

# GLOBULUS 3.0 model

BRIEF DESCRIPTION & EQUATIONS

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# 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.

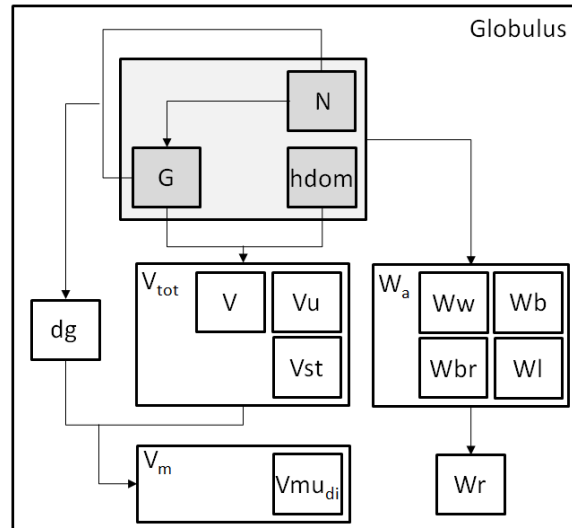
## Model Description

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.

<b>Site Index and Dominant height</b>			
$(1) SI = A \left( \frac{hdom}{A} \right)^{\left( \frac{t}{tp} \right)^n} \quad (2) hdom_2 = A \left( \frac{hdom_1}{A} \right)^{\left( \frac{t_1}{t_2} \right)^n} \quad A = a_0 + a_1 DR$			
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	
$(1) G = A_G e^{-k_G \left(\frac{t}{t_1}\right)^{n_{Gp} + n_{GN}}}$	$(2) G_2 = A_G \left(\frac{G_1}{A_G}\right)^{\left(\frac{t_1 n_{GN1}}{t_2 n_{GN2}}\right) \left(\frac{t_1}{t_2}\right)^{n_{Gp}}}$
$A_G = (a_{G0} + a_{G1} DR)$	$K_G = k_{G0} + k_{G1} SI + k_{G2} \frac{100}{SI \sqrt{Npl}} + k_{G3} rot$
$n_{Gp} = n_{G0} + \frac{n_{G1}}{\left(1 - \left(\frac{cota}{2000}\right)\right)} + n_{G2} rot$	$n_{GNi} = n_{G3} \frac{N_i}{1000}$

model	a <sub>G0</sub>	a <sub>G1</sub>	k <sub>G0</sub>	k <sub>G1</sub>	k <sub>G2</sub>	k <sub>G3</sub>	n <sub>G0</sub>	n <sub>G1</sub>	n <sub>G2</sub>	n <sub>G3</sub>
(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 sprouts for stands under 3 years of age (5) and Coppice stand's density of sprouts 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 <sub>0</sub>	am <sub>1</sub>	am <sub>2</sub>	am <sub>3</sub>	b <sub>0</sub>	b <sub>1</sub>	b <sub>2</sub>	b <sub>3</sub>
(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<sub>stools</sub> is the number of stools; N<sub>sprouts</sub> 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)	$V_i = Kv \ t^a \ hdom^b \ G^c$	$kv = kv_0 + kv_1 \text{rot} + \left( \frac{kv_2}{1 - \left( \frac{cota}{2000} \right)} \right) + kv_3 \frac{100}{SI \sqrt{N_0}}$					
(2)	$V_{i_2} = V_{i_1} \left( \frac{t_2}{t_1} \right)^a \left( \frac{hdom_2}{hdom_1} \right)^b \left( \frac{G_2}{G_1} \right)^c$						
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 Vi represents the following stand volumes: Vu is the under-bark volume with stump, Vb is the volume of bark, Vst volume of stump; hdom 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; N0 represents NPL for planted stands and Nsprouts by age of 3 years for coppice stands.

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

Merchantable Volume							
$V_{umdi} = (V_u - V_{st}) e^{a \left( \frac{di}{d_{gdom}} \right)^b}$							
$a = a_0 + a_1 \text{rot} + a_2 \left( \frac{Npl}{1000} \right) + a_3 \left( \frac{100}{SI \sqrt{N_0}} \right) + \left( \frac{a_4}{1 - \left( \frac{cota}{2000} \right)} \right)$ $b = b_0 + b_1 \text{rot}$							
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; V<sub>st</sub> volume of stump; d<sub>gdom</sub> 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 N<sub>sprouts</sub> by age of 3 years for coppice stands.

**Table 6.** Biomass prediction functions.

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

Where W<sub>i</sub> represents the following biomass components: W<sub>w</sub> is the biomass of wood, W<sub>b</sub> is the biomass of bark, W<sub>br</sub> is the biomass of branches and W<sub>l</sub> is the biomass of leaves; W<sub>a</sub> is the total aboveground biomass; W<sub>r</sub> is the biomass of roots; h<sub>dom</sub> 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.



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## List of Symbols

- DR** – weight average of the central values of the classes of the number of days with precipitation  $\geq 0.1$  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);
- t<sub>1</sub>** – Stand age at instant 1 (years);
- t<sub>2</sub>** – Stand age at instant 2 (years);
- t<sub>p</sub>** – Standard age, which for eucalyptus corresponds to 10 years (years);
- hdom** – Stand dominant height (m);
- hdom<sub>1</sub>** – Stand dominant height at instant 1 (m);
- hdom<sub>2</sub>** – Stand dominant height at instant t<sub>2</sub> (m);
- N** – Stand density (ha<sup>-1</sup>);
- N<sub>1</sub>** – Stand density at instant 1 (ha<sup>-1</sup>);
- N<sub>2</sub>** – Stand density at instant 2 (ha<sup>-1</sup>);
- N<sub>pl</sub>** – Stand density at plantation (ha<sup>-1</sup>);
- N<sub>stools</sub>** – Number of stools after the first harvest (ha<sup>-1</sup>);
- N<sub>sprouts t=2</sub>** – Number of sprouts before sprouts selection (ha<sup>-1</sup>);
- N<sub>sprouts t=3</sub>** – Number of sprouts after sprouts selection (ha<sup>-1</sup>);
- N<sub>harv</sub>** – Number of trees by the end of the 1<sup>st</sup> rotation (ha<sup>-1</sup>);
- 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 (m<sup>2</sup> ha<sup>-1</sup>);
- G<sub>1</sub>** – Stand basal area at instant 1 (m<sup>2</sup> ha<sup>-1</sup>);
- G<sub>2</sub>** – Stand basal area at instant 2 (m<sup>2</sup> ha<sup>-1</sup>);
- V<sub>u</sub>** – Stand volume under-bark with stump (m<sup>3</sup> ha<sup>-1</sup>);
- V<sub>b</sub>** – Stand volume of bark (including the bark of stump?!) (m<sup>3</sup> ha<sup>-1</sup>);
- V<sub>st</sub>** – Stand volume of stump (m<sup>3</sup> ha<sup>-1</sup>);
- V<sub>umdi</sub>** – Stand mercantile volume without stump and bark up to a top diameter of di (m<sup>3</sup> ha<sup>-1</sup>);
- di** – top diameter with bark (cm);
- dgd** – Stand quadratic mean d.b.h of the dominant trees (cm<sup>2</sup> ha<sup>-1</sup>);
- W<sub>i</sub>** – Stand biomass per component, where i represents: w, b, l, br or r (Mg ha<sup>-1</sup>);
- W<sub>w</sub>** – Stand wood biomass (Mg ha<sup>-1</sup>);
- W<sub>b</sub>** - Stand bark biomass (Mg ha<sup>-1</sup>);
- W<sub>l</sub>** – Stand leaves biomass (Mg ha<sup>-1</sup>);
- W<sub>br</sub>** - Stand branches biomass (Mg ha<sup>-1</sup>);
- W<sub>r</sub>** - Stand roots biomass (Mg ha<sup>-1</sup>);
- W<sub>a</sub>** – Stand aboveground biomass (Mg ha<sup>-1</sup>);
- W<sub>r</sub>** - Stand belowground (roots) biomass (Mg ha<sup>-1</sup>);
- W<sub>t</sub>** - Stand total biomass (Mg ha<sup>-1</sup>);