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GLOBULUS 3.0 model

BRIEF DESCRIPTION & EQUATIONS

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Globulus 3.0 Model

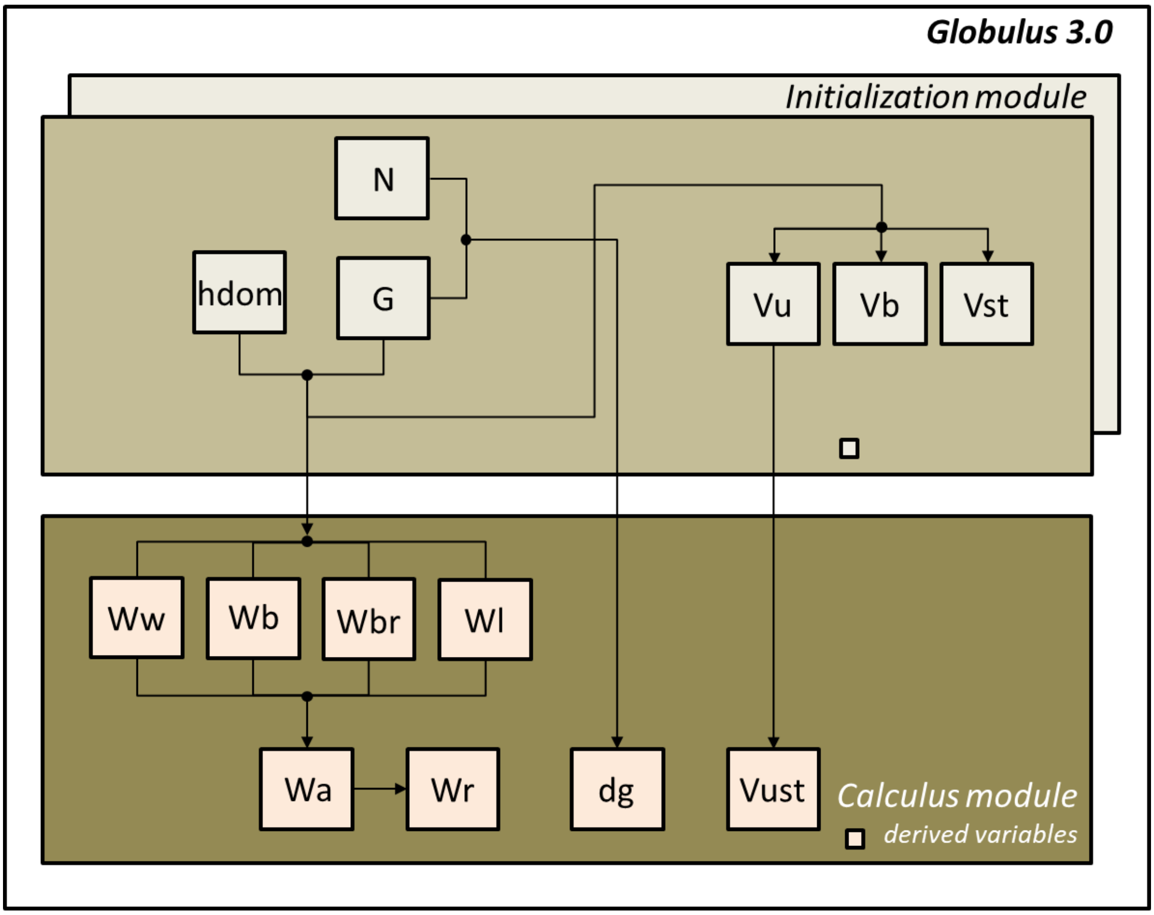
Background Introduction

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 predicted with growth functions or derived variables when their values are estimated using allometric equations or calculated from principal variables and/or other derived variables (**Figure 1**).



Where: N, stand density; hdom; dominant height; G, stand basal area; dg, quadratic mean diameter at breast height; Vu, volume under-bark with stump; Vb, volume of bark; Vst, volume of stump; Vust, volume under-bark without stump; Wa, aboveground biomass; Ww, biomass of stem wood; Wb, biomass of stem bark; Wbr, biomass of branches; Wl, biomass of leaves and Wr, biomass of roots.

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

On the other hand, the external variables control the development of the state variables and can be of three different sub-types: management related, environmental 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 predicts the variable over time. On the other hand, derived variables are estimated as a function of principal variables, control variables and other derived variables obtained in previous steps. 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 and the precipitation.

The model has three modules, the initialization and the growth module and the calculus 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. This module is essential to allow initializing a new stand by either planting or coppice and can be used to simulate the growth of a new plantation (yield table) or several ie simulating the growth of a plantation for a family of site index curves. The equations present in this module are all growth function in the integral form. The growth 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 of the growth module are growth functions formulated as first order non-linear difference equations and all have one or more parameters expressed as a function of site/stand variables.

The greatest achievements of Globulus 3.0 in relation to previous versions are:

(i) allows simulating the transition between rotations, by simulating growth for coppice stands before shoots selection usually occurring between age 2 and 3 of the coppice,

(ii) 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 as well as the volumes. 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 growth 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 growth 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

$$(1)\ SI = A\left(\frac{hdom}{A}\right)^{\left(\frac{t}{tp}\right)^{n}} \qquad (2)\ hdom_2 = A\left(\frac{hdom_1}{A}\right)^{\left(\frac{t_1}{t_2}\right)^{n}} \qquad A = a_0 + a_1\ DR$$

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

$$(1)\ G = A_G\ e^{-k_G\left(\frac{1}{t}\right)^{(n_{Gp}+n_{GN})}} \qquad (2)\ G_2 = A_G\left(\frac{G_1}{A_G}\right)^{\left(\frac{t_1{}^{n_{GN1}}}{t_2{}^{n_{GN2}}}\right)\left(\frac{t_1}{t_2}\right)^{(n_{Gp})}}$$

$$A_G = (a_{G0} + a_{G1}\ DR) \qquad K_G = k_{G0} + k_{G1}\,SI + k_{G2}\frac{100}{SI\sqrt{Npl}} + k_{G3}\ rot$$

$$n_{Gp} = n_{G0} + \frac{n_{G1}}{\left(1-\left(\frac{cota}{2000}\right)\right)} + n_{G_2}rot \qquad n_{GNi} = n_{G3}\frac{N_i}{1000}$$

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) $N = Npl\; e^{-am\; t}$

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

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	-	-	-	-	-

Coppice Stands:

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

(4) $N_{stools\,2} = N_{stools\,1}\; e^{-am\;(t_2 - t_1)}$ (*number of stools projection*)

(5) $N_{sprouts\;t \le 2} = N_{stools}\; b_0 + b_1\, t$ (*number of sprouts before shoots selection*)

(6) $N_{sprouts\;t=3} = \dfrac{N_{stools}}{1 - e^{-\left(am_2 \frac{N_{stools}}{1000} + am_3 \frac{1}{SI}\right)}}$ (*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

$$am = am_0 + am_1\,rot + am_2 \frac{Npl}{1000} + am_3 \frac{1}{SI}$$

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 dominant height and stand basal area (principal variables) have been initialized and predicted, other principal variables, such as the volumes, (**Tables 4** and **5**) and also the derived variables merchantable volume and biomass components (**Table 6**) are estimated and the quadratic mean diameter can be calculated..

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

Volume Total

(1) $$V_i = Kv\ t^{a}\ hdom^{b}\ G^{c}$$ $$kv = kv_0 + kv_1\,rot + \left(\frac{kv_2}{1-\left(\frac{cota}{2000}\right)}\right) + kv_3 \frac{100}{SI\ \sqrt{N_0}}$$

(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, V_b is the volume of bark, V_{st} 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 $N_{sprouts}$ 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

$$Vumdi = (Vu - Vst)\, e^{a\left(\frac{di}{dgdom}\right)^{b}}$$

$$a = a_0 + a_1\, rot + a_2 \left(\frac{Npl}{1000}\right) + a_3 \left(\frac{100}{SI\ \sqrt{N_0}}\right) + \left(\frac{a_4}{1 - \left(\frac{cota}{2000}\right)}\right) \qquad b = b_0 + b_1\, rot$$

model	a_0	a_1	a_2	a_3	a_4	b_0	b_1
V umdi	-1.1075	-0.3436	0.0741	1.2604	0.2660	3.1854	0.5513

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_{st} 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 $N_{sprouts}$ by age of 3 years for coppice stands.

Table 6. Biomass prediction functions.

Biomass

$$W_i = a\, G^{b}\, hdom^{c} \qquad b = b_0 + b_1\, rot + b_2 \left(\frac{N}{1000}\right) + b_3 \left(\frac{SI}{1000}\right) + b_4 \left(\frac{t}{1000}\right)$$

$$W_a = W_w + W_b + W_l + W_{br} \qquad W_r = a\, W_a \qquad W_t = W_a + W_r$$

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 ttotal 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.

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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);

t_1 – Stand age at instant 1 (years);

t_2 – Stand age at instant 2 (years);

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

hdom – Stand dominant height (m);

$hdom_1$ – Stand dominant height at instant 1 (m);

$hdom_2$ – Stand dominant height at instant t_2 (m);

N – Stand density (ha^{-1});

N_1 – Stand density at instant 1 (ha^{-1});

N_2 – Stand density at instant 2 (ha^{-1});

Npl – Stand density at plantation (ha^{-1});

N_{stools} – Number of stools after the first harvest (ha^{-1});

$N_{sprouts\ t\leq2}$ – 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 ($m^2\ ha^{-1}$);

G_1 – Stand basal area at instant 1 ($m^2\ ha^{-1}$);

G_2 – Stand basal area at instant 2 ($m^2\ ha^{-1}$);

V_u – Stand volume under-bark with stump ($m^3\ ha^{-1}$);

V_b – Stand volume of bark (including the bark of stump?!) ($m^3\ ha^{-1}$);

V_{st} – Stand volume of stump ($m^3\ ha^{-1}$)

V_{umdi} – Stand mercantile volume without stump and bark up to a top diameter of di ($m^3\ ha^{-1}$);

di – top diameter with bark (cm);

dgdom – Stand quadratic mean d.b.h of the dominant trees ($cm^2\ ha^{-1}$);

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 ($Mg\ ha^{-1}$);