the 7th European Community Framework Programme (project under grant agreement PIRSES-GA-2010-269257).

1 Introduction to SIMfLOR

ForChange team is one of the 4 research groups at the Forest Research Centre (CEF) one of the 3 research centres at School of Agriculture (ISA). CEF was created in 1976 and was initially oriented towards the research of the eucalypt ecosystem. Presently, it embraces wider research topics covering multifunctionality of ecosystems, sustainable management under climatic, social and economic changes, with a full resource use in a bioeconomy context.

ForChange group focuses on the management of Southern European Atlantic and Mediterranean forests, encompassing a variety of ecosystems ranging from intensive forest plantations for timber production to coastal dunes stabilization forests, and agroforestry systems. Because of ForChange's collaboration in several national and international research projects, the group dedicates to forest inventory and monitoring activities gathering valuable data on the impact of silviculture on ecosystems. The development of growth and yield models is one of the core research topics of the group that has been involved in the development of a wide range of forest growth and yield models. However, models are as valuable as the number of practitioners that can use them in decision-making processes. For this reason, this research team has dedicated to the integration of forest growth models into computer programs, commonly called forest simulators, and to the development of a user-friendly interface - SIMfLOR.

1.1 SIMfLOR platform structure

SIMfLOR platform, a simulators platform, was created to harmonize the interfaces of the different growth models and simulators developed within ForChange. This interface was created to assist users in the preparation of the input files required to run the simulators. The platform aims to encourage users from different research fields, forest managers and forest owners to make use of the forest simulators in an easy way.

Different stand and regional level simulators, including **StandsSIM** and **SUBER**, have been integrated in a common environment where the user can find other tools developed, such as the "Generator" that helps creating the management related inputs for the simulators (**Figure 1**).

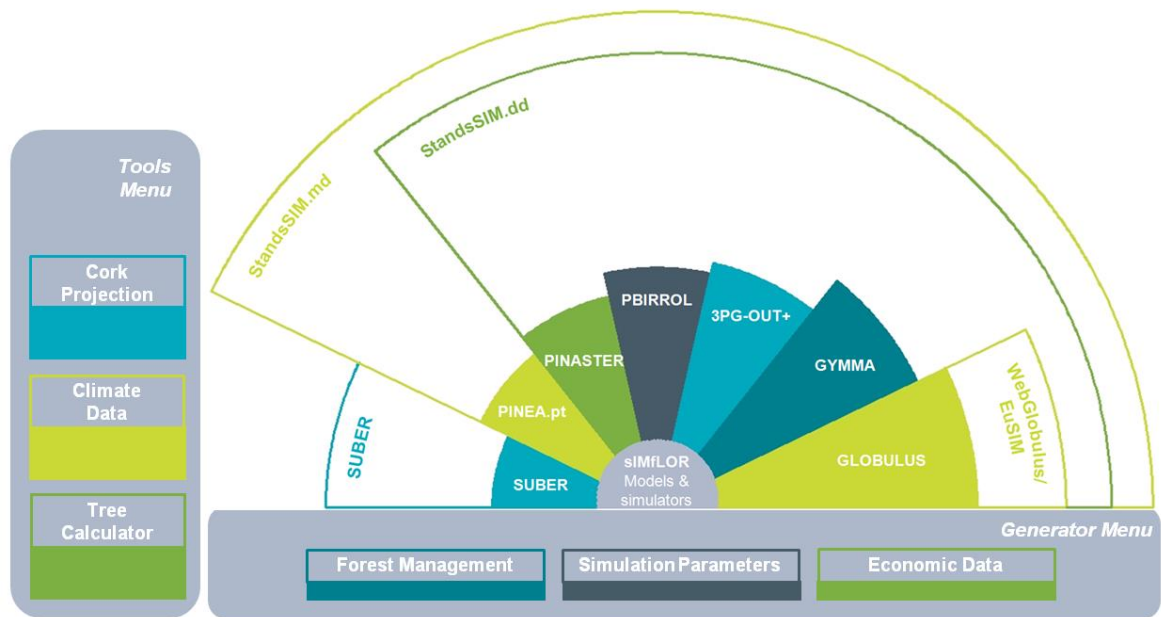


Figure 1. Simplified overview of the SIMfLOR structure.

Forchange Tools website, **FCTools** (<http://www.isa.ulisboa.pt/cef/forchange/fctools/en>) was created to facilitate the access of all users to the existing tools allowing the free download of its latest versions (registration on FCTools required prior to download). In this website the user will find the descriptions of the growth models and simulators developed for the main tree species in Portugal as well as supporting bibliography.

2 Brief description of forest models and simulators

A forest model can be defined as a dynamic quantitative representation of the forest based on a set of (sub-)models or modules that together predict the dynamics of the forest. For practical applications, forest models should be implemented in computer programs with user-friendly interfaces – usually designated as forest simulators. A forest simulator is a computer tool that is based on a set of forest models and makes long-term predictions of the status of the forests under different scenarios of climate, forest policy and/or forest management. Forest simulators usually predict, for each point in time, wood and non-wood products from the forest.

The core of any forest simulator is the growth module responsible for updating the values of state variables. This module comprises the suite of fitted growth functions/sub-models, in the case of empirical models, or algorithms representing processes, in the case of process-based models. The value of each state variable in the following instant in time is dynamically predicted based on the present characteristics of the stand and environment. The calculation module contains fitted functions/sub-models and other components that permit the estimation of other tree and stand variables. This module is static which means that all variables refer to the same instant in time. For simplicity reasons, sub-models will be referred to as models. Silvicultural practices influence stand development and long-term site properties. Besides management, simulations are usually driven by additional external drivers such as disturbances, demand, or landuse changes, all of which are usually implemented in individual modules (**Figure 2**).

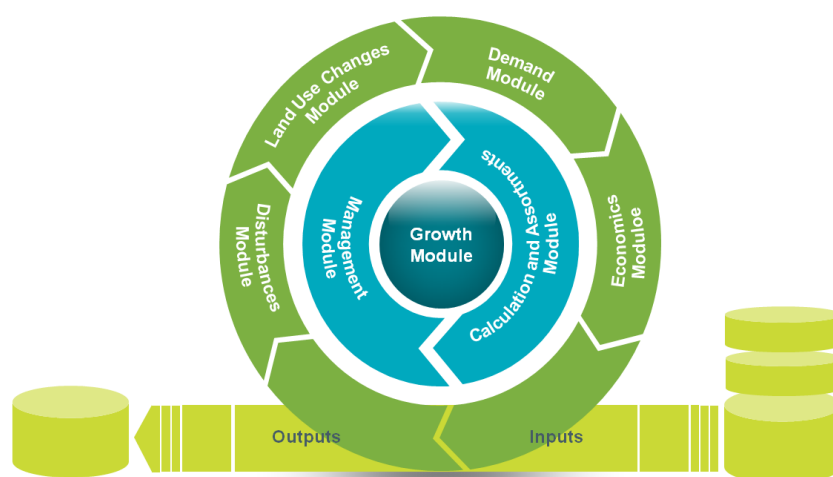


Figure 2. Simplified overview of a simulator.

3 StandsSIM.md simulator

StandsSIM simulator has a management driven version **StandsSIM.md** and a demand driven version **StandsSIM.dd**. Because the demand driven version is meant for regional applications requiring national level inputs it has not been made available in **simfLOR** and all the descriptions within the handbook will refer to the management driven version.

StandsSIM.md is a management driven simulator developed to assist sustainable management of forest landscapes for different stakeholders allowing comparing the evolution of forest dynamics for alternative management approaches. **StandsSIM.md** is a wide-range simulator that allows the user to simulate the growth of a new stand (yield table), an existing stand or multiple stands by filling in the information required in the corresponding forms in **simfLOR**'s platform (see chapter 3). Being driven by management, the simulator relies on two core concepts:

- a) The FMA describes the set of silvicultural operations that the user desires to carry out from stand regeneration until final harvest (**Figure 3**). Therefore, FMAs must be defined up to the maximum harvest age considered (even-aged stands) or up to the rotation time (uneven-aged stands). For each FMA, even- or uneven-aged, several management options, characterized by different sets of silvicultural operations, and how they are distributed over time, can be considered.

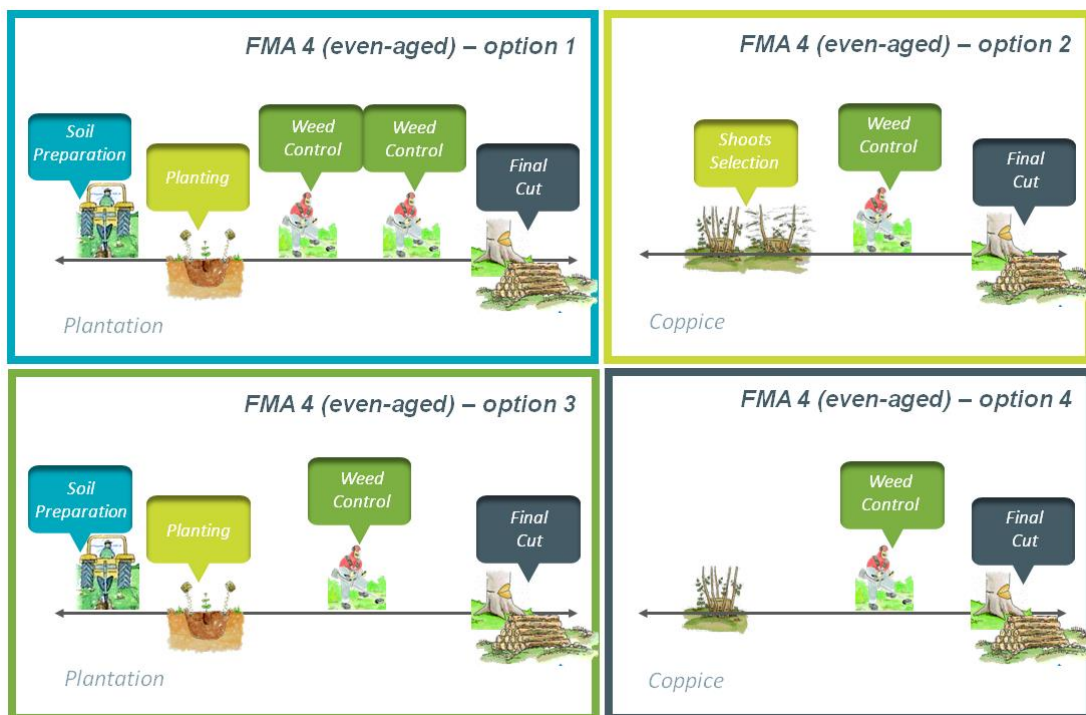


Figure 3. Illustration of different alternative ways to manage even-aged stands.

b) The management prescription corresponds to a sequence of FMAs to be applied to a stand over a given planning horizon (**Figure 4**). The set of cycles, from stand regeneration until final harvest, can be made up of

- different FMAs/options (Prescriptions A and B)
- the same FMA repeatedly (Prescription C).
- a single FMA (Prescription D)

In the process of building the prescriptions, you have to guarantee that each prescription is defined in a way that will permit covering the whole period considered by the planning horizon. For this reason, it is preferable to have prescriptions defined with a number of cycles that exceed the planning horizon and not the other way around (prescription B)

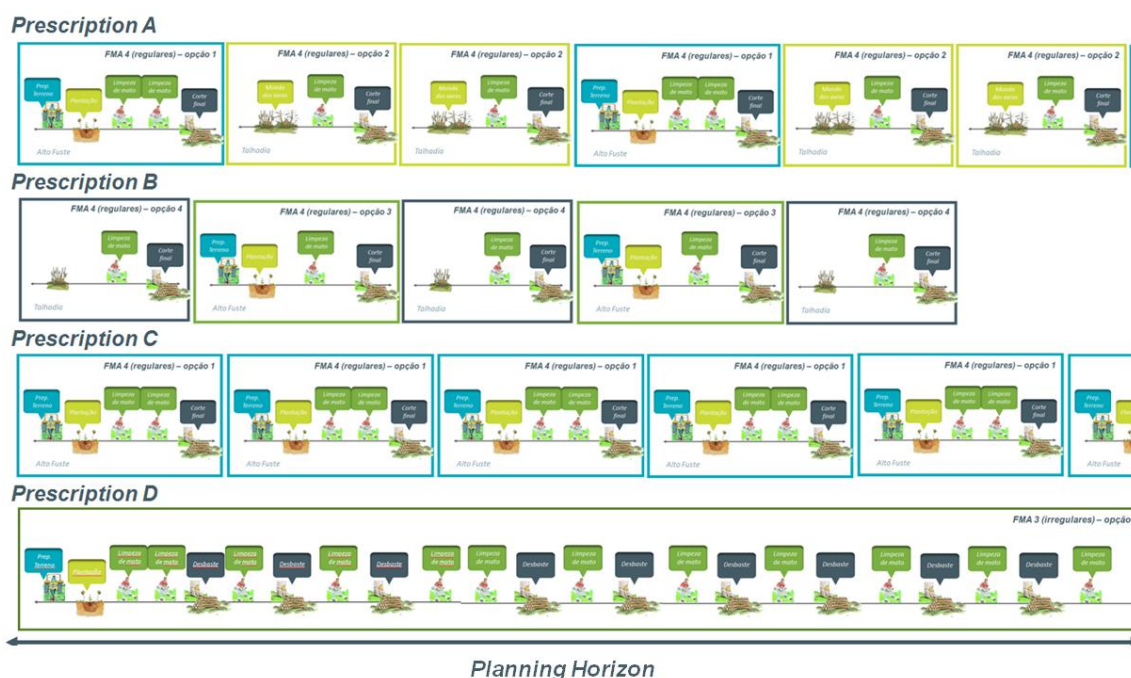


Figure 4. Illustration of different prescriptions.

The simulator allows predicting the evolution of forest stands under different management alternatives producing a wide range of environmental and economic indicators. **StandsSIM.md** integrates a set of growth models organized in modules responsible for initializing new stands or simulating thinning:

- a) Stands initialization module: simulates the diameter distribution of trees when the stands reaches a dominant height of 5 m. The distribution is based on data from trials monitored by ForChange group.

- b) Thinning module: considers several types of thinning: from below or according to user defined probabilities depending on tree size and based on different criteria such as the Wilson factor, the residual basal area or the percent thinned basal area.

Additional inputs have to be provided to characterize forest resources in the starting point of simulation, the cost of silviculture operations, the assortments to be consider for each species and climate. The simulator runs on an.

StandsSIM.md starts with forest inventory information at plot/stand level to characterize the forest resources in a region. Once forest resources are characterized for the first year of simulation, it uses the growth and yield models to predict the development of forest resources in the region taking into account the influence of external variables – commonly called drivers – such as forest management (**Figure 5**). The simulator runs for as many years as defined by the user (the planning horizon) with an annual time-step.

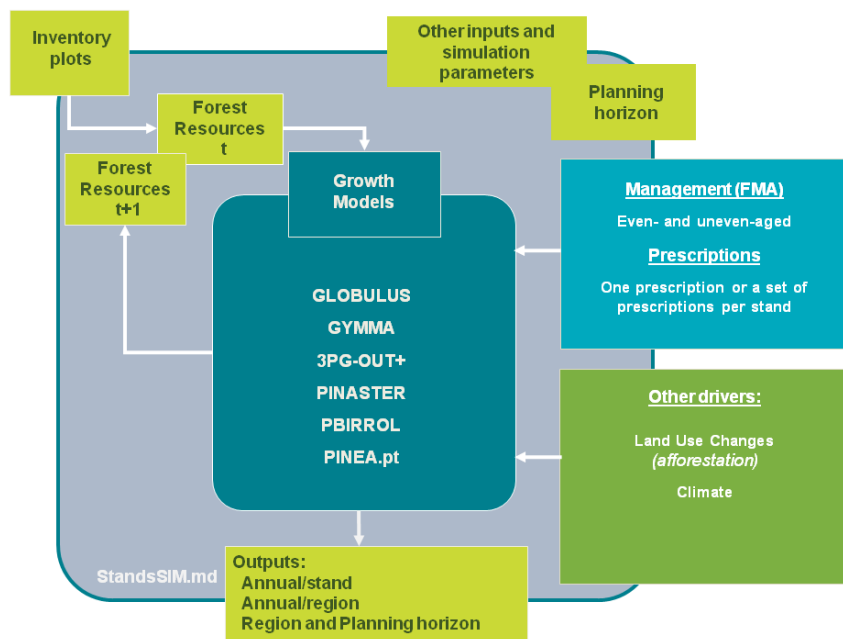


Figure 5. StandsSIM.md structure.

The simulator integrates different forest growth and yield models for the main tree species in Portugal: Eucalypt (*Eucalyptus globulus*), maritime pine (*Pinus pinaster*) and stone pine (*Pinus pinea*). Growth and Yield projections are either based on single-tree or stand level growth models depending on the tree species and /or stand structure (**Table 1**). When you define the species and the stand structure for **StandsSIM.md** to select the proper model to be used in the simulation. At present, the simulator only considers the simulation of pure (even and uneven-aged) stands.

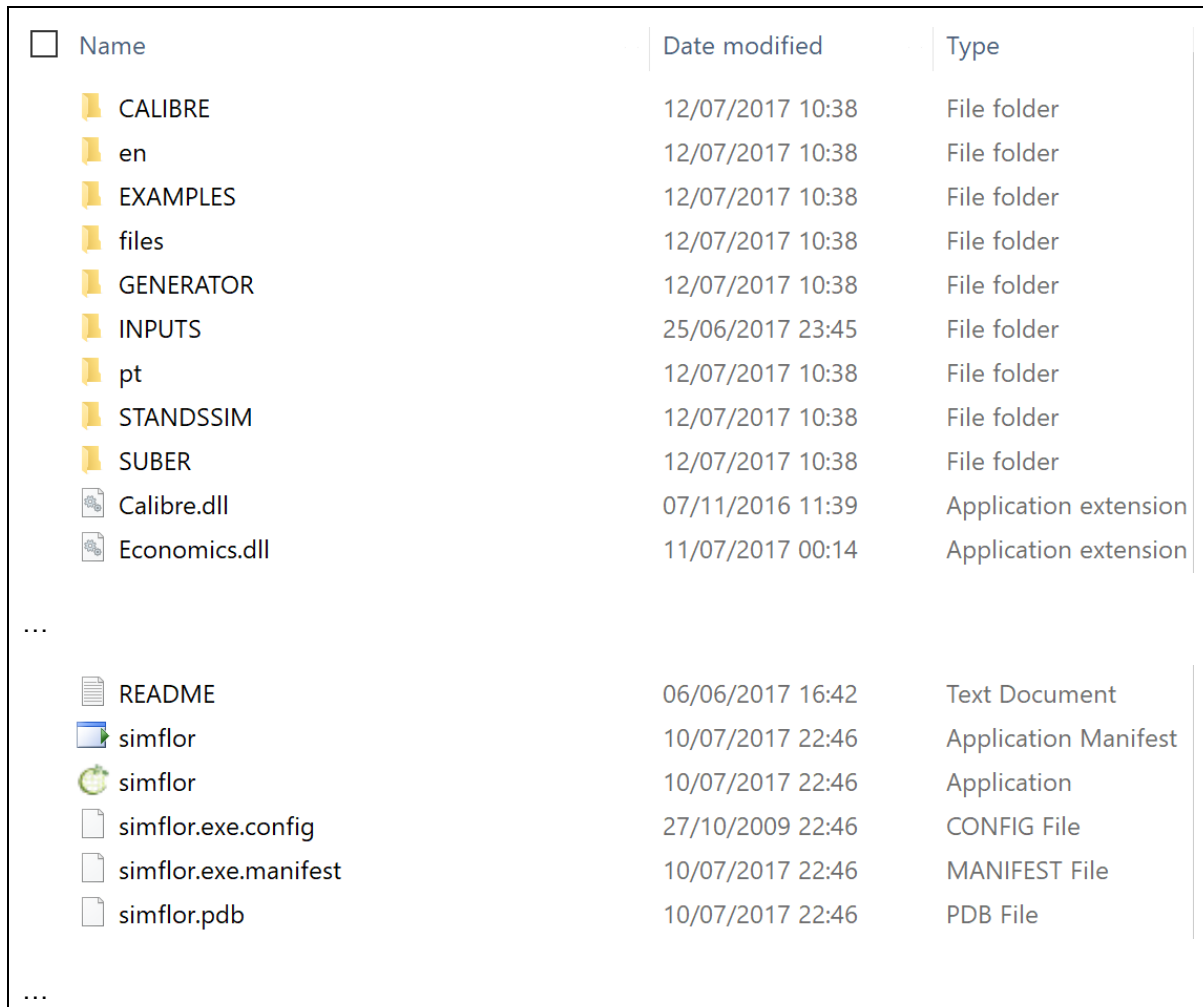
Table 1 - . Summary of the Growth and Yield models available for the main tree species in Portugal.

Tree Species	Stand Structure	Model Name	Model Type	Model Input level	Model Time-step
<i>Eucalyptus globulus</i>	Even-aged	Globulus3.0	Empirical	Stand	Year
		3PG-out+	Process-based (hybrid)	Stand	Month
	Uneven-aged	GYMMA	Empirical	Stand	Year
<i>Pinus pinaster</i>	Even-aged	PINASTER	Empirical	Tree	Year
	Uneven-aged	PBirrol	Empirical	Stand	Year
<i>Pinus pinea</i>	Even-aged	PINEA.pt	Empirical	Tree	Year

For additional details on the growth and yield models visit FCTools website where all the bibliography is listed.

4 StandsSIM.md within sIMfLOR- sIMfLOR_2017 folder structure

If you don't have any default input files, the first step, is generating the forest management approaches (FMAs) inputs and the Economic inputs. But before that let us take a look at the structure of the downloaded sIMfLOR_2017 folder (**Figure 6**).



Name	Date modified	Type
CALIBRE	12/07/2017 10:38	File folder
en	12/07/2017 10:38	File folder
EXAMPLES	12/07/2017 10:38	File folder
files	12/07/2017 10:38	File folder
GENERATOR	12/07/2017 10:38	File folder
INPUTS	25/06/2017 23:45	File folder
pt	12/07/2017 10:38	File folder
STANDSSIM	12/07/2017 10:38	File folder
SUBER	12/07/2017 10:38	File folder
Calibre.dll	07/11/2016 11:39	Application extension
Economics.dll	11/07/2017 00:14	Application extension
...		
README	06/06/2017 16:42	Text Document
simflor	10/07/2017 22:46	Application Manifest
simflor	10/07/2017 22:46	Application
simflor.exe.config	27/10/2009 22:46	CONFIG File
simflor.exe.manifest	10/07/2017 22:46	MANIFEST File
simflor.pdb	10/07/2017 22:46	PDB File
...		

Figure 6. sIMfLOR_2017 folder structure.

The most important sub-folder is the EXAMPLES containing default input files, some of them specific for each tree species, (**Figure 7**). The species name is identified by a two-letters code, where Ec stands for Eucalyptus, Pb for maritime pine and Pm for stone pine. Inside the folders “FMA”, “inventario” and “prescricao” the user will find species-specific csv files for the FMA, the plot/stand characterization and the prescription, respectively. The names of the files in the FMA sub-folder begin with *FMA_31*.csv* and *FMA_41*.csv*, where the number 3 stands for uneven-aged stand structure, whereas 4 for even-aged stand structure. In turn, the following number indicates the different options of FMA3 or FMA4 that have been defined (e.g.

FMA_42.csv* corresponds to the second forest management option for even-aged stands that was generated by the interface).

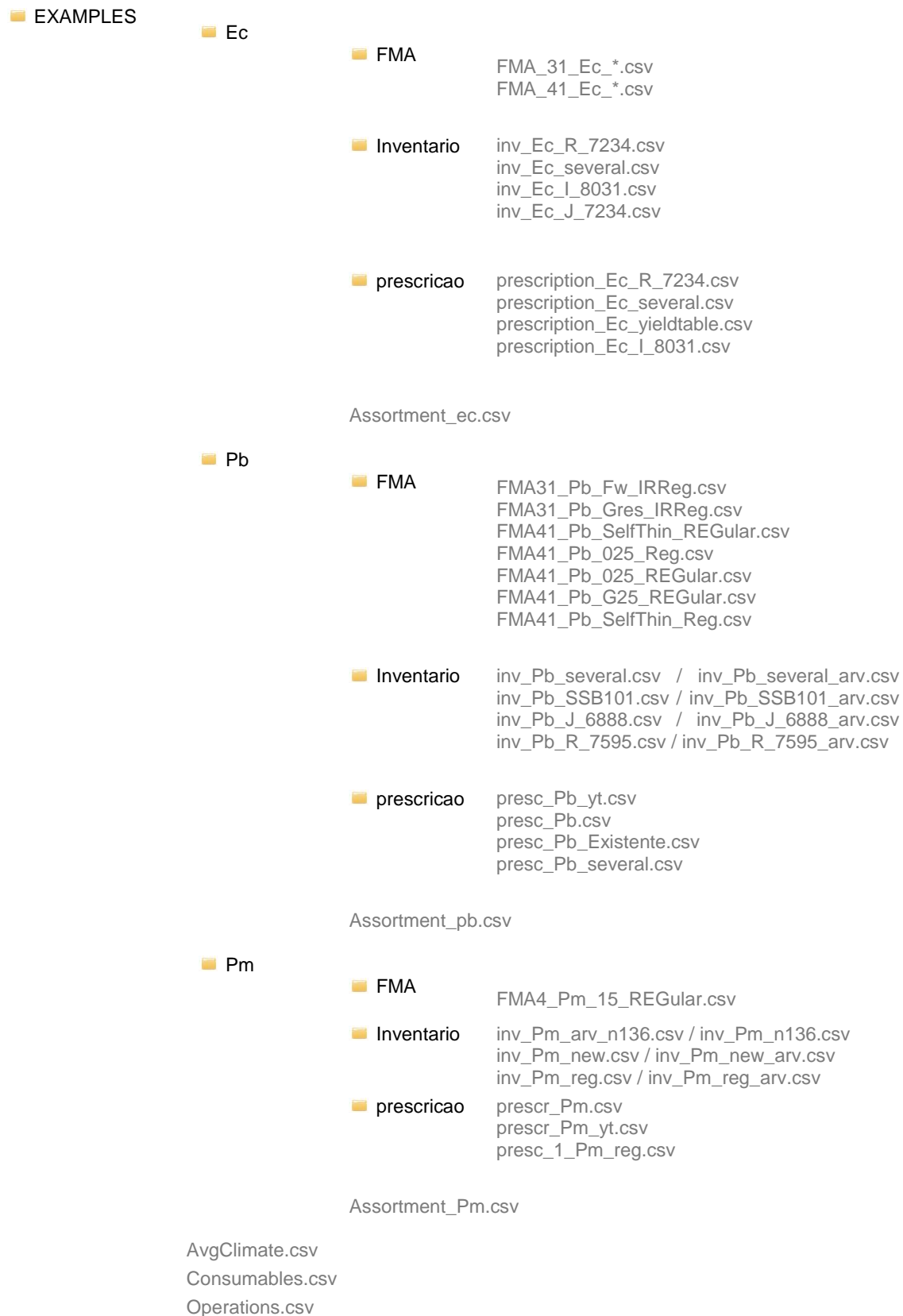


Figure 7. Structure of the folders within the EXAMPLES folder of *simfLOR_2017*

The files generated using the interface are saved in STANDSSIM folder, inside the corresponding tree species folder or in the OUTPUT folder (**Figure 8**), *file names marked in green*). Inside each of the species folders you will find the complete set of input files required to run StandsSIM.md simulator for each of the species (*the ones in grey were not created using the interface*).



Figure 8. Structure of the sub-folders within the STANDSSIM folder of sIMfLOR_2017.

4.1 StandsSIM.md input files created with the Generator

In general terms, one can say that **StandsSIM.md** requires 3 different types of inputs: the forest inventory inputs (stand and/or tree level), the forest management inputs (describing the

FMA and prescription) and the economic inputs (setting the prices for the silvicultural operations in the FMA, consumables, definition of assortments and its prices).

All inputs can be prepared in excel files and converted to csv files. However, to facilitate the use of **StandsSIM.md**, **sIMfLOR** was created and interfaces developed to facilitate the preparation of inputs. The input files related to silvicultural operations, their costs and the definition of assortments and their prices can be prepared in the Generator. The inputs characterizing trees and stands and the site (e.g. climate, topography), can be created by filling in the required information in the forms. The number and type of files that can be generated through **sIMfLOR** depend on what you want to simulate: a new plantation (Yield Table), an Existing Stand or Multiple Stands (**Figure 9**). The latest option will require most of the inputs to be prepared outside **sIMfLOR**. Please note that when creating a yield table for a tree species simulated using a tree level growth model, the *input_tree.csv* file is generated containing a single tree with all its variables set to zero.

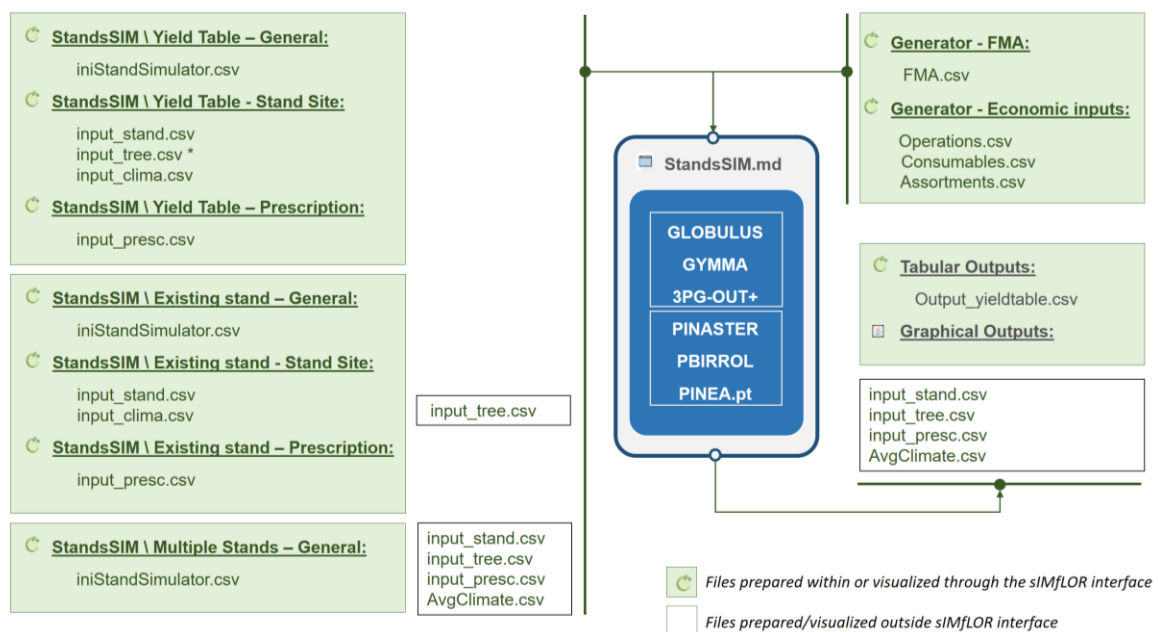


Figure 9. StandsSIM.md input and output files and their relation with sIMfLOR interface

It is important to know how the information provided through the interface is saved in the different input files. In **Appendix 1**, you can find the list of all the variables contained in each input file and the corresponding description.

4.1.1 Forest Management Data

A forest management alternative (FMA) is characterized by a set of user-defined silvicultural operations selected out of a vast list (CAOF 2016) grouped according to the mechanization level (e.g. manual, mixed, mechanical and infrastructures).

When an FMA file other than the default is desired, a new one can be created using the Generator. In this menu you will be asked to select the tree species for which you want to describe the forest management (FMA) - let us take eucalypt as an example (Figure 10). You will be asked to provide details about the silvicultural model you desire to follow (even-aged, uneven-aged or even-aged for energy). You will also have to define the type of regeneration and in the case of eucalypt if you want to consider coppice management you must choose “coppice”. Under “planting” the tool will assume the stands will never reach the second rotation. Before you select the silvicultural operations, you have to define the number of years for which you want to define management. This number can coincide with the period from stand regeneration until harvest or exceed. The number of years for which management is defined is the same for the planted and coppiced rotations.

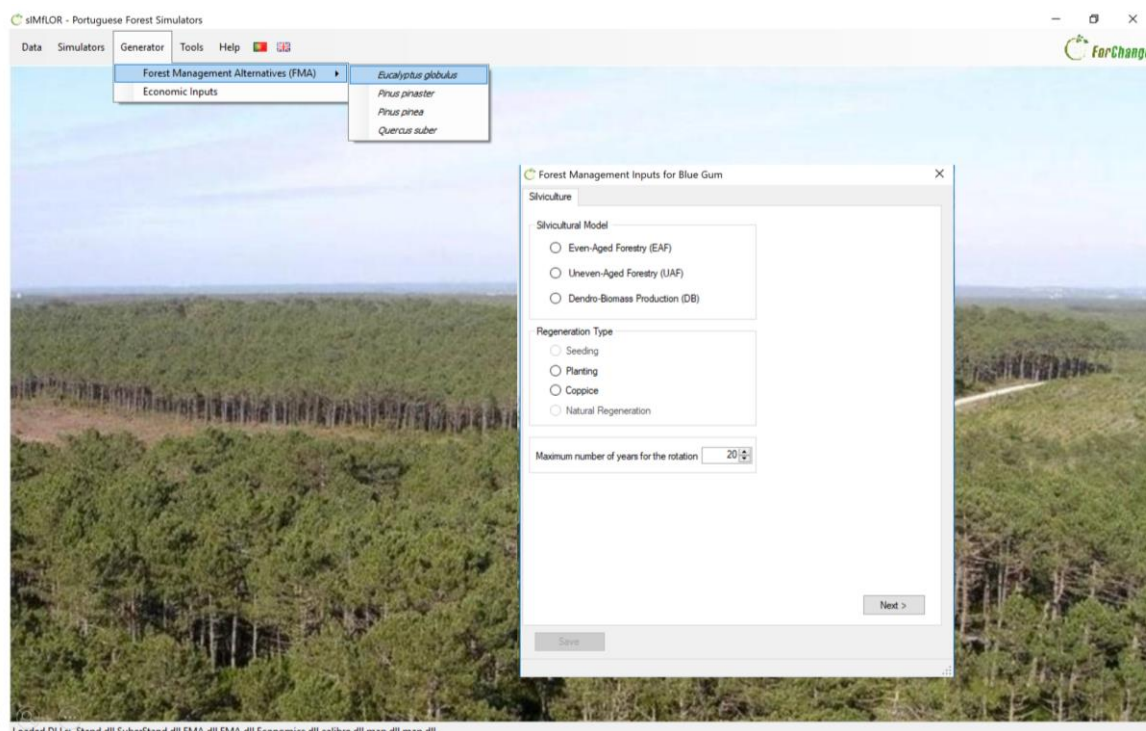


Figure 10. Print screen of the form Silviculture under the Generator\FMA\Eucalyptus globulus

In the “Operations” tab, the definition of the FMA involves selecting the operations from the list. After selected, operations will show on the table below and you will have to define when and how often these will take place (Figure 11). In the case of coppice, you should not forget

to select the operations for the coppice rotation before moving to the next tab. Please note that all coppices will be managed in the same way under the same FMA.

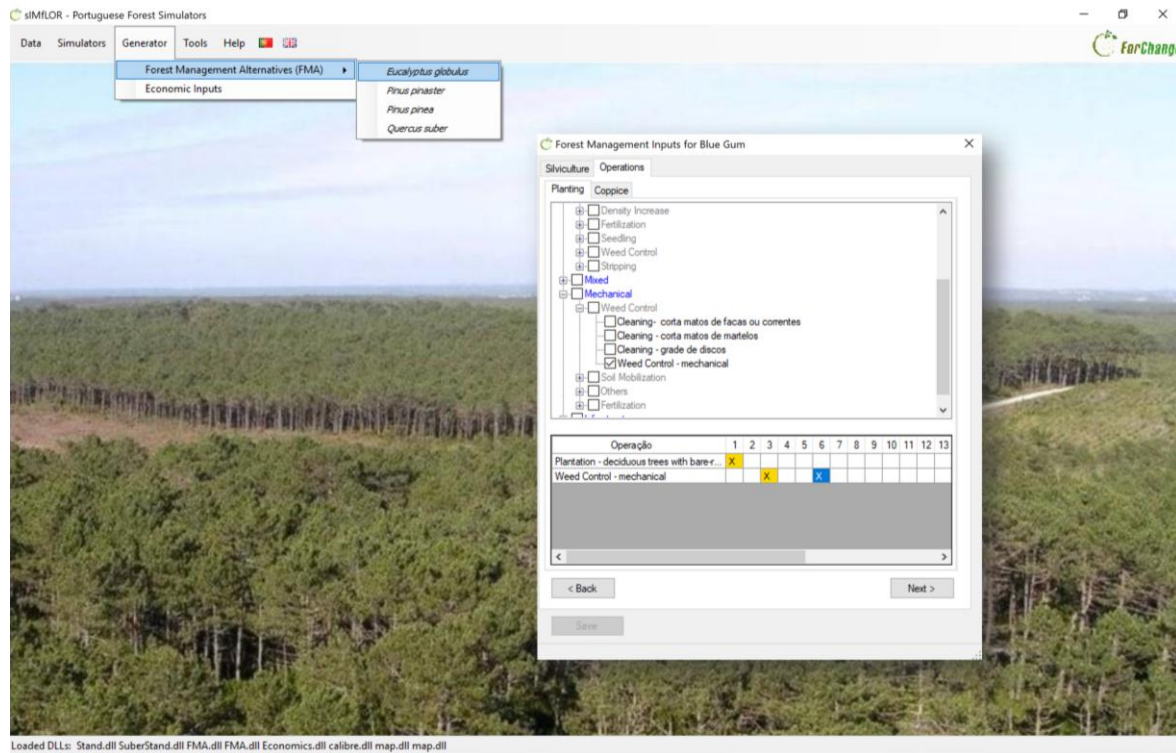


Figure 11. PrintScreen of the form Operations under the Generator\FMA\Eucalyptus globulus

As you move to the next tab, you might be asked to provide additional information for some of the operations you selected (e.g. planting requires information on the number of trees to plant; shoots selection requires information on how many shoots to leave per stool) (**Figure 11**).

After the details have been provided and saved you can take a look at the FMA file structure by opening it using the link in blue in the bottom of the window. The FMA file generated through the interface consists of matrix of 68 silvicultural operations (columns) over time (rows) with some additional information for some specific operations (the silvicultural details). The operations selected to take place are marked with 1 whereas the ones which haven't been selected will show the value zero. Thus, the X_{ij} matrix of 0/1 values, where i is the silvicultural operation whereas j represents the simulation year. For example, $X(13,3)=1$, means that the operation 13 is carried out at year/age 1. The top rows of the FMA file describe: 1) the silvicultural model (4 - even-aged or 3 - uneven-aged); 2) the regeneration type (planting or coppice); and 3) the number of years for which you want to define management (**Figure 12**).

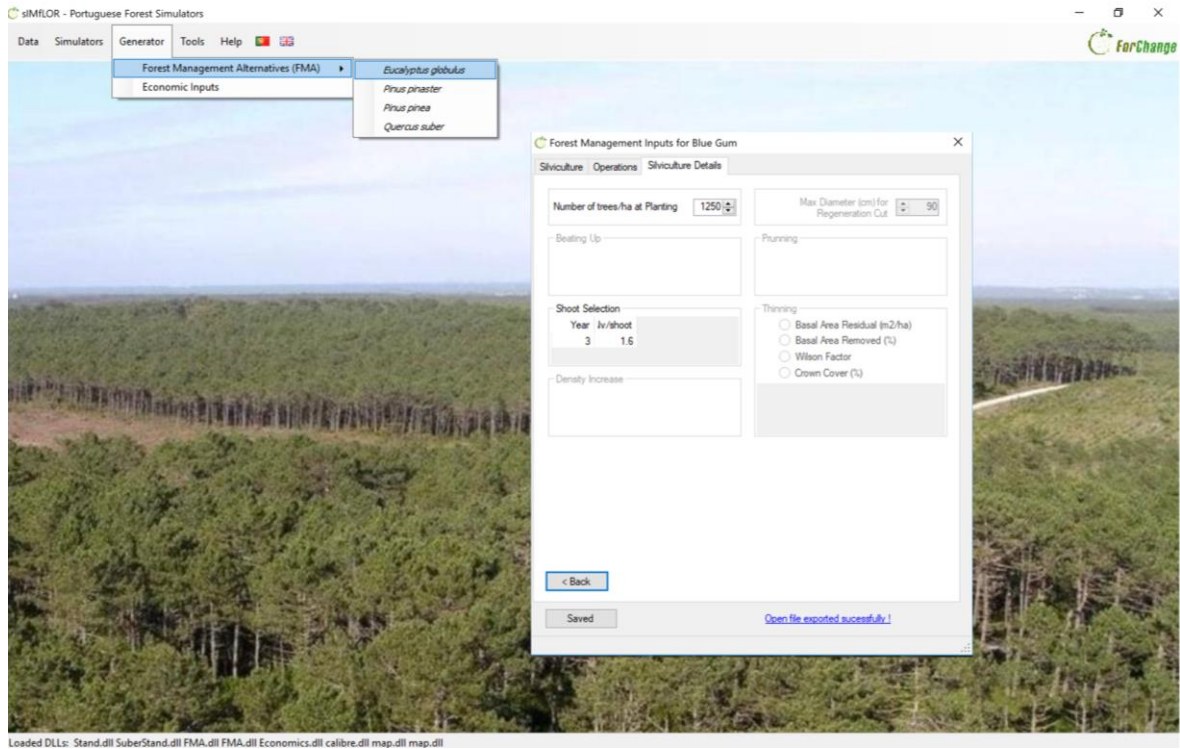


Figure 11. PrintScreen of the form Silviculture Details under the Generator\FMA\Eucalyptus globulus

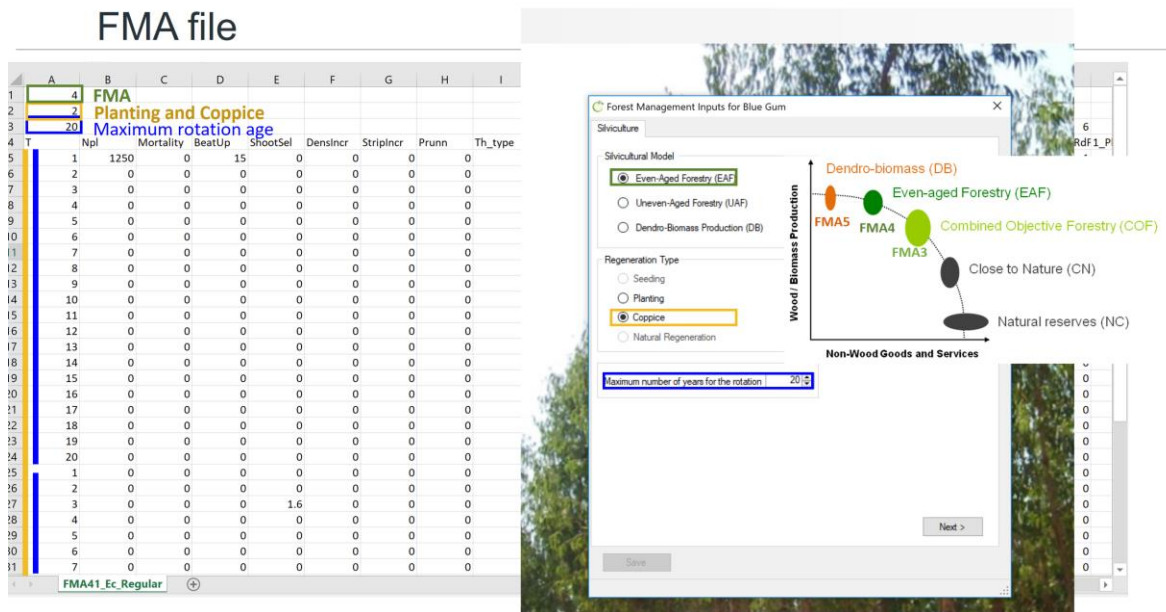
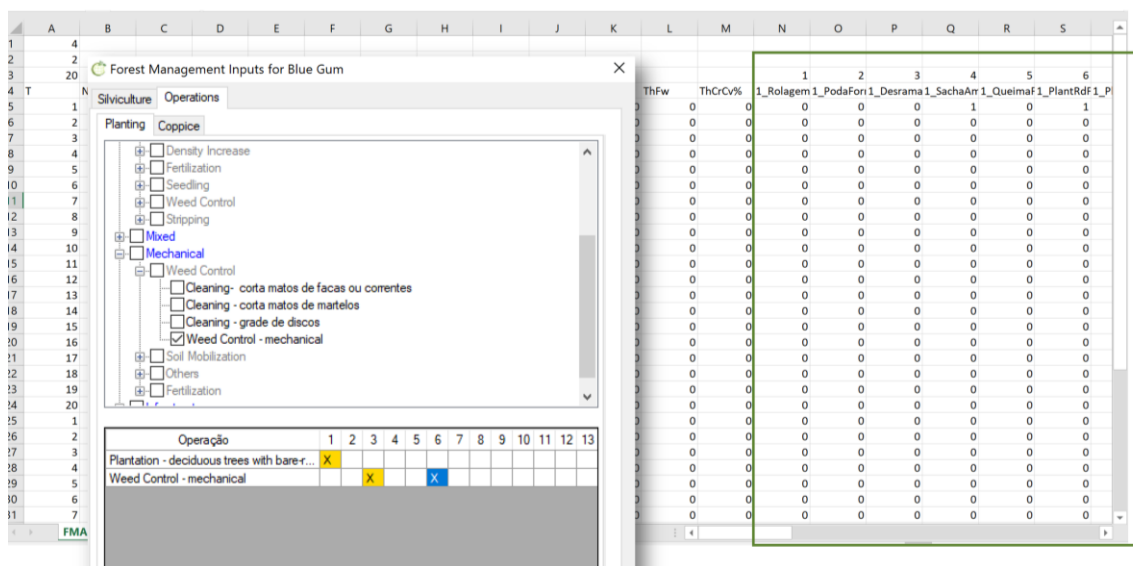


Figure 12. Side by side comparison of the transcription of the information provided in the Silviculture form and the content of the FMA file.

In the FMA file you will find a numeric identifier from 1 up to 68 is assigned to each silvicultural operation that allows you to locate the 0/1 Matrix within the file (**Figure 13** , marked in green), while the details show in the initial columns (Figure xxx.1 , marked in yellow). The FMA file is saved in the EXAMPLES folder (see Table 2 for the structure of the folder).

FMA file

Silvicultural operations: matrix (0,1)



FMA file

Silvicultural operations' details

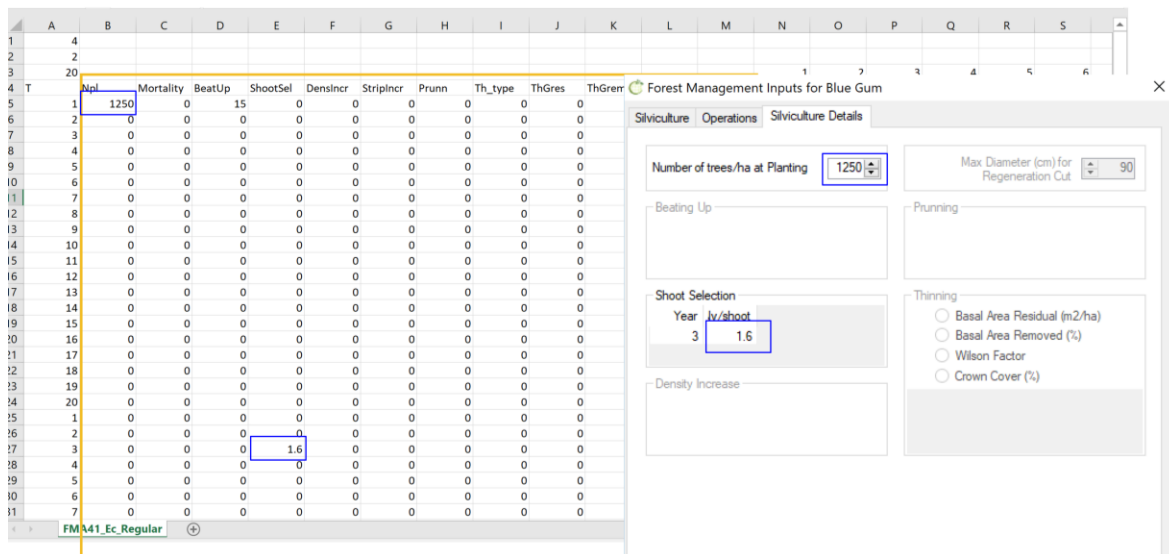


Figure 13. Side by side comparison of the transcription of the information provided in the forms for Operations and Silviculture Details and the content of the FMA file.

4.1.2 Economic Data

The costs for the operations listed under the FMA tab have been made available since 2002 and are updated every 2 years (CAOF 2016). The economic data comprises the costs for the 68 silvicultural operations (Operations Values tab), the costs for the products used in management such as plants or fertilizers (Other Values tab), the price of woody (Wood Products tab) and non-wood products (Non-wood Products tab).

In the Operations Values tab, after uploading the default costs file, the labour costs for the 68 silvicultural operations are displayed by operation type: Manual, Mixed, Mechanical and Infrastructures (**Figure 14**). Costs vary with the working conditions (e.g.: steepness, stoniness of the terrain and presence of shrubs) with the minimum costs linked to easy working conditions. You can edit the average cost and save the changes. In this tab, you will also have to define the discount rate that will be used in the calculus of the net present value.

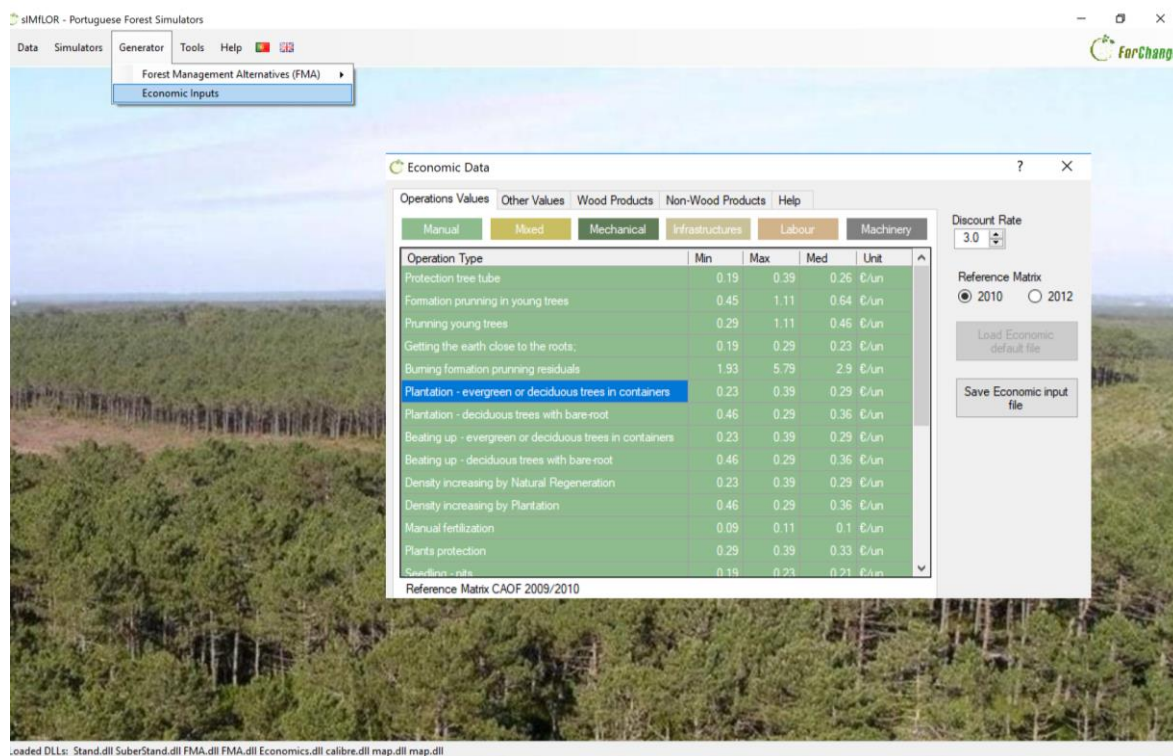


Figure 14. Print screen of the form Operations Values under the Generator\Economic Inputs.

If you open the file (INPUTS folder) you will find the 68 operations listed by row and the costs distributed by 4 different columns depending on the unit of the cost (e.g €/tree, €/km, €/m³ and €/ha) (Figure xxx.3 - in olive green). On the top row, you have the discount rate, followed by the number of additional discount rates and the additional discount rates you would like to have use for computing the EEA (Figure xxx).

Operations/economics file

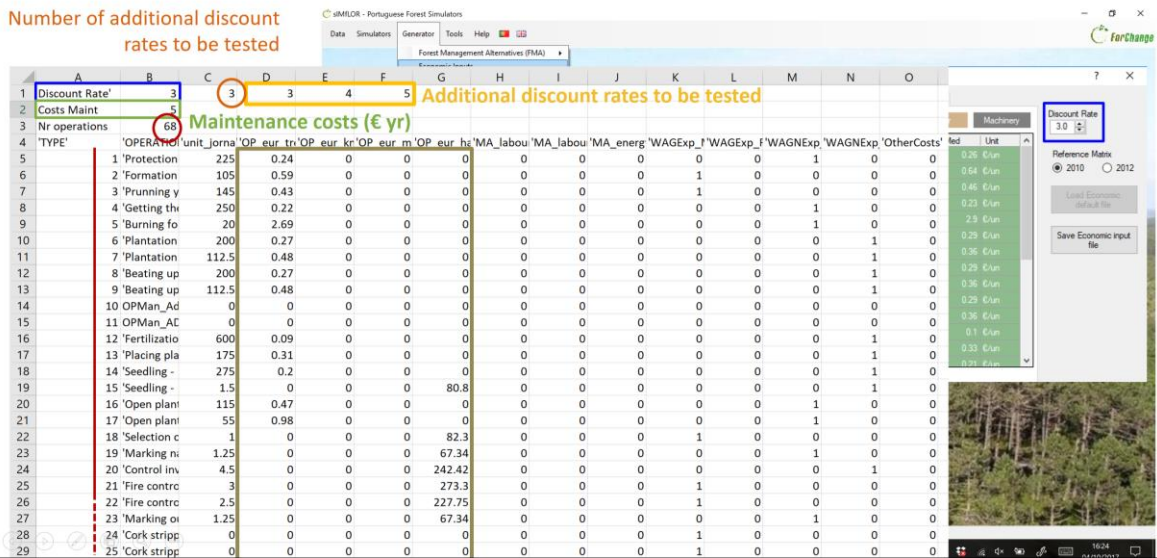


Figure 15. Side by side comparison of the transcription of the information provided in the form for Operations Values and the content of the Operations file.

In the Other values tab you will find the prices of some products used in some of the operations (e.g. the labour cost for planting can be found under the Operations Values tab, while the price for plants is here). These values can also be edited and saved (**Figure 16**).

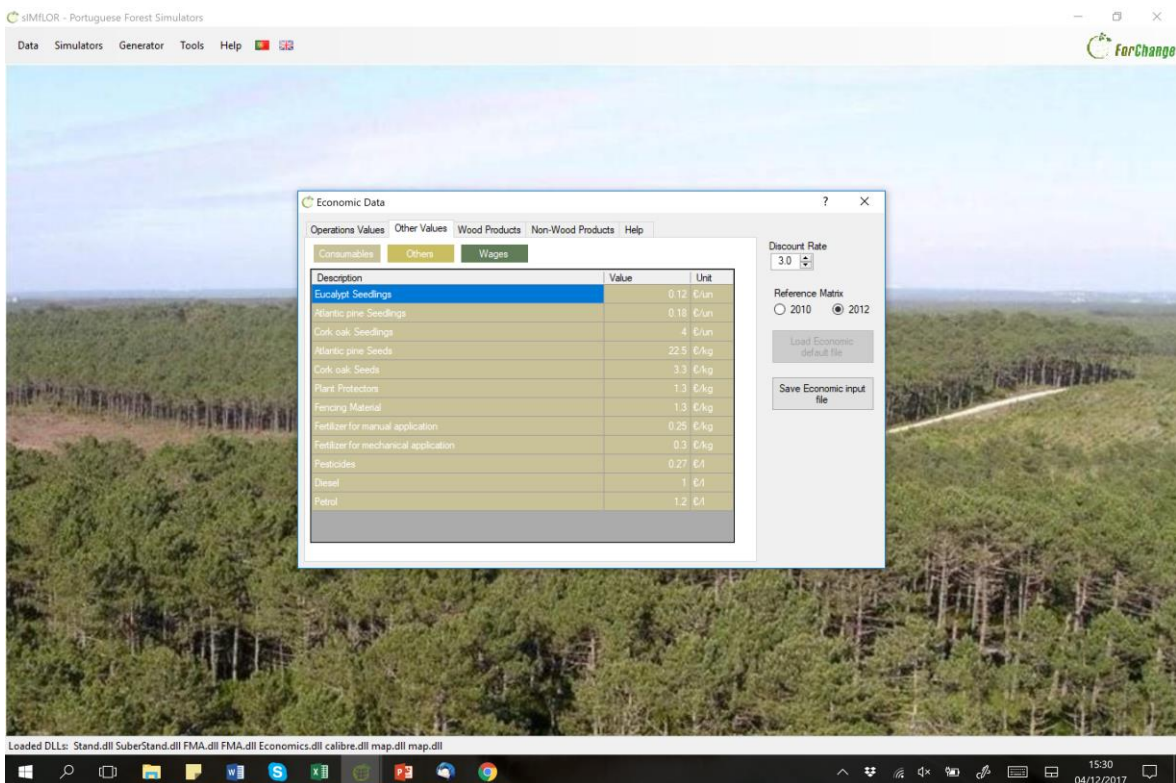


Figure 16. Print screen of the form Other Values under the Generator\Economic Inputs.

4.1.3 Assortments

Under the Wood Products tab, after selecting the tree species, the number of assortments has to be set and characterized by defining the log threshold diameters (cm), the log length (m), whether you want to consider assortments with (1) or without bark (0), and finally the value of each assortment (€/m³). In the case of eucalypt, because the wood is used for pulp there is only the need to define the top diameter. You can name the assortments and decide whether you want to run the simulation considering the removal of harvest residues by ticking the corresponding boxes (**Figure 17**, marked in blue). So far, the Non-wood Products tab is only active for cork oak. After filling in the information required under the economic data tab you must click the button “save economic data”, and 3 inputs files are generated (*operations.csv*, *consumables.csv* and *assortments.csv*) and saved in the folder INPUTS.

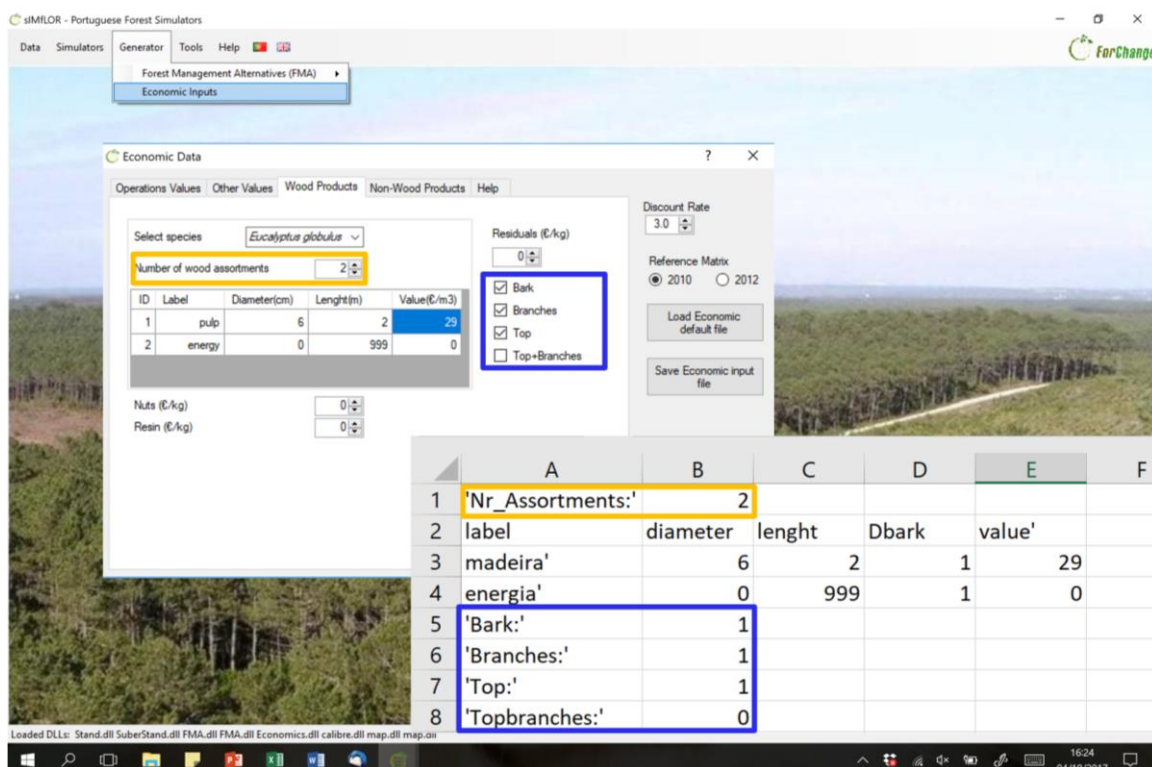


Figure 17. Side by side comparison of the transcription of the information provided in the form for Wood Products and the content of the Assortments file.

4.2 StandsSIM.md input files – Prescriptions and Stands

A prescription is the sequence of forest management approaches (FMA) that are used along the planning horizon for a given stand or group of stands. Therefore, a prescription is composed of k cycles, each one corresponding to an FMA. When running the tool under the FMA MODE, each cycle is characterized by 4 variables: the tree species, stand structure,

rotation and the FMA id. You have to make sure that for the 1st cycle these 4 variables match the characteristics of the stand or stands to each the prescription is assigned. For example, if you want to simulate the growth of an eucalyptus even-aged stand in the second rotation, the 1st cycle of the prescription must have the rotation (rot) set to 2 (**Figure 18**).

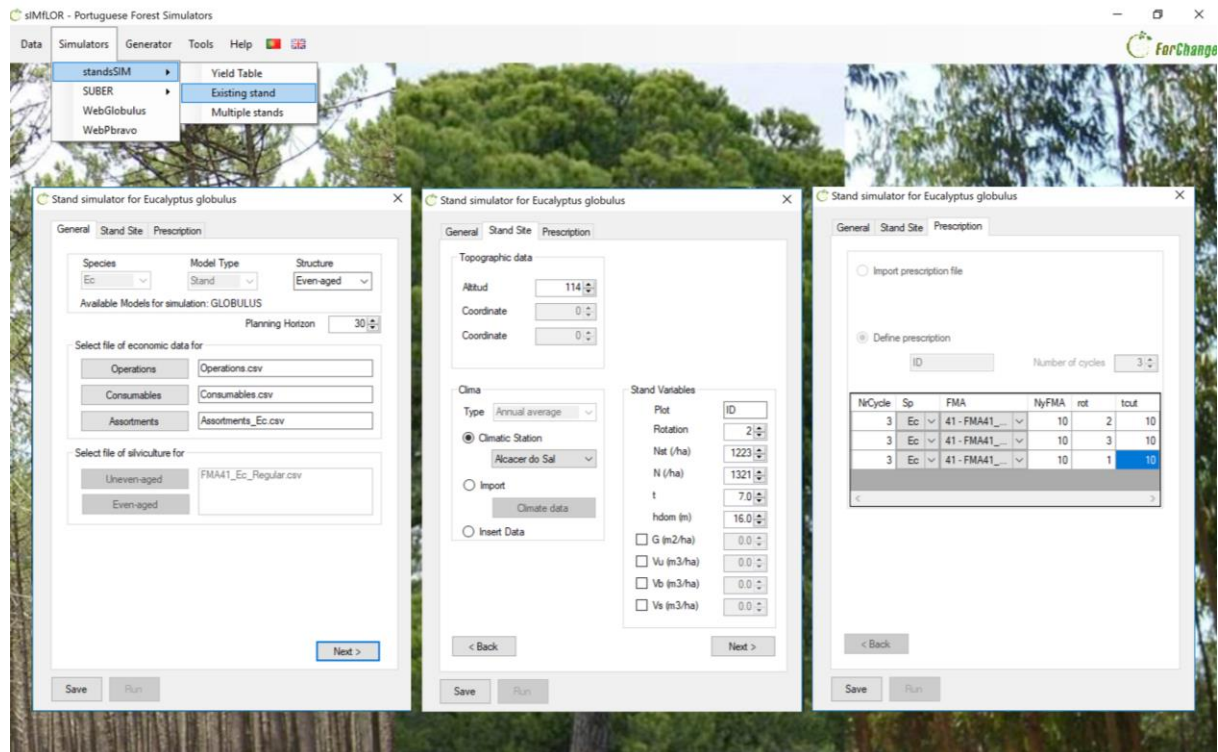


Figure 18. Print screen of the filled in forms for an existing eucalyptus stand in the second rotation considering a prescription composed of repetitions of the same FMA.

At a first look, it might seem that the prescription has the correct number of cycles given that the planning horizon was set to 30 and the harvest ages of the 3 cycles were set to 10. However, because the stand has 7 years, only the last 3 years of the 1st cycle will be used, on the other hand a 4th cycle is needed to cover for the last 7 years of simulation (**Figure 19**).

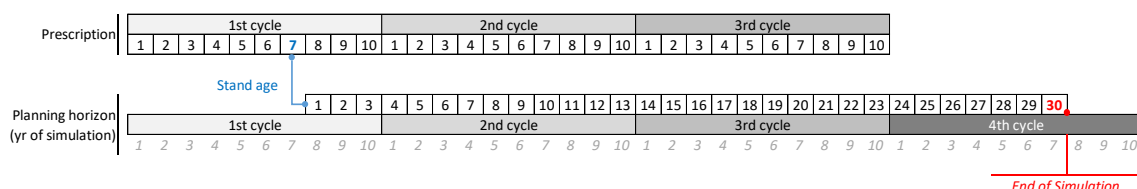


Figure 19. Schematic overview of the application of a prescription to existing stands older than 1.

When the prescription does not cover the entire planning horizon, you get a warning in the black window, advising you to revise the prescription (**Figure 20**). This is the reason why you

are always advised to define prescriptions with one cycle more than what it seems required at a first look.

```
C:\BACKUP\Susana\Aulas\Classes_2017-2018\SIMFLOR_2017\STANDSSIM\standsimulator.exe
*****
Climate data used by standsSIM:

Climate data:
C:\BACKUP\Susana\Aulas\Classes_2017-2018\SIMFLOR_2017\STANDSSIM\GLOBULUS\input_
clima.csv

*****
SUMMARY of the simulations:

stand  presc  Nyears  S      NPV    EAA    maiV   Vharv
ID     ID     terminated before the planning horizon - check prescriptions
ID     ID     7      23.0  4165.0  443.8  15.1   174.9

Total number of plots simulated:  1
                                even-aged plots:  1
                                uneven-aged plots:  0

Total volume harvested (m3) :    174.9
Annual volume harvested (m3):    14.6

Press ENTER to finish
```

Figure 20. Print-screen of the black window showing the summary results of a run containing a warning for a short prescription (not covering the entire planning horizon).

In the example in **Figure 18**, a single FMA was selected over the planning horizon. However, a prescription can be composed of different FMAs (**Figure 21**). These have to be selected in a single step (see section 5.3). The one that shows first in the box (*FMA41_Ec_Regular.csv*) is assigned the FMA/opt id of 41, whereas the second (*stp_FMA42_Ec_Regular.csv*) the id FMA/opt of 42. These id results of concatenating the information in columns FMA (4) and opt (1 or 2) in the *input_prescr.csv* file (see section 5.3.1).

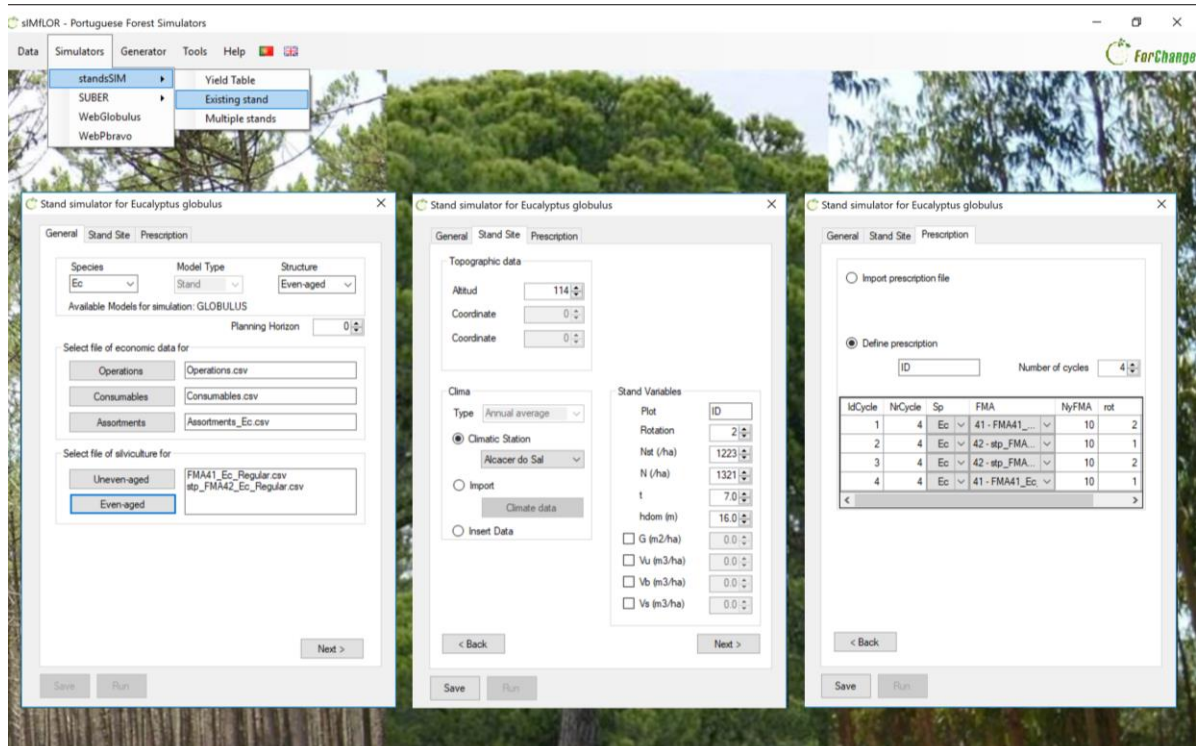


Figure 21. Print-screen of the filled in forms for an existing eucalyptus stand in the second rotation considering a prescription composed of different FMAs.

5 Simulating with StandsSIM.md

To run a simulation you must go to the Simulators\StandsSIM and choose whether to simulate a yield table (new plantation), an Existing Stand or Multiple Stands. We will now take a look at each of the situations, for which an exercise is presented and solved.

5.1 Simulating a Yield table

The simulation of a yield table is the less demanding in terms of inputs with the possibility of generating all inputs using SIMfLOR interface (Figure y). When you want to simulate a new plantation, you have to characterize the site and the management throughout the planning horizon in the interface forms so that the required inputs are generated. Take the eucalypt plantation described below and see **Figure 22** for the description on how to run the simulation.

Build a yield table for a eucalypt for a planning horizon of 30 years considering:

- i) a plantation followed by two coppices;
- ii) final harvest at 10 years for all rotations;

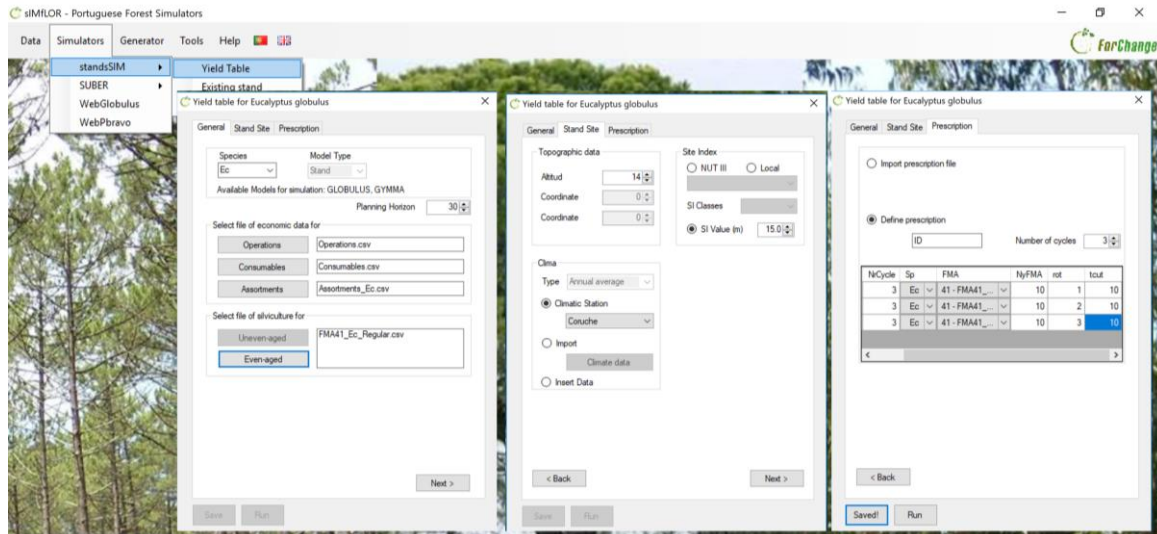
Site Characteristics:

Location: *Coruche municipality*

Altitude: 14 m (if you don't know the altitude you can use the webGLOBULUS stand simulator to obtain it)

Site index: 15 m (base age 10 years)

iii) managed according to the FMA described in *FMA41_Ec_Regular.csv*



StandSIM input files created: C:\SIMFLOR_2017\STANDSSIM\input_standsSIM.csv
 C:\SIMFLOR_2017\STANDSSIM\GLOBULUS\input_stand.csv
 C:\SIMFLOR_2017\STANDSSIM\GLOBULUS\input_clima.csv
 C:\SIMFLOR_2017\STANDSSIM\GLOBULUS\input_prescr.csv

Figure 22. Print-screen of the filled in forms for building a Yield Table for eucalypt.

After filling in the information and you press run, usually a black window shows presenting a summary of your simulation run (**Figure 23**).

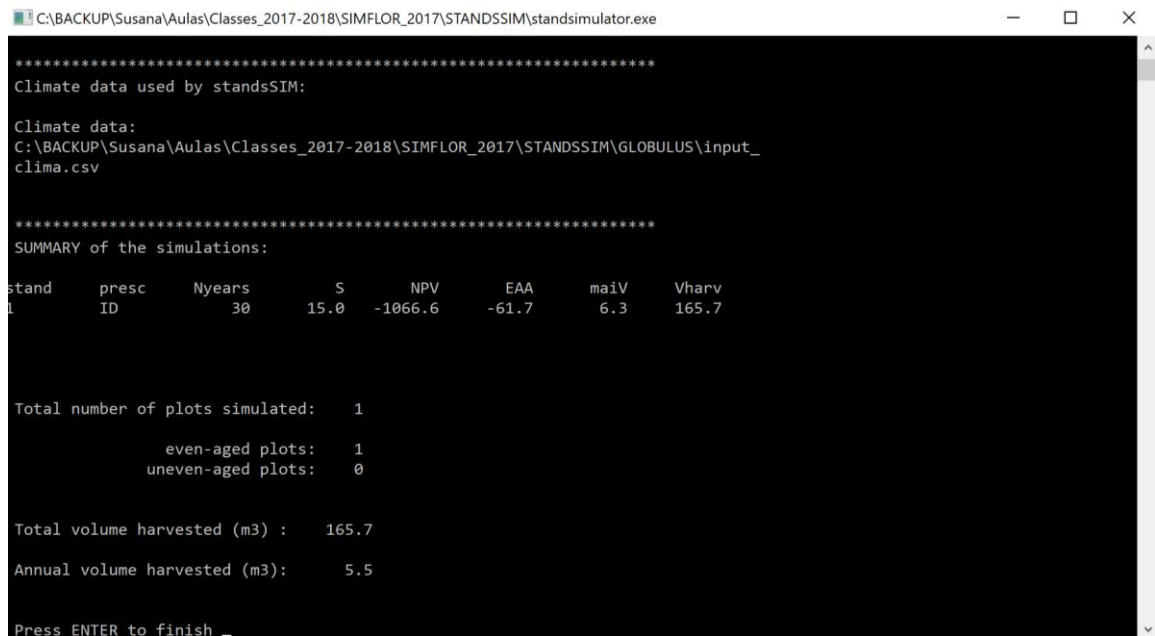


Figure 23. Print-screen of the black window showing the summary results of a successful run.

Yield table for Eucalyptus globulus

General Stand Site Prescription Results [output](#)

ID	t	rot	hdom	dg	Net
1	0	1	0	0	1250
1	1	1	1.2	1.1	1250
1	2	1	3.6	2.9	1250
1	3	1	5.7	4.5	1250
1	4	1	7.6	5.8	1233
1	5	1	9.2	7	1217
1	6	1	10.7	8	1201
1	7	1	11.9	8.8	1185
1	8	1	13.1	9.6	1169
1	9	1	14.1	10.3	1153
1	10	1	15	11	1138
1	10	1	0	0	0
1	1	2	1.2	0.7	899
1	2	2	3.6	2.2	889
1	3	2	5.7	3.6	878
1	3	2	5.7	4.1	878
1	4	2	7.6	5.3	867
1	5	2	9.2	6.3	857
1	6	2	10.7	7.2	846
1	7	2	11.9	8	836

Save Run Table Graphs Distribution

This indicates the simulation is completed and by pressing “enter” you return to the interface where by clicking on “Table” you can display a summary of the outputs in tabular form (**Figure 24**). In the upper corner, you will read the word “output”, in blue, and by clicking the word you will be allowed to open the complete output file (*output_yieldtable.csv*).

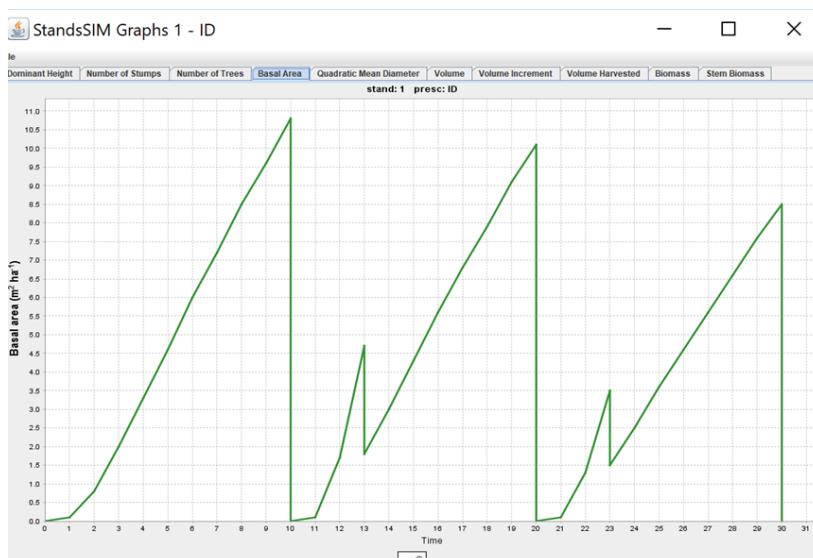
Alternatively, you can opening it directly going to:

c:\SIMFLOR_2017\STANDSSIM\OUTPUT.

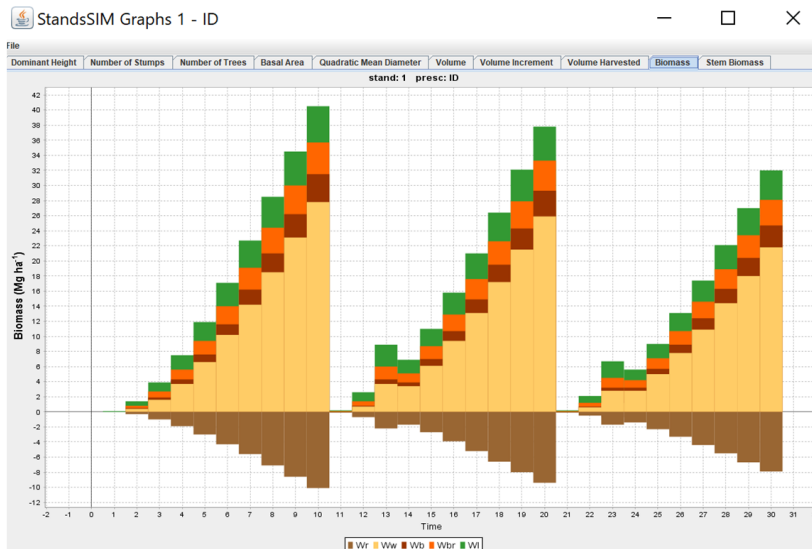
In this file you will find the evolution of a wide range of stand variables over time (see the **Appendix 2** for the description of the output variables).

Figure 24. Print-screen of the table with the summary of the outputs.

Back to the interface, you also have the possibility to visualize the evolution of the most important stand variable in a graphical format using the button “Graphs” (**Figure 25**).



Evolution of stand basal area (G , m^2ha^{-1}) over time for the 3 rotations, where the big decreases observed at years 10, 20 and 30 result of the final cut operation, whereas the smaller reductions in the 2 coppiced rotations are the result of the selection of shoots.



Evolution of stand biomass by tree component (W_i , $Mgha^{-1}$) over time.

Figure 25. Print-screen of some graphics available automatically generated by the interface.

You will not find significant differences if you choose to build a yield table for maritime pine or stone pine. However, when running StandsSIM.md for these species you will find that after saving the input information provided using the interface an additional input is created at **C:\SIMFLOR_2017\STANDSSIM\GLOBULUS: *input_tree.csv***. This file is automatically generated because the growth and yield models for both pines are tree level models, therefore requiring information for trees when simulating existing stands (for plantations tree level information is not required, if you open the file you will see it contains a single tree for which there is no information). Another difference is that for tree level models you have the possibility to seeing the evolution of the diameter distributions over time by clicking on the button “Distribution”, next to the “Graphs”.

To run your simulations smoothly for a yield table you have to make sure that:

- 1) the sum of harvest ages (or number of years to simulate each cycle) in the prescription is enough to cover the planning horizon. To achieve this you either create enough cycles or increase the harvest ages.
- 2) the FMA is defined for a number of years greater or equal to any harvest age (or number of years to simulate a cycle) you intent to consider. If you define your FMA using the Generator the “Maximum number of years of the rotation” needs to exceed the harvest ages. On the other hand if you are using an existing FMA file, open it first to make sure management is defined to cover the whole rotations.

5.2 Simulating an Existing stand

The biggest difference between simulating an existing stand and a plantation lies in the fact that you will also have to characterize the existing stand, and its trees in case the tree species are simulated using an individual tree level models beside characterizing the site. Suppose you have the maritime pine existing stand described below. Follow the correct filling in of the forms in **Figure 26**.

Simulate the growth of a maritime pine stand managed as uneven-aged for 35 years after which the stand will be harvested and a plantation of the same species made.

Simulate the growth of these stands applying the suggested FMAs:

FMA31_Pb_Gres_Irreg.csv

FMA41_Pb_025_REGular.csv.

Site Characteristics:

Location: Alcácer do Sal municipality

Altitude: 100 m (if you don't know the altitude you can use the webGLOBULUS stand simulator to obtain it)

Stand Characteristics:

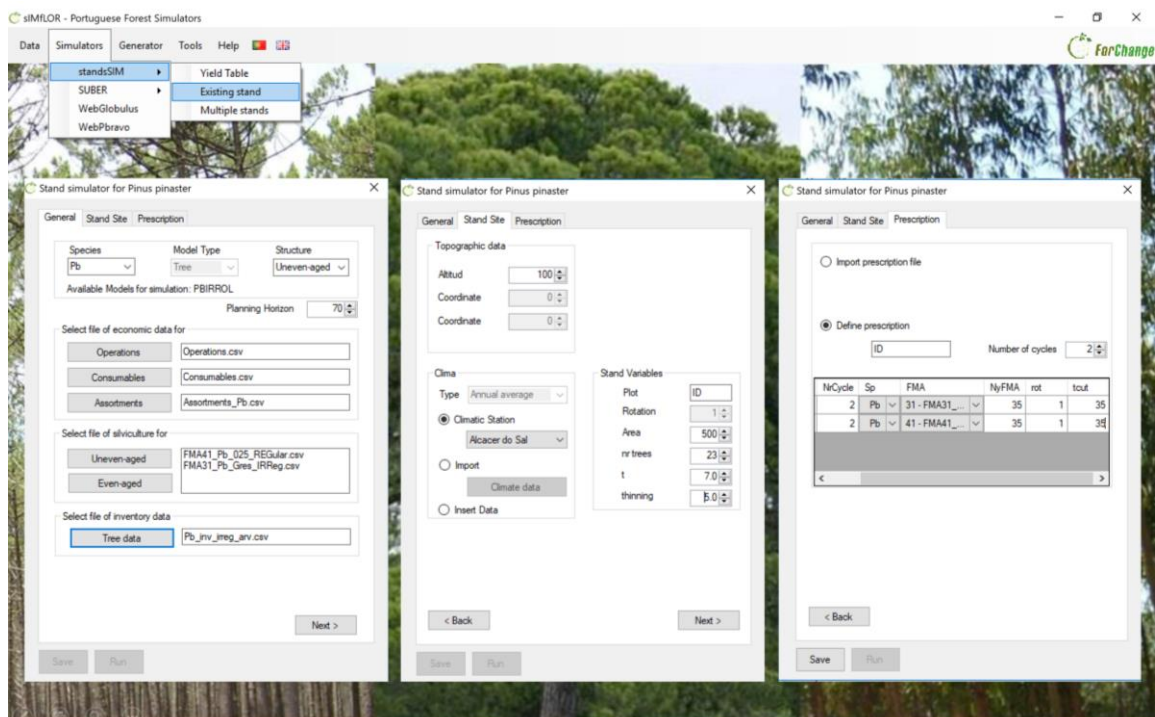
Stand structure: uneven-aged

Plot area: 500 m²

Tree data file: *Pb_inv_irreg_arv.csv*

Number of trees in the plot: 23 trees

Number of years since the last thinning: 5



StandsSIM input files created:

C:\SIMFLOR_2017\STANDSSIM\ini_standsSIM.csv

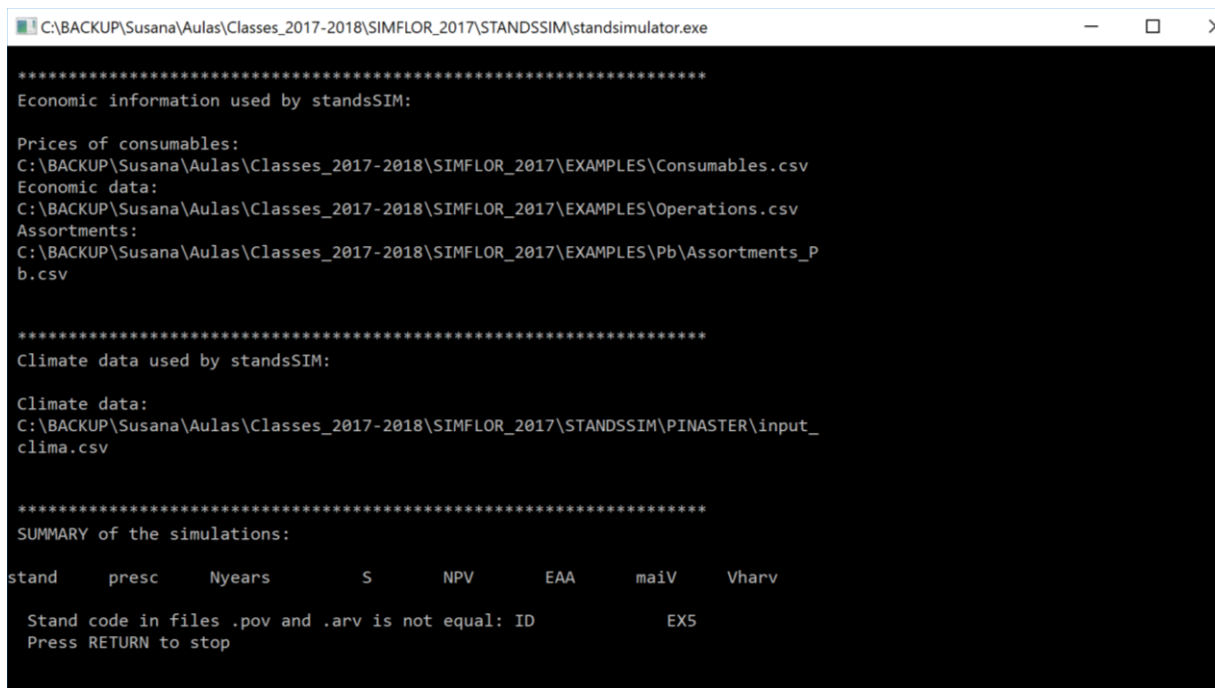
C:\SIMFLOR_2017\STANDSSIMPINASTER\input_stand.csv

C:\SIMFLOR_2017\STANDSSIMPINASTER\input_clima.csv

C:\SIMFLOR_2017\STANDSSIMPINASTER\input_prescr.csv

Figure 26. Print-screen of the filled in forms for simulating a maritime pine existing stand.

After saving the information (generating the input files) you can run your simulation. When the simulation is terminated, you get the black window with a summary of the run (**Figure 27**).



```
C:\BACKUP\Susana\Aulas\Classes_2017-2018\SIMFLOR_2017\STANDSSIM\standsimulator.exe
*****
Economic information used by standsSIM:

Prices of consumables:
C:\BACKUP\Susana\Aulas\Classes_2017-2018\SIMFLOR_2017\EXAMPLES\Consumables.csv
Economic data:
C:\BACKUP\Susana\Aulas\Classes_2017-2018\SIMFLOR_2017\EXAMPLES\Operations.csv
Assortments:
C:\BACKUP\Susana\Aulas\Classes_2017-2018\SIMFLOR_2017\EXAMPLES\Pb\Assortments_Pb.csv

*****
Climate data used by standsSIM:

Climate data:
C:\BACKUP\Susana\Aulas\Classes_2017-2018\SIMFLOR_2017\STANDSSIM\PINASTER\input_clima.csv

*****
SUMMARY of the simulations:

stand   presc   Nyears   S       NPV     EAA     maiV    Vharv
-----
Stand code in files .pov and .arv is not equal: ID          EX5
Press RETURN to stop
```

Figure 27. Print-screen of the black window showing a warning message for an inconsistency detected in the input files.

You must always read the information provided in this window. In **Figure 27** there is a warning informing you of an inconsistency detected between the stand ID in the stand and tree files. At this point, if you press “Run”, the summary of outputs will not be made available when pressing on “Table”. To solve the problem click “Back” until you reach the “Stand Site” tab (clicking directly on this tab will not allow editions); then, under the section “Stand variables” change the stand ID to “EX5” (the stand ID in the tree input file), save the change and run the simulation. If for any reason you are not allowed to make this correction, repeat the process making sure you have the same stand ID is used in both files, either by changing it in one or the other. After this second run, you will get the message indicating a successful run: “**Press enter to finish**” and the summary of the evolution of the most important stand variables will be displayed by clicking on “Table”. After the summary is displayed, the Graphs functionality becomes available.

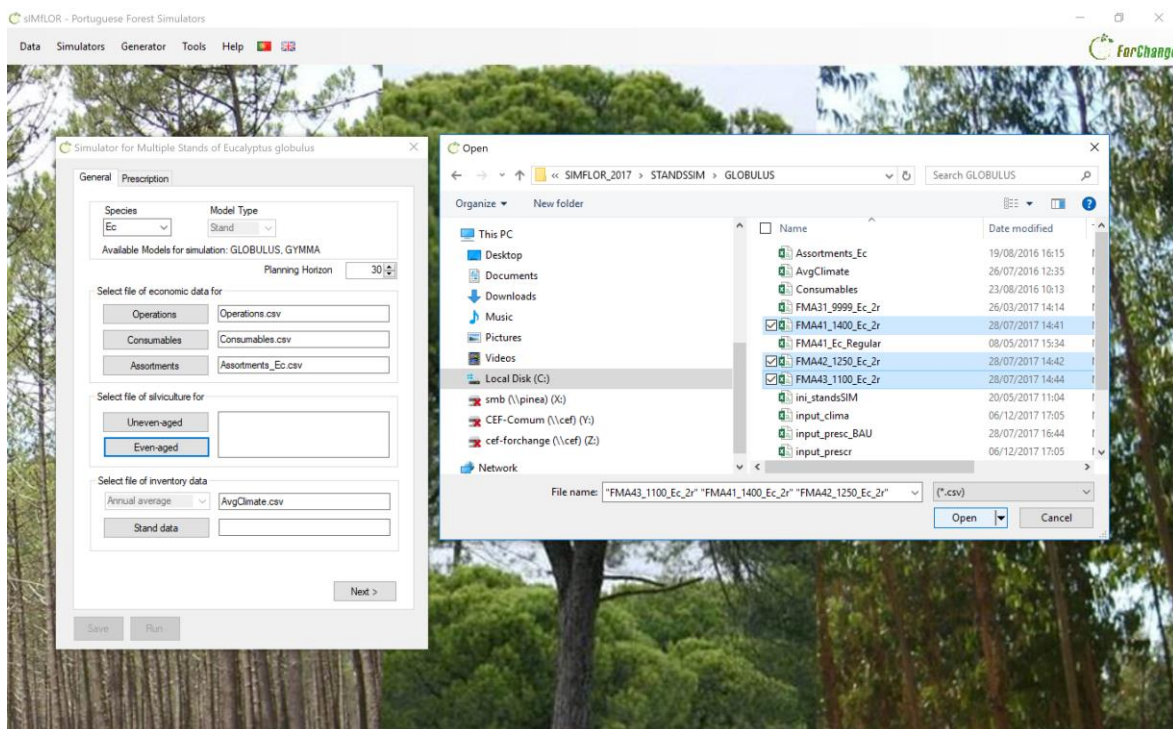
To run your simulations smoothly for an existing stand you have to make sure that:

- 1) the same requirements listed for the yield table simulation run are both met

2) no inconsistencies between the stand and tree input files exist, in terms of Stand ID or number of trees in the plot.

5.3 Simulating Multiple stands

simfLOR was not conceived for generating the input files for more than one stand, thus if you want to simulate several stands, you will have to prepare most of the inputs outside the interface. In fact, the interface will only be used to create the *ini_standsSIM.csv* file. When you simulate several stands it is likely that you will need to use more than one FMA. The FMAs for even- and uneven-aged stand structures have to be imported separately, but all FMA of the same type MUST BE imported in a single step. Suppose you want to simulate 330 eucalypt even- and uneven-aged stands to which you want to assign 1 uneven-aged FMA and 3 even-aged FMAs. **Figure 28** illustrates a situation for which the user desires to import 3 FMAs for even-aged management and one for uneven-aged management. By clicking on “Even-aged” you are given the possibility to select the 3 files at the same time. After these appear in the FMA box, you can then select the uneven-aged FMA.



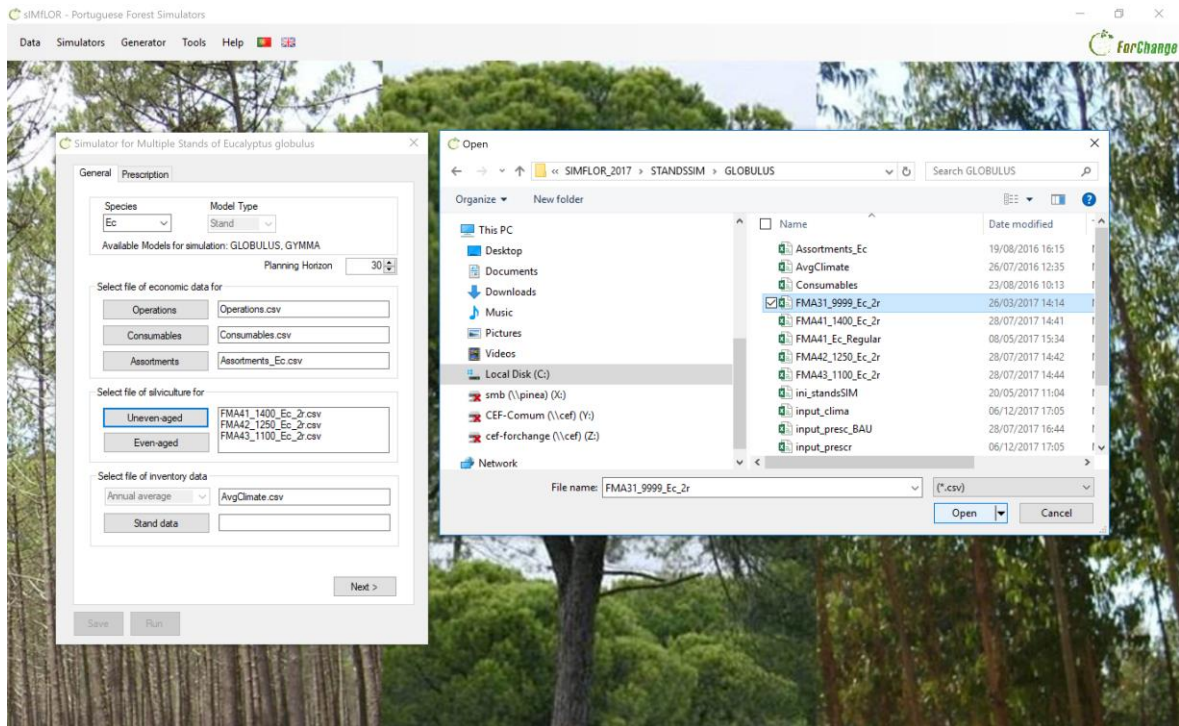


Figure 28. Print-screen illustrating the process of importing several FMAs.

After importing the FMA files, you have to import the stand inventory file. The last step will be importing the prescription file (**Figure 29**).

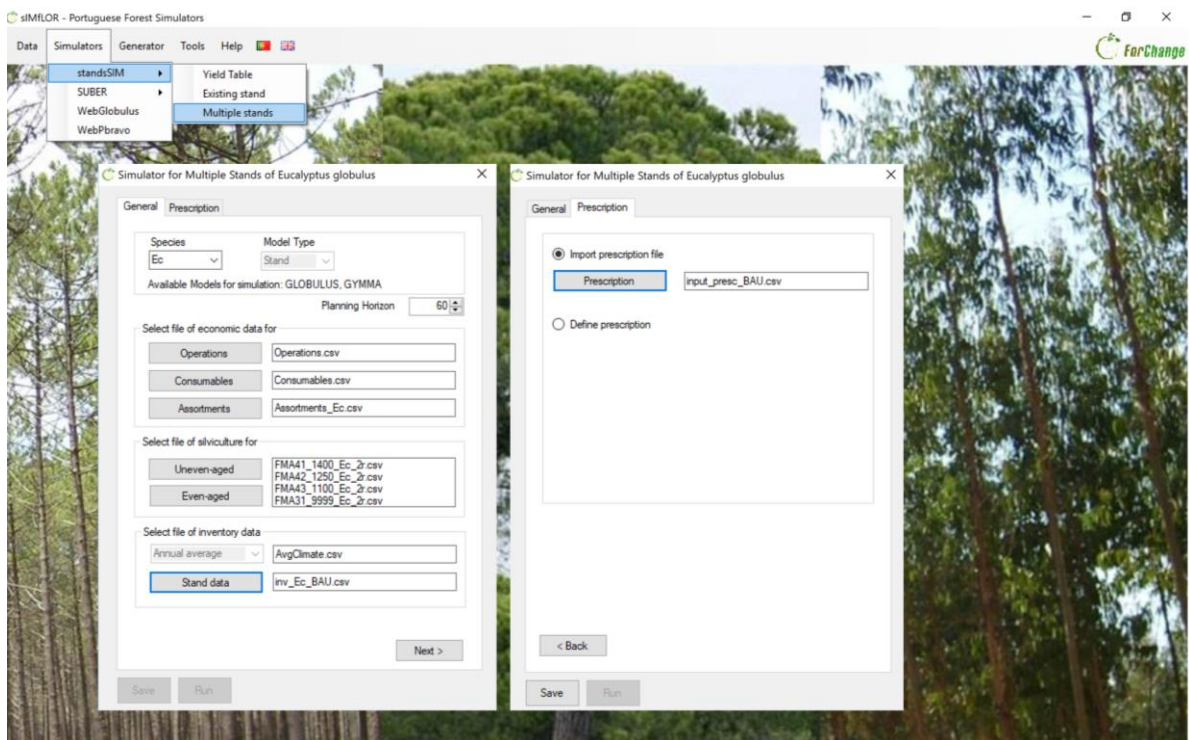


Figure 29. Print-screen illustrating the filled in forms for a simulation run for Multiple Stands.

Please note, if you import the FMAs for even-aged management individually (several steps), they will all show in the in the box, HOWEVER only the first one will be truly imported (to which the code 4,1 is assigned) and will be written in the *ini_standsSIM.csv* (Figure 30).

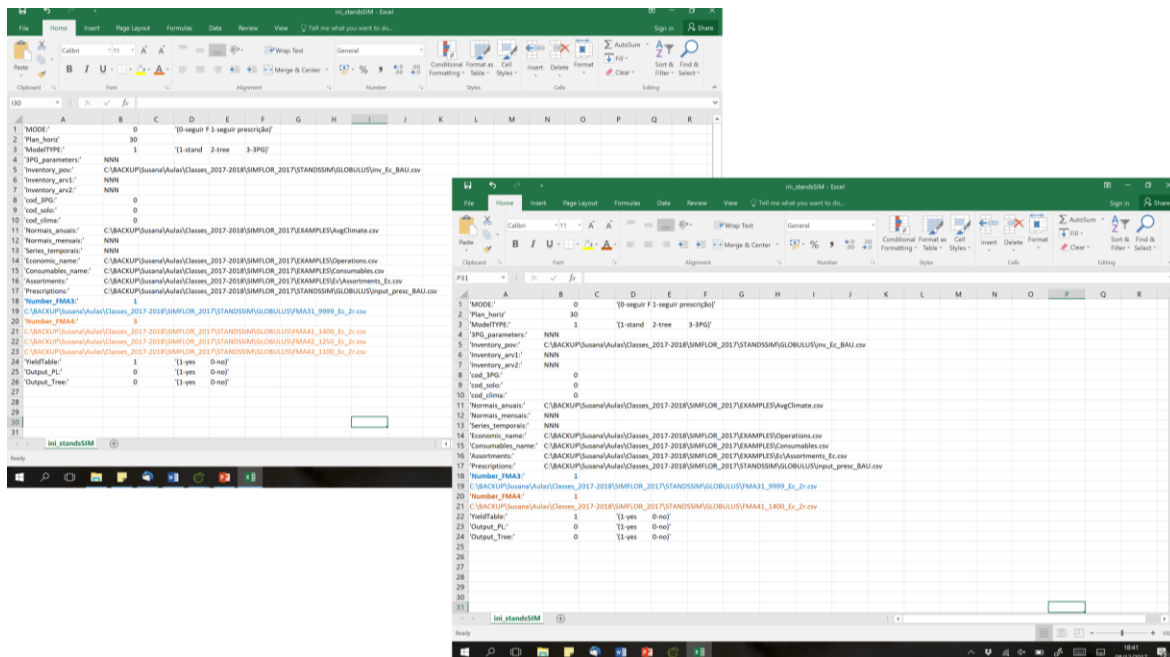


Figure 30. Illustration of the *ini_standsSIM.csv* file with the 3 FMAs imported in a single step (left handside) and with the 3 FMAs imported in three steps (right handside).

In case you import the even-aged FMAs individually, you will not get any error message or warning. The simulator will run, but the black window will show some NAN and/or infinity values for the stands that had an FMA of 4,2 or 4,3 assigned in the stand input file that could not be found in the *ini_standsSIM.csv* file (Figure 31).

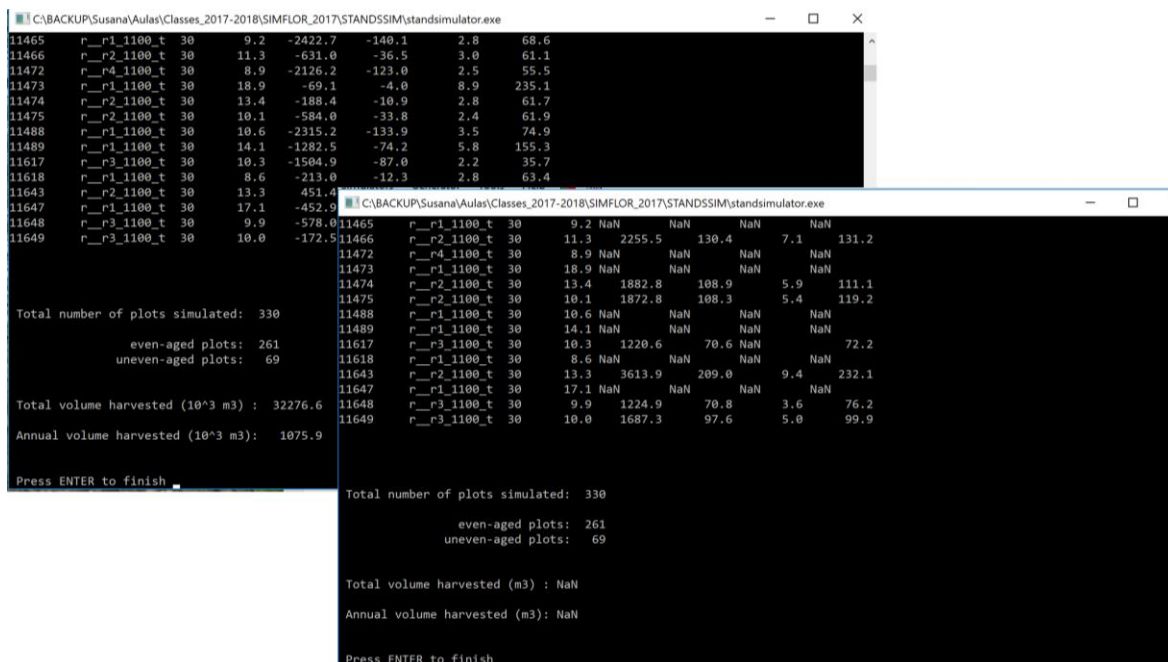


Figure 31. Print-screen of the black window showing the summary of the simulation details for a situation for which the 3 FMAs were imported in a single step (left) and in three steps (right).

5.3.1 Consistency between input files

The consistency between the information provided in the different input files must be considered when running the tool under the Multiple Stands mode. The consistency between the variables in the different files will be explained using “*file name*”.”*variable name*”, follow the files and variables in **Figure 32**. The core of all inputs are the files describing the stand and trees, in the case of individual tree level models. In this case, the first consistency that needs to be ensured is between these 2 files where:

- `input_stand.id_stand = input_tree.id_plot`
- `input_stand.narvp = count(input_tree.id_arv)`
- `input_stand.Sp1 = input_stand.Sp2 = input_tree.specie`

The next consistency is between the stand file and the prescription file, where:

- `input_stand.id_presc = input_prescr.idPresc`
- Only for the 1st prescription cycle (NrCiclos=1):
 - `input_stand.Sp1 = input_stand.Sp2 = input_prescr.sp1 = input_prescr.sp1`
 - `input_stand.rotation = input_prescr.rot`
 - `input_stand.structure = input_prescr.FMA` (with Structure=R -> FMA=4; Structure=J -> FMA=3)

The following consistency relates to the weather and is between the stand file and the clima file, where:

- `input_stand.id_meteo=input_clima.id_met`

Finally, the last consistency is between the prescription and the FMA files, where:

- Input_FMA.“A1 cell in the file”=input_prescr.FMA
- When different FMAs of the same type are imported they are assigned a number of order that represents an option for a given type of management. The set of numbers of order available will identify which FMA to apply in each cycle through the input_prescr.opt.

	Stand level models	Individual tree level models				
StandsSIM input files:	input_stand	input_stand	input_tree	input_FMA	input_presc	input_clima
Variables in the files:	idstand Area_ug id_presc tlag CoordX CoordY id_meteo Altitude year month Composition plot_Type Sp1 Sp2 structure S rot t tst tsd hdom ...	id_stand Area_ug id_presc tlag CoordX CoordY id_meteo Altitude year month Composition Plot_Type Sp1 Sp2 Structure S Rotation t tst tsd Aplot narvp	id_plot id_arv specie d h cod_dom cod_estado nr of trees in each plot	A1 cell in the file Must match the number of order by which the different FMAs of the same type are selected	IdPrescr NrCiclos sp1 sp2 sp3 FMA Opt NyFMA tlag Npl rot tcut nsprouts t_nsprouts thin_type thin_crit thin_weight t_1st_thin thin_gap t_last_thin	id_met daysRain rain Temp daysFrost Prec3 Prec4 X Y

Figure 32. List of input files and their variables with the common variables marked with the same colours.

6 References

Comissão de Acompanhamento das Operações Florestais (CAOF), 2012. Matriz de Referência com Custos Mínimos e Máximos para as Principais Operações (Re)Arborização e Execução de Infraestruturas para 2010. ANEFA. [online] URL: <http://www.anefa.pt/servicos/representatividade.html>

APPENDIX 1 – INPUT VARIABLES DESCRIPTION

List of variables in the different input files and variables description

inicia_standsSIM.csv

'MODE:'	Simulation mode, indicates whether to follow the instructions in the FMA file (0) or in the prescription file (1)
'Plan_horiz'	Number of years for which you want to run the simulation
'ModelTYPE:'	Model type: empirical stand level model (1), empirical individual tree level model (2), process-based stand level model (3)
'3PG_parameters:'	only filled in if ModelType=3 (path to the trees species parameters file of the 3PG)
'Inventory_pov:'	only filled in if ModelType=2 (path to the stand inventory file)
'Inventory_arv1:'	only filled in if ModelType=1 (path to the stand inventory file)
'Inventory_arv2:'	only filled in if ModelType=1 (path to the tree inventory file)
'cod_3PG:'	only filled in if ModelType=3 ()
'cod_solo:'	only filled in if ModelType=3 ()
'cod_clima:'	only filled in if ModelType=3 ()
'Normais_anuais:'	only filled in if ModelType<>3 (path to the climate file)
'Normais_mensais:'	only filled in if ModelType=3 (path to the climate file with monthly averages per month)
'Series_temporais:'	only filled in if ModelType<>3 (path to the climate file with monthly values for a series of years)
'Economic_name:'	path to the cost of operations file
'Consumables_name:'	path to the cost of consumables file
'Assortments:'	path to the assortments and wood prices file
'Prescriptions:'	path to the prescriptions file
'Number_FMA3:'	number of uneven-aged FMA files to be used in the simulation
IF Number_FMA3 >0 THEN path	to the FMA files (one per each row) ELSE line deleted
'Number_FMA4:'	number of even-aged FMA files to be used in the simulation
IF Number_FMA4 >0 THEN path	to the FMA files (one per each row) ELSE line deleted
'YieldTable:'	Whether you wish the output_yieldtable.csv file (keeps track of the evolution of all stand variables) to be written: yes (1), no (0)
'Output_PL:'	Whether you wish the output_PL.csv file (input for the Linear Programming) to be written: yes (1), no (0)
'Output_Tree:'	Whether you wish the output_tree.csv file (keeps track of the growth of each tree) to be written: yes (1), no (0)

input_stand.csv (ModelTYPE=1)

idstand	identifier of the stand
Area_ug	area of the management unit characterized by the stand
id_presc	identifier of the prescription

tflag	number of years to wait before the prescription will start being implemented
CoordX	xx rectangular coordinate of the stand centroid
CoordY	yy rectangular coordinate of the stand centroid
id_meteo	identifier of the meteorological station
Altitude	altitude of the stand (m)
year	year of measurement
month	month of measurement
Composition	stand composition: pure or mixed
plot_Type	Type of plot: Stand, gap, clump, burnt, harvested
Sp1	dominant tree species: Ec= eucalyptus; Pb= maritime pine; Pm= some pine; Sb= cork oak
Sp2	dominated tree species: Ec= eucalyptus; Pb= maritime pine; Pm= some pine; Sb= cork oak
structure	stand structure: J=uneven-aged; R=even-aged
S	site index (m)
rot	rotation: 1=planted; 2= 1st coppice; 3=2nd coppice, ...
t	stand age (years)
tst	number of years since the last thinning (only for Pm and Pb)
tsd	number of years since the last debarking (only for Sb)
hdom	stand dominant height (m)
Nst	Number of trees (ha-1), of stools for eucalyptus
N	Number of trees (ha-1), of sprouts for eucalyptus
G	Stand basal area (G2 ha-1)
Vu	Volume with stump under bark (m3 ha-1)
Vb	Volume of bark (m3 ha-1)
Vs	Volume of stump (m2 ha-1)
Wr	Root stand biomass (Mg ha-1)
Ww	Wood stand biomass (Mg ha-1)
Wb	Bark stand biomass (Mg ha-1)
Wbr	Branches stand biomass (Mg ha-1)
WI	Leaves stand biomass (Mg ha-1)

input_stand.csv (ModelTYPE=2)

id_stand	identifier of the stand
Area_ug	area of the management unit characterized by the stand
id_presc	identifier of the prescription
tflag	number of years to wait before the prescription will start being implemented
CoordX	xx rectangular coordinate of the stand centroid
CoordY	yy rectangular coordinate of the stand centroid
id_meteo	identifier of the meteorological station
Altitude	altitude of the stand (m)
year	year of measurement
month	month of measurement
Composition	stand composition: pure or mixed
Plot_Type	Type of plot: Stand, gap, clump, burnt, harvested

Sp1	dominant tree species: Ec= eucalyptus; Pb= maritime pine; Pm= some pine; Sb= cork oak
Sp2	dominated tree species: Ec= eucalyptus; Pb= maritime pine; Pm= some pine; Sb= cork oak
Structure	stand structure: J=uneven-aged; R=even-aged
S	site index (m)
Rotation	rotation: 1=planted; 2= 1st coppice; 3=2nd coppice, ...
t	stand age (years)
tst	number of years since the last thinning (only for Pm and Pb)
tsd	number of years since the last debarking (only for Sb)
Aplot	area of the plot measured in the field (m2)
narvp	number of trees in the plot

input_tree.csv (ModelType=2)

id_plot	identifier of the stand
id_arv	identifier of the tree
specie	tree species: Ec= eucalyptus; Pb= maritime pine; Pm= some pine; Sb= cork oak
d	tree diameter at 1.30m height (cm)
h	tree height (m)
cod_dom	dominant tree code (dominant=1, not dominant=0)
cod_estado	status tree code (living=0, dead=4)

input_prescr.csv

IdPrescr	identifier of the prescription
NrCiclos	identifier of the cycle within the prescription (from 1 up to the number of cycles need to cover the planning horizon)
sp1	dominant tree species: Ec= eucalyptus; Pb= maritime pine; Pm= some pine; Sb= cork oak
sp2	dominated tree species: Ec= eucalyptus; Pb= maritime pine; Pm= some pine; Sb= cork oak
sp3	terciary tree species: Ec= eucalyptus; Pb= maritime pine; Pm= some pine; Sb= cork oak
FMA	identifier of the FMA (4= even-aged; 3 uneven-aged)
Opt	identifier of the FMA option (from 1 up to the number of FMAs of the FMA type imported)
NyFMA	number of years during which you want to manage according to the combination of (FMA,opt) defined for the current cycle
tflag	number of years to wait before the prescription/FMA,opt for the first cycle will start being implemented (not active at the moment)
Npl	number of trees at planting (ha-1) (only active under MODE=1)
rot	rotation: 1=planted; 2= 1st coppice; 3=2nd coppice, ...
tcut	harvest age
nsprouts	number of sprouts left per stool (only active under MODE=1)
t_nsprouts	stand age at which the sprouts selection is carrid out in the field (only active under MODE=1)

thin_type	Thinning type (1=FW; 2= residual basal area) (only active under MODE=1)
thin_crit	Thinning criteria (1=from below; 2= from above) (only active under MODE=1)
thin_weight	Thinning weight (1=from below; 2= from above) (only active under MODE=1)
t_1st_thin	Age of the first thinning (only active under MODE=1)
thin_gap	Thinning periodicity (only active under MODE=1)
t_last_thin	Age of the last thinning (only active under MODE=1)

input_clima.csv

id_met	identifier of the meteorological station
daysRain	Number of days with rain
rain	Precipitation >0.1 (mm)
Temp	Average temperature (°C)
daysFrost	Number of days with frost
Prec3	Precipitation >0.1 (mm)
Prec4	Precipitation >1 (mm)
X	xx rectangular coordinates of the meteorological station
Y	yy rectangular coordinates of the meteorological station

Assortments.csv

'Nr_Assortments:'	indicates the number of assortments to be considered
label	name given to each assortment and for each assortment the following information needs to be provided (<i>by column</i>): diameter - diameter of the log (cm), length – length of the log(m), bark – whether bark is considered in the assortment (1 if bark is included, 0 if excluded), value – price of the assortment (€ /m3)
	as many rows with the label name as the number of assortments defined above
'Bark:'	Havest residues - bark removal indicator (1 if removed from the stand, 0 if left on the site)
'Branches:'	Havest residues - branches removal indicator (1 if removed from the stand, 0 if left on the site)
'Top:'	Havest residues - top removal indicator (1 if removed from the stand, 0 if left on the site)
'Topbranches:'	Havest residues - top + branches removal indicator (1 if removed from the stand, 0 if left on the site)
Pinha_kg	Stone pine cone price (€/Kg)

Consumables.csv

Ncons:	number of consumables
'Description'	Prices of the different consumables distributed by unit type (by column): Price of 'Atlantic pine Seedlings' ('eur_tree') Price of 'Eucalypt Seedlings' ('eur_tree') Price of 'Cork oak Seedlings' ('eur_tree') Price of 'Atlantic pine Seeds' ('eur_kg')

Price of 'Cork oak Seeds' ('eur_kg')

Price of 'Fertilizer for manual application (slow release)' ('eur_kg')

Price of 'Fertilizer for mechanical application' ('eur_kg')

Price of 'Fertilizer for mechanical application (subsoil)' ('eur_kg')

Price of 'Plant Protectors' ('eur_tree')

Price of 'Pesticides' ('eur_tree')

Price of 'Diesel' ('eur_l')

Price of 'Petrol' ('eur_l')

Price of 'Maintenace annual costs' ('eur_year')

Price of 'Fencing' ('eur_km')

Price of 'Game additional costs (licences)' ('eur_year')

Price of 'Game guard' ('eur_year')

Price of 'Cost of red deer male' ('eur_animal')

Price of 'Cost of red deer female' ('eur_animal')

Price of 'Game trophy' ('eur_animal')

Price of 'Game meat' ('eur_kg')

Price of 'Specialized male labour cost' ('eur_h')

Price of 'Non-specialized male labour cost' ('eur_h')

Price of 'Specialized female labour cost' ('eur_h')

Price of 'Non-specialized female labour cost' ('eur_h')

Economics.csv

'ActualRate'	First column: Interest rate (integer value, e.g. 3, 4, 5) Second column: Number of additional interest rates Following columns: Additional Interest rates (integer value, e.g. 3, 4, 5)
CostsMaint	Maintenance costs (€/year)
Noperations	Number of operations
<i>By column:</i>	<i>For each of the 68 silvicultural operations in each row</i>
Type	Silvicultural operation identifier
'OPERATIONS'	Name of the silvicultural operation
'unit_jorna'	Number of working hours
'OP_eur_tree'	Price of the operation (€/tree)
'OP_eur_km'	Price of the operation (€/km)
'OP_eur_m3'	Price of the operation (€/m ³)
'OP_eur_ha'	Price of the operation (€/ha)
'MA_labour_h_km'	Labour Machinery work (h/km)
'MA_labour_h_ha'	Labour Machinery work (h/ha)
'MA_energy_l_h'	Labour Machinery work (l/h)
'WAGExp_M'	Indicator for the male expert labour (1 if yes, 0 if no)
'WAGExp_F'	Indicator for the female expert labour (1 if yes, 0 if no)
'WAGNExp_M'	Indicator for the male non-expert labour (1 if yes, 0 if no)
'WAGNExp_F'	Indicator for the female non-expert labour (1 if yes, 0 if no)
Other costs	Other costs (€)

Input FMA.csv

<i>First row:</i>	Forest Management Approach ID (4 for even-aged stands; 3 for uneven-aged stands)
<i>Second row:</i>	Indicator of management (1 represents plantation management, 2 represents plantation followed by coppice management after the first harvest)
<i>Following row:</i>	Maximum number of years for which the management operations will be defined (when the indicator of management is set to 2, the number of years defined will be applied both to the plantation and the coppice)
<i>By column:</i>	<i>For each stand age and rotation in each row</i>
T	Stand age (years)
Npl	Number of trees at planting (ha ⁻¹)
Mortality	Percentage of trees that die (%)
BeatUp	Percentage of trees that died and will be replaced by new ones (0-100)
ShootSel	Average number of sprouts left per stool after the shoots selection
DensIncr	Stand density increase (trees ha ⁻¹)
Striplncr	Debarking height increase (m)
Prunn	Percentage of trees to be pruned
Th_type	Thinning type (1 if Wilson Factor, 2 if Residual Basal Area)
ThGres	Residual basal area value (m ² ha ⁻¹)
ThGrem	Removed basal area value (m ² ha ⁻¹) (<i>not implemented in this version</i>)
ThFw	Wilson factor value (varies from 0.1 up to 4)
ThCrCv%	Crown cover percentage left after thinning (<i>not implemented in this version</i>)
Operations 68	Identifier of occurrence of the silvicultural operation (for each of the 68 operations; 0 if is not carried out, 1 if it is carried out)

Silvicultural operation ID	Description of the silvicultural operation (costs unit)
1	'Protection tree tube' ('OP_eur_tree')
2	'Formation pruning in young trees' ('OP_eur_tree')
3	'Pruning young trees' ('OP_eur_tree')
4	'Getting the earth close to the roots;' ('OP_eur_tree')
5	'Burning formation pruning residuals' ('OP_eur_tree')
6	'Plantation - evergreen or deciduous trees in containers' ('OP_eur_tree')
7	'Plantation - deciduous trees with bare-root' ('OP_eur_tree')
8	'Beating up - evergreen or deciduous trees in containers' ('OP_eur_tree')
9	'Beating up - deciduous trees with bare-root' ('OP_eur_tree')
10	OPMan_AdensaRdFdCont ('OP_eur_tree')
11	OPMan_ADensaFdRaiz ('OP_eur_tree')
12	'Fertilization' ('OP_eur_tree')
13	'Placing plants protectors' ('OP_eur_tree')
14	'Seedling - a covacho' ('OP_eur_tree')
15	'Seedling - a lanço' ('OP_eur_ha')
16	'Open plants holes (30 x 30 x 30 cm)' ('OP_eur_tree')
17	'Open plants holes (40 x 40 x 40 cm)' ('OP_eur_tree')
18	'Selection of future trees' ('OP_eur_ha')
19	'Marking natural regeneration' ('OP_eur_ha')
20	'Control invasive plants' ('OP_eur_ha')

-
- 21 'Fire control in forestland' ('OP_eur_ha')
 - 22 'Fire control in shrubland' ('OP_eur_ha')
 - 23 'Marking out with stakes' ('OP_eur_ha')
 - 24 'Cork stripping - virgin' ()
 - 25 'Cork stripping' ()
 - 26 'Sanitary pruning' ('OP_eur_tree')
 - 27 'Pruning adult trees' ('OP_eur_tree')
 - 28 'Formation pruning' ('OP_eur_tree')
 - 29 'Shoot selection' ('OP_eur_tree')
 - 30 'Reducing density in deciduous stands (> 8 years)' ('OP_eur_tree')
 - 31 'Reducing density in umbrella pine stands (> 8 years)' ('OP_eur_tree')
 - 32 'Reducing density in others conifers stands (< 8 years)' ('OP_eur_tree')
 - 33 'Reducing density in others conifers stands (> 8 years)' ('OP_eur_tree')
 - 34 'Harvesting shrubland for forestation - motorroçadora' ('OP_eur_ha')
 - 35 'Control spontaneous plants in line' ('OP_eur_ha')
 - 36 'Control total spontaneous plants' ('OP_eur_ha')
 - 37 'Control total invasors plants' ('OP_eur_ha')
 - 38 'Control high density' ('OP_eur_ha')
 - 39 'Harvesting shrubland for forestation - corta matos de facas ou correntes ' ('OP_eur_ha')
 - 40 'Harvesting shrubland for forestation - corta matos de martelos' ('OP_eur_ha')
 - 41 'Harvesting shrubland for forestation - grade de discos' ('OP_eur_ha')
 - 42 'Harrowing low cover of spontaneous vegetation' ('OP_eur_ha')
 - 43 'Harrowing - breaking of clods' ('OP_eur_ha')
 - 44 'Ripping - depth 3 m - 1 dente >= 60cm (*)' ('OP_eur_ha')
 - 45 'Ripping - depth 3 m - 2 dentes >= 60 cm (*)' ('OP_eur_ha')
 - 46 'Ripping - depth 3 m - 3 dentes >=60 cm (*)' ('OP_eur_ha')
 - 47 'subsoiling - depth 3 m - 1 dente - tractor with moldboard' ('OP_eur_ha')
 - 48 'subsoiling - depth 3 m - 3 dentes - tractor with moldboard' ('OP_eur_ha')
 - 49 'Ditch and bund 3m with 30cm depth' ('OP_eur_ha')
 - 50 'Ditch and bund 3m with 40cm depth' ('OP_eur_ha')
 - 51 'Ditch and bund 3m with 50cm depth' ('OP_eur_ha')
 - 52 'Ploughing' ('OP_eur_ha')
 - 53 'Open channels for seedling' ('OP_eur_ha')
 - 54 'Open holes for seedling' ('OP_eur_ha')
 - 55 'Eucalyptus stump destruction' ('OP_eur_ha')
 - 56 'Fertilization in line - wheels tractor' ('OP_eur_ha')
 - 57 'Fertilization in line - caterpillar tractor' ('OP_eur_ha')
 - 58 'Fertilization total - wheels tractor' ('OP_eur_ha')
 - 59 'Fertilization total - caterpillar tractor' ('OP_eur_ha')
 - 60 'Drip irrigation' ('OP_eur_ha')
 - 61 'Control spontaneous plants' ('OP_eur_ha')
 - 62 'Phytosanitary treatments' ('OP_eur_ha')
 - 63 'Open forest roads' ('OP_eur_km')
 - 64 'Improvement of forest roads' ('OP_eur_km')
 - 65 'Open fire breaks' ('OP_eur_km')
 - 66 'Improvement of fire breaks' ('OP_eur_km')
 - 67 'Open water point' ('OP_eur_m3')
 - 68 'Dam construction' ('OP_eur_m3')
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APPENDIX 2 – OUTPUT VARIABLES DESCRIPTION

List of variables in the most important output files and the variables description.

output_yieldtable.csv

Ndead	Number of dead trees per hectare (ha^{-1})
N_ing	Number of ingrowth trees per hectare (ha^{-1})
Fw	Wilson factor – relative stand density measure (varies from 0.2 up to 0.4)
G	Stand basal area ($\text{m}^2 \text{ha}^{-1}$)
dg	Quadratic mean diameter at breast height – corresponds to the diameter of the average tree in the stand(cm)
Vu	Standing volume under-bark including stump ($\text{m}^3 \text{ha}^{-1}$)
Vb	Volume of the bark including stump ($\text{m}^3 \text{ha}^{-1}$)
Vst	Volume of the stump ($\text{m}^3 \text{ha}^{-1}$)
V	Standing volume over-bark including stump ($\text{m}^3 \text{ha}^{-1}$)
V_as1	Harvested volume of assortment 1 ($\text{m}^3 \text{ha}^{-1}$)
V_as2	Harvested volume of assortment 2 ($\text{m}^3 \text{ha}^{-1}$)
V_as3	Harvested volume of assortment 3 ($\text{m}^3 \text{ha}^{-1}$)
V_as4	Harvested volume of assortment 4 ($\text{m}^3 \text{ha}^{-1}$)
V_as5	Harvested volume of assortment 5 ($\text{m}^3 \text{ha}^{-1}$)
Vharv	Total harvested volume sum of all assortments (thinning + final harvest)
Vtot	?
maiV	volume mean annual increment ($\text{m}^3 \text{ha}^{-1}$)
iV	volume current annual increment ($\text{m}^3 \text{ha}^{-1}$)
Ww	Stand wood biomass (Mg ha^{-1})
Wl	Stand leaves biomass (Mg ha^{-1})
Wb	Stand bark biomass (Mg ha^{-1})
Wbr	Stand branches biomass (Mg ha^{-1})
Wa	Stand aboveground biomass (Mg ha^{-1})
Wr	Stand root biomass (Mg ha^{-1})
WPmnuts	Stand pine-nuts biomass - stone pine (Mg ha^{-1})
Wtop	Stand residues biomass - top biomass (Mg ha^{-1})
Wtopbr	Stand residues biomass - top and branches biomass (Mg ha^{-1})
Wb_bic	Stand residues biomass - bark (Mg ha^{-1})
Wbrl	Stand residues biomass - leaves and branches (Mg ha^{-1})
C_seq_prod	Carbon sequestered in the products (Mg ha^{-1})
PC_tot	Total production costs from inside and outside the forestry wood chain and labour costs (seedling, seeds) (€)
PC_in	Production costs from inside the forestry wood chain (seedling, seeds) (€)
PC_out	Production costs from outside the forestry wood chain (fertilizers, fences,...) (€)
PC_lab	Production costs labour (€)

R_wood	Wood revenues (€)
R_biom	Biomass revenues (€)
R_Pmnuts	Pinenuts revenues (€)
NPV	Net present value (€)
NPVsum	Sum of the net present value (€)
EEA	? (€)

output_dd.csv

id_stand	Stand residues biomass - top and branches biomass (Mg ha ⁻¹)
id_presc	Carbon sequestered in the products (Mg ha ⁻¹)
year	Production costs from outside the forestry wood chain (fertilizers, fences,...) (€)
Thinning	Net present value (€)
Debark	Sum of the net present value (€)
0	Number of trees in the diameter class [0 - 2.5[(cm)
5	Number of trees in the diameter class [2.5 - 7.5[(cm)
10	Number of trees in the diameter class [7.5 - 12.5[(cm)
15	Number of trees in the diameter class [12.5 - 17.5[(cm)
20	Number of trees in the diameter class [17.5 - 22.5[(cm)
25	Number of trees in the diameter class [22.5 - 27.5[(cm)
30	Number of trees in the diameter class [27.5 - 32.5[(cm)
35	Number of trees in the diameter class [32.5 - 37.5[(cm)
40	Number of trees in the diameter class [37.5 - 42.5[(cm)
45	Number of trees in the diameter class [42.5 - 47.5[(cm)
50	Number of trees in the diameter class [47.5 - 52.5[(cm)
55	Number of trees in the diameter class [52.5 - 57.5[(cm)
60	Number of trees in the diameter class [57.5 - 62.5[(cm)
65	Number of trees in the diameter class [62.5 - 67.5[(cm)
70	Number of trees in the diameter class [67.5 - 72.5[(cm)
75	Number of trees in the diameter class [72.5 - 77.5[(cm)
80	Number of trees in the diameter class [77.5 - 82.5[(cm)
85	Number of trees in the diameter class [82.5 - 87.5[(cm)
90	Number of trees in the diameter class [87.5 - 92.5[(cm)
95	Number of trees in the diameter class [92.5 - 97.5[(cm)
100	Number of trees in the diameter class [97.5 - 102.5[(cm)
>102.5	Number of trees in the diameter class greater than 102.5 (cm)

output_annual.csv

year	year
V_Thin	Sum of thinned volume in all stands (m ³ ha ⁻¹)
V_harv	Sum of harvested volume in all stands (m ³ ha ⁻¹)
