Calibration and testing of a generalized process-based model for use in Portuguese eucalyptus plantations

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Abstract: The work described in this paper aimed to establish a single set of parameter values for a process-based model (3-PG), applicable to *Eucalyptus globulus* Labill. in Portugal. Initial testing was done with parameter values from Australia using climate, biometric, and soils data from an irrigation and fertilization trial and a spacing trial. The model provided good estimates for stem mass and basal area, poor estimates for leaf mass, and reasonable estimates for volume. The fit between simulated and observed values was then improved by tuning parameter values to produce a final set. The calibrated model was tested, and performed well, against data from permanent sample plots (PSPs) at different locations across Portugal. Volume and basal area predictions made by 3-PG for PSPs were then compared with predictions made by the empirical model in use for *E. globulus* plantations in Portugal. Differences were negligible. Model outputs with the Australian parameter set and the optimum set for Portugal indicated that partitioning of carbohydrates (net primary productivity) was very different in *E. globulus* grown in Portugal and Australia. The study has confirmed the potential of this process-based model as a practical tool to support forest management decision-making.

Résumé : Le travail décrit dans cet article visait à établir un ensemble unique de valeurs des paramètres pour un modèle basé sur les processus (3-PG) et applicable à l'*Eucalyptus globulus* Labill. au Portugal. Un test initial a été réalisé à l'aide de valeurs des paramètres provenant d'Australie et de données climatiques, biométriques et pédologiques provenant d'un dispositif d'éclaircie et de fertilisation. Le modèle a fourni de bonnes estimations de la biomasse des tiges et de la surface terrière, des estimations médiocres de la biomasse foliaire et des estimations raisonnables du volume. L'ajustement entre les valeurs observées et estimées a ensuite été amélioré en réglant la valeur des paramètres dans le but d'obtenir un ensemble final. Le modèle calibré a été testé et a bien performé dans des placettes-échantillons permanentes (PEPs) dans plusieurs endroits du Portugal. Les prédictions du volume et de la surface terrière du modèle 3-PG pour les PEPs ont ensuite été comparées à celles d'un modèle empirique actuellement utilisé pour les plantations d'*E. globulus* au Portugal. Les différences étaient négligeables. Les prédictions du modèle à partir de l'ensemble australien de paramètres et de l'ensemble optimal pour le Portugal ont montré que l'allocation des hydrates de carbone (production primaire nette) était très différente chez *E. globulus* au Portugal et en Australie. L'étude a confirmé le potentiel de ce modèle basé sur les processus comme outil pratique pour supporter la prise de décision en aménagement forestier.

[Traduit par la Rédaction]

Introduction

Eucalyptus are exotic to Portugal, having been introduced to the country in 1830, mainly for ornamental purposes. Nowadays, eucalyptus plantations cover more than 672 000 ha — about 21% of the total forest area in Portugal. Because of its importance for the pulp industry, the species has been the subject of more growth and yield studies than any other in the country. The first permanent plots were established in 1970, and the first growth model dates from 1975. Today, users can choose among several empirical growth and yield models for eucalyptus, for example, GLOBUS (Tomé et al. 1995), TWIGGY/EUSOP (Carvalho et al. 1994), SOP (Amaro 1997), GLOBULUS 1.0 (Tomé et al. 1998), SILVICAIMA-LEI (Yuancai 1998), and most recently, GLOBULUS 2.1 (Tomé et al. 2001).

Empirical models based on mensuration data provide quantitative information for management and planning that

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is accurate within the limits of sampling and measurement accuracy; they can be used to predict growth and yield over the periods for which the historical conditions that governed growth can be assumed to apply, and they can provide information about log sizes and size distribution (product profile). However, these models are generally site specific and often depend on the logically circular concept of site index (SI). They lack flexibility and the capacity to simulate the results of environmental stresses, such as drought, or significant departures from the conditions that pertained during the period when the measurements were made. These problems can, in principle, be overcome by using process-based models developed in terms of plant–soil interactions and the processes governing carbon, nutrient, and water dynamics. For example, the G'Day process-based model (Corbeels et al. 2005*b*) has been used with success to model the growth and nitrogen mineralization of *Eucalyptus globulus* Labill. forest plantations in Australia (Corbeels et al. 2005*c*), as well as long-term changes in productivity in those plantations in relation to different management scenarios (Corbeels et al. 2005*a*). However, detailed process-based models developed primarily for the purpose of understanding mechanisms are likely to include many parameters for which values are not readily available, to need large amounts of input data, and to produce output values that may be of little interest to managers. Very little effort has been put into the development of process-based models in Portugal; the only examples of studies in this direction are the calibration of MAESTRO for *E. globulus* (Tomé 1997) and an examination of the application of PROMOD (Battaglia and Sands 1997) to Portuguese conditions.

The 3-PG model was developed by Landsberg and Waring (1997) in a deliberate attempt to bridge the gap between conventional growth and yield models and detailed process-based models. 3-PG is a simple process-based stand model requiring few parameter values and only readily available data as inputs. The outputs produced are of direct interest and value to forest managers. The 3-PG model has already been used over a wide range of climates and site conditions in Australia, New Zealand, the United States, Brazil, South Africa, Great Britain, Chile, China, Sweden, and Finland. It has been parameterized for several species including *E. globulus* (Sands and Landsberg 2002), *Eucalyptus grandis* W. Hill ex Maid. × *Eucalyptus urophylla* S.T. Blake (Stape et al. 2004), *E. grandis* × *Eucalyptus camaldulensis* Dehnhardt (Dye et al. 2004), *E. grandis* (Almeida et al. 2004*a*; Esprey et al. 2004), *Pinus taeda* L. (Landsberg et al. 2001*a*), *Pinus ponderosa* Dougl. ex P. & C. Laws. (Coops et al. 2005; Law et al. 2000), *Pseudotsuga menziesii* (Mirb.) Franco (Waring and McDowell 2002), *Pinus patula* Schiede ex Schlect. & Cham. (Dye 2001), *Picea sitchensis* (Bong.) Carr. (Waring 2000), *Corymbia maculata* Hill & Johnson, *Araucaria cunninghamii* Ait. ex D. Don, *Eucalyptus pilularis* Sm., *Eucalyptus delagatensis* R.T. Bak., *Picea abies* (L.) Karst., *Pinus radiata* D. Don, and *Pinus elliottii* Engelm. (Landsberg et al. 2001*b*, 2003). The 3-PG model has been utilized to improve decision-making processes for forest management (Landsberg 2003*a*; Almeida et al. 2004*b*) and has been successfully used to estimate biomass productivity of large areas using geographic information systems (GIS) (Coops and Waring 2001; Tickle et al. 2001; Almeida et al. 2004*b*; Coops et al. 2004, 2005). On the basis of published evidence, it was decided to evaluate the performance of this model in relation to *E. globulus* plantations in Portugal with a view to its possible use as a tool in forest-management decisions such as fertilization, purchase of land for the establishment of new plantations, and quantification of the risks associated with production (e.g., effects of drought) and strategic scenarios (e.g., long-term wood supply planning).

Previously published work has shown that it is possible to obtain very good fits when calibrating 3-PG for a wide range of species and site conditions. The aim of the work described in this paper was to determine whether it would be possible to establish a single set of parameter values that would serve for *E. globulus* grown under most Portuguese conditions. Therefore, 3-PG was tested, using published parameter values, against detailed experimental data from a fertilized and irrigated experiment on *E. globulus*, and against growth data for the same species grown at widely different stocking densities in a spacing trial. The parameter values were then adjusted to improve the correspondence between observed and predicted growth in both trials, with the intention of establishing a single, optimum, set of parameter values that would apply across the full range of conditions. We tested the results obtained with that optimum set of parameters against independent data from permanent sample plots (PSPs).

Materials and methods

The 3-PG model

The 3-PG model (Landsberg and Waring 1997) is a stand-level model that uses monthly or, in the case of the version used with remote sensing (Coops and Waring 2001; Coops et al. 2005), annual time steps. It requires as inputs initial stand data (stem number and stem, foliage, and root biomasses), soil data, and weather data for the site(s) under consideration. A number of the parameter values needed are generic (e.g., the values describing stomatal response to vapor pressure deficit), readily estimated from general knowledge of the ecology of the species under study (e.g., temperature limits and optimum), or readily available from forestry literature (e.g., wood density). There is an extensive list of outputs after each time interval including stem, root, and foliage biomass; available soil water; stand transpiration; leaf area index; stem volume; mean stem diameter at breast height (DBH); mean annual stem volume increment; and stem number. The basic driver for 3-PG is the absorbed photosynthetically active radiation (APAR). The conversion factor (canopy quantum efficiency) is constrained by environmental effects through multiplicative modifiers based on atmospheric vapor pressure deficit (VPD), available soil water, mean air temperature, frost days per month, site nutrition, and stand age. The model accounts for differences in growth patterns that may arise as a result of fertilization because the coefficient that determines biomass partitioning ratios depends on the site fertility rating. The proportion of net primary productivity (NPP) going to roots is reduced on fertile sites and in good growing conditions, and increases as site fertility declines (see Landsberg and Waring 1997, Fig. 6 and eq. 15; Sands and Landsberg 2002, eq. A7). The 3-PG model consists of five simple submodels: biomass production; allocation of biomass among foliage, roots, and stem (including branches and bark); mortality; soil water balance; and the conversion of the stem biomass into standard forestry stand variables. This last submodel can be substituted by an empirical model, thereby creating a hybrid model. Because 3-PG has already been widely used, good detailed descriptions of the structure of the original model (Landsberg and Waring 1997) have been published, as have descriptions of several structural modifications (Sands and Landsberg 2002; Sands 2004*b*).

Experimental data

The irrigation × fertilization trial

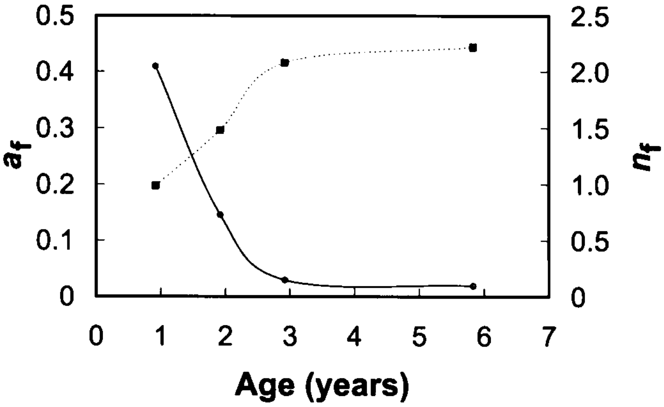
For the work reported here, data from an irrigation and fertilization (IF) trial were selected to provide information about plantations growing with different availability of water and nutrients, including a treatment that mimics an environment without restrictions. The trial was located at Quinta do Furadouro, in the central region of Portugal, 10 km from the Atlantic Ocean, which has a Mediterranean climate with maritime influence. Mean annual rainfall is 850 mm, but less than 10% occurs between May and September. The soils are of low fertility and low organic carbon content (0.23%–0.28%). They are mostly sandy and may be classified as Arenosols (Pereira et al. 1989; Madeira et al. 1995).

The experimental design consisted of eight plots of equal size grouped in two blocks. Each plot was surrounded by a buffer zone consisting of two rows of trees and divided into two subplots: (*i*) for nondestructive biometric measurements (1089 m^2) with 3 m × 3 m spacing and (*ii*) for destructive biomass sampling (792 m^2) with 1.5 m × 1.5 m spacing, which were thinned before the seedlings started to compete. Seedlings were planted in March 1986 after soil ploughing to 80 cm depth. Before planting, 1.5 $Mg \cdot ha^{-1}$ of dolomitic limestone (66.5% $CaCO_3$, 32.5% $MgCO_3$) was applied to the experimental area (Madeira et al. 2002). Three months after planting, the following treatments were applied (*i*) control: rain-fed plots without fertilization except the initial application of fertilizers at planting; (*ii*) solid fertilization, pelleted solid fertilizers were distributed in March and October, which are periods with frequent precipitation,and micronutrients in adequate amounts were added; (*iii*) irrigation: from April through October, drip irrigation tubes placed along each row of trees supplied water daily, which varied with the season and was estimated to maintain the soil moisture content at ≥80% of field capacity, to avoid plant water stress; and (*iv*) optimum: water was supplied daily as in the irrigation treatment, and a complete liquid fertilizer was supplied once a week with the irrigation water to simulate "near-optimal" nutrition as defined by Ingestad (1982, 1987).

Height and diameter (d) at 1.30 m height of every tree in the nondestructive plots were measured monthly during the first 22 months. Height and diameter measurements started in April 1986 and February 1987, respectively. After January 1988, diameter and height were measured twice per year. In January 1991, one of the blocks was harvested, and the remaining block was measured again in January 1992.

Several trees per treatment were destructively sampled on several occasions to determine stem diameter, stem mass, foliage mass, and specific leaf area. Twelve trees in each treatment were harvested in September 1986 and February 1987 (0.5 and 0.9 years, respectively), 10 in February 1988 and 1989 (1.9 and 2.9 years, respectively), and 8 in January 1992 (5.8 years). In February 1987 and February 1988, six trees per treatment were selected for root biomass determination. At the end of the experiment in 1992, only one block was available, and one tree with a diameter representing the treatment mean was chosen in each plot for root biomass studies.

Fig. 1. Variation with tree age of the coefficients a_f (○) and n_f (■) from eq. 1.



The coefficients of the allometric equation were calculated from these data using the following equation so that estimates of foliage mass and stem mass could be made at intermediate times from the nondestructive measurements.

$$[1] \quad w_i = a_i d^{n_i}$$

where d is the diameter at breast height (cm), a_i and n_i are fitted coefficients, and the subscript i denote stems (s) or foliage (f). The coefficients in the equations for foliage mass and stem diameter varied with age; they were plotted against stand age (Fig. 1), and estimates of foliage mass per hectare for experimental plots were made using appropriate values for each age, which were obtained by interpolation in those graphs.

Litterfall data were available from measurements (traps) between 3 and 6 years in the Furadouro trial. There was seasonal variation, in particular for the control and fertilized treatments, with peaks in the month of July. Overall, there was a decrease of the mean monthly rate of leaf litterfall from 0.06 of total foliage mass at age 3 years to 0.03 at age 6 years.

The spacing trial

The spacing trial was established in April 1990 at Quinta do Paço, located in the northern coastal part of Portugal. This region receives around 1500 mm of rainfall per year, and therefore, *E. globulus* is generally quite productive. The trial had two blocks with five treatments corresponding to five densities: (*i*) 1 m × 2 m spacing (5000 $trees \cdot ha^{-1}$); (*ii*) 1 m × 3 m spacing (3333 $trees \cdot ha^{-1}$); (*iii*) 2 m × 2 m spacing (2500 $trees \cdot ha^{-1}$); (*iv*) 3 m × 2 m spacing (2167 $trees \cdot ha^{-1}$); and (*v*) 3 m × 3 m spacing (1111 $trees \cdot ha^{-1}$). The plots were different sizes to contain the same number of trees, 14 trees × 14 trees plus four edge rows. Generally, di-

Table 1. Data from the permanent sample plots.

Latitude (N)	Longitude (W)	Plot	No. of measurements	Values at last measurement: Age (years)	N	d_g (cm)	SI (m)
39°22′	9°14′	C058	8	8	900	18.1	28.1
39°20′	9°13′	A001	14	15.6	1026	21.1	27.3
		A002	14	15.5	1036	16.1	22.9
		A003	14	15.5	956	14.8	14.3
		A004	13	15.6	1079	22.0	29.3
39°21′	9°14′	A009	21	24.7	1000	22.9	25.1
		AV03	12	17.9	981	20.2	22.0
40°12′	8°40′	B050	10	15.2	1183	17.3	26.2
		B051	10	15.1	976	20.7	31.9
41°38′	8°29′	QP09	11	13.3	879	20.6	28.5
40°03′	8°39′	C020	8	14.1	1211	15.6	22.4
		C021	8	11.6	1111	16.1	23.5
41°16′	8°31′	VL21	16	10.1	1042	17.7	26.7
		VL33	17	10.1	1024	15.9	22.2

Note: N, stem number; d_q, quadratic mean diameter at breast height; SI, site index (dominant height at base age 10 years).

ameter at breast height was measured on every tree, and height was measured on at least the dominant trees; however when not available, tree heights were estimated with an existing height–diameter curve applicable to the whole country (Tomé et al. 2006). Volume equations (Tomé and Tomé 1994), applied to the diameter and height measurements in the trials, were used to obtain the "observed" values for stand volume (V), and basal area (G) was also computed. The coefficients for eq. 1, which was used to estimate standing biomass values, with measured d as the independent variable, were derived from a large data set obtained from the destructive sampling of several trees at many locations across the country described by António et al. (2007).

The permanent sample plots

There is a large data set from permanent plots and trials relating to the growth of *E. globulus* plantations in Portugal. These plots were established between 1971 and 1994. Several permanent sample plots (PSPs) located in different regions were selected to represent the variability in climate and soil present in the eucalyptus area of expansion in Portugal. Selected PSPs were remeasured several times during the rotation (Table 1), between January 1971 and November 1994. All plots chosen were initially established with stand densities between 1111 and 1250 trees·ha^{-1} and were all established with seedlings (no clonal material was used). Volume, basal area, and biomass data for each plot were calculated in the same way as described for the spacing trial.

It can be argued that the older PSPs (established in the 1970s) might not be as useful as newer ones because the trees on them will not have been improved by breeding. However, there is no published information indicating the proportion of the total area in the country that is currently under improved material nor is there any evidence that the "improved" material performs better under the different site conditions. These data are necessary to support the assumption that the products of tree-breeding programs are better than unimproved stock. Furthermore, it is incumbent on breeders to indicate what physiological mechanism is responsible for improved productivity (Landsberg 2003*b*).

Climate and soil data

Each of the selected plots and trials was characterized in terms of climate by monthly mean values of the variables from the most appropriate meteorological stations from the Portuguese National meteorological station network. Soils were evaluated from soil pits, and the soil profiles were analyzed by the soil scientist on the team with considerable experience in soil fertility assessment. The 3-PG fertility rating (FR), which has values between 0 and 1, was estimated from this information. Fertility rating was assumed to be 1 for the fertilized plots (optimum and fertilization treatments from the IF trial). It is possible that soil fertility will change through a rotation; however, this cannot be modeled, and the FR is held constant unless fertilizer is applied, when FR will increase by an amount considered appropriate to account for the increase in fertility. Maximum available soil water (MaxASW) is particularly important in Mediterranean climates, where the summer season can be essentially rainless for as long as 4 months, but good estimates of this parameter from physical characteristics of the soil in the volume assumed to be exploited by roots are difficult, since the actual volume of soil explored by the roots of *E. globulus* is generally unknown. It has been assessed by thorough analysis of the soil profile.

Data analysis

Initial testing and calibration

The current version of 3-PG (3-PGpjs, version 2.5; Sands 2004*a*), parameterized for *E. globulus* by Sands and Landsberg (2002), was used for the initial tests against data from the IF trial at Furadouro and data from the spacing trial. Three parameters and the stem mass – stem diameter allometric equation were modified as follows on the basis of the Portuguese data.

(1) Changes were made to the coefficients in the equation used in 3-PG to define the changes in specific leaf area (m^2·kg^{-1}) with age. The equation used was

$$\sigma_t = 4.2 + (13.1 - 4.2)e^{-\ln 2(t/1.5)^2} \quad [2]$$

Table 2. Results from testing 3-PG with the original parameters on data from the Furadouro trial.

	Control			Fertilization only			Irrigation only			Irrigation and fertilization		
Parameter	Mean	RMSE	ME	Mean	RMSE	ME	Mean	RMSE	ME	Mean	RMSE	ME
W_s	17.0	6.4	0.90	25.1	7.8	0.92	27.2	5.8	0.97	33.7	9.3	0.94
$\hat{W}_s$	16.6			23.8			31.5			41.5		
W_f	2.8	2.5	–0.72	3.9	2.7	–0.24	4.3	3.5	–0.44	5.1	4.3	–0.42
$\hat{W}_f$	4.8			6.1			7.3			8.8		
V	29.2	19.8	0.73	42.9	26.7	0.73	52.4	27.4	0.83	64.9	26.5	0.89
$\hat{V}$	20.8			29.6			39.5			52.1		
G	5.2	1.6	0.90	7.3	2.1	0.89	8.1	1.3	0.97	9.8	1.2	0.98
$\hat{G}$	5.0			6.6			7.9			9.7		

Note: The trees were 5.8 years old. RMSE, root mean square error; ME, modeling efficiency. W_s and $\hat{W}_s$, observed and estimated stem biomass ($Mg{\cdot}ha^{-1}$); W_f and $\hat{W}_f$, observed and estimated foliage biomass ($Mg{\cdot}ha^{-1}$); V and $\hat{V}$, observed and estimated stand volume ($m^3{\cdot}ha^{-1}$); G and $\hat{G}$, observed and estimated basal area ($m^2{\cdot}ha^{-1}$).

where σ_t is specific leaf area at age t and t the age in years.

(2) Changes were made to the coefficients in the equation used to define wood density and its variation with age. The 3-PG basic density function has a default value of 0.500 $Mg{\cdot}m^{-3}$ for *E. globulus*. From the Australian data sets for trees from 1 to 14 years old, basic density may vary between 0.482 and 0.733 $Mg{\cdot}m^{-3}$ (Ilic et al. 2000). In Portugal, the values vary between 0.380 $Mg{\cdot}m^{-3}$ at 6 months (Pereira et al. 1994) and 0.582 $Mg{\cdot}m^{-3}$ at 18 years (Tomé et al. 1994). The equation used was

$$[3] \quad \rho_t = 0.582 + (0.380 - 0.582)e^{-\ln 2(t/4)}$$

where ρ_t is the basic density at age t.

(3) Changes were made to the coefficients of the allometric relationship (eq. 1) between stem biomass and tree diameter at breast height which, in 3-PG, is inverted to estimate mean stem diameter from stem biomass:

$$w_s = 0.0557d^{2.7062}$$

where w_s is stem biomass (stem, branch, and bark, kg) and d is diameter at breast height (cm).

To evaluate the performance of 3-PG in relation to observed data, modeling efficiency (ME) (Soares et al. 1995; Stape et al. 2004) was calculated as follows

$$[4] \quad \mathrm{ME} = 1 - \frac{\Sigma(y_i - \hat{y}_i)^2}{\Sigma(y_i - \bar{y})^2}$$

where y_i is the observed data, $\bar{y}$ is the mean of the observed data, and $\hat{y}_i$ is the estimated data. The ideal value for ME is 1, indicating a perfect fit; 0 indicates that the model is no better than an average, and a negative value indicates poor performance by the model.

The root mean square error (RMSE) was used to give the mean distance of an observed data point from the modeled estimate, measured along a vertical line:

$$[5] \quad \mathrm{RMSE} = \sqrt{\frac{1}{n}(y_i - \hat{y}_i)^2}$$

The Excel Solver[2] optimization program was used to calibrate the model for improved performance by minimizing the following objective function:

$$[6] \quad \mathrm{Loss} = \frac{\Sigma(Ws_i - \hat{W}s_i)^2}{\Sigma Ws_i^2} + \frac{\Sigma(Wf_i - \hat{W}f_i)^2}{\Sigma Wf_i^2}$$

where: Ws_i and Wf_i are, respectively, the observed stem (stem, bark, and branches) and foliage biomass per hectare and the notations W and $\hat{W}$ are the predicted values, respectively.

During calibration, FR and MaxASW were allowed to vary within ±0.1 units and within ±50 mm, respectively, from the field-estimated values. Although there was need for FR and MaxASW tuning in most of the plots, the tuned values were within ±0.1 units and ±15 mm from the field estimates for MaxASW and FR, respectively.

Following the initial test with the Sands and Landsberg parameters (see Tables 2 and 3), the fit between observations and model predictions was improved by tuning parameters for the Furadouro trial and then adjusting them, if necessary, for the spacing trial. Tuned parameters were constrained to avoid biologically unrealistic values. The adjustments needed were relatively minor (see the following). From this exercise, a set of parameters that gave a good fit for all treatments was obtained. Because the objective was to find a unique parameter data set applicable to all Portuguese site conditions, these were evaluated against data from the PSPs.

Testing against permanent sample plot data

The performance of 3-PG with the "universal" parameter set, compared with data from the PSPs, was assessed in terms of the proportion of the variance in the observed variables accounted for by the predicted values (Fig. 2) and in terms of ME (see Table 4).

In this test process, the values initially used for FR and MaxASW were those obtained from the field assessments. However, because of the uncertainties in this process, FR and MaxASW were allowed to vary ±0.1 units and ± 50 mm, respectively, from the field estimated values during the final model validation exercise, i.e., a principle of "allowable uncertainty" was adopted in the values of this parameter on the grounds that exact values cannot be known — at least for field

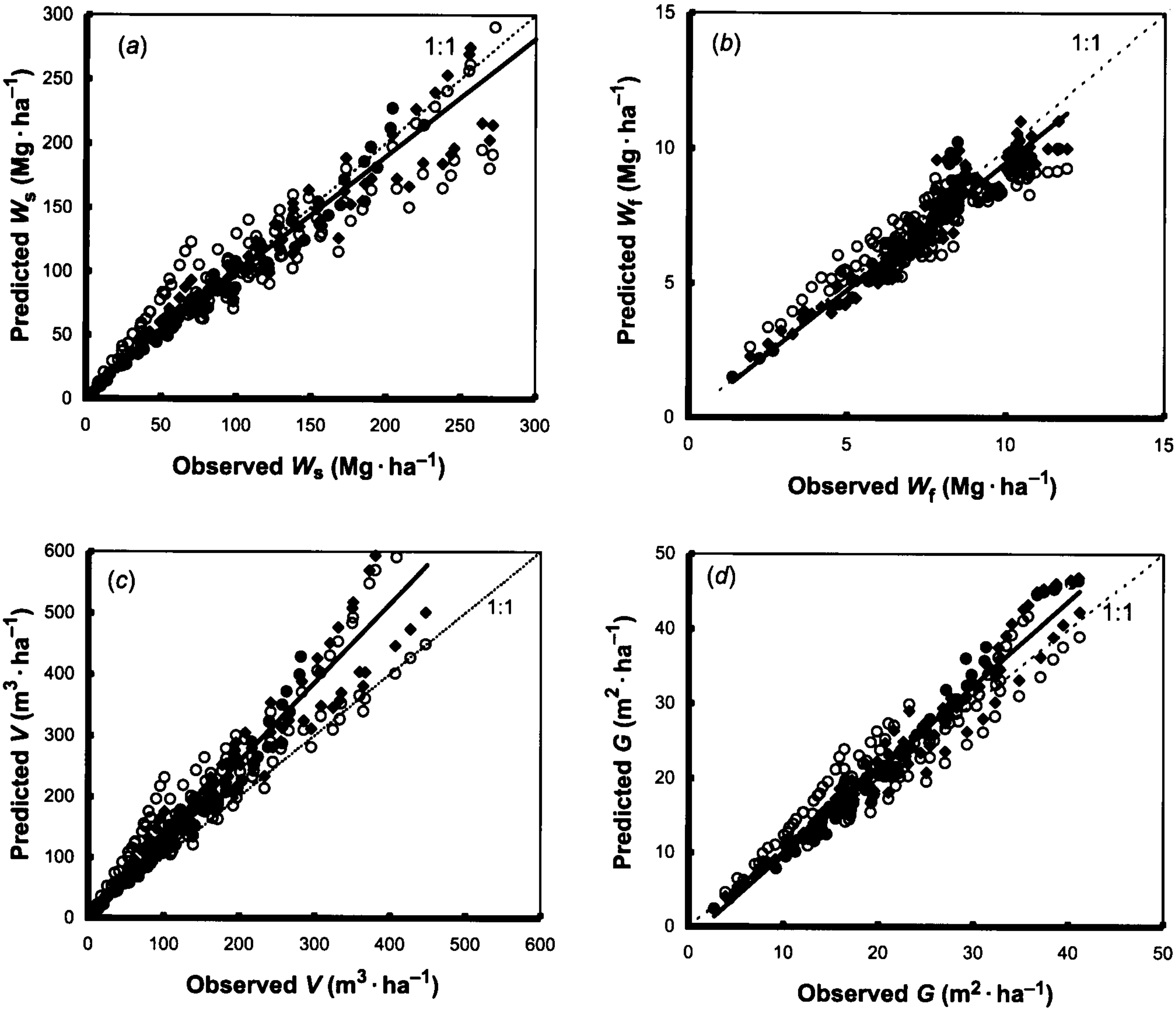
[2] Use of the product name does not imply endorsement.

Table 3. Results from testing 3-PG with the original parameters on data from the spacing trial.

	3 m × 3 m spacing (1111)			2 m × 2 m spacing (2500)			1 m × 3 m spacing (3333)			1 m × 2 m spacing (5000)		
Parameter	Mean	RMSE	ME	Mean	RMSE	ME	Mean	RMSE	ME	Mean	RMSE	ME
W_s	105.4	43.6	0.62	132.4	53.6	0.57	139.0	57.9	0.55	136.2	53.8	0.54
$\hat{W}_s$	69.4			85.7			88.9			88.3		
W_f	6.5	1.3	0.69	8.1	2.8	−0.2	9.0	3.2	−0.45	9.3	4.6	−2.16
$\hat{W}_f$	7.2			10.7			12.0			13.5		
V	194.5	99.1	0.26	247.5	125.4	0.19	262.4	137.0	0.12	261.2	133.8	0.03
$\hat{V}$	101.9			125.7			130.4			129.4		
G	19.5	3.3	0.86	24.2	3.3	0.90	26.7	2.6	0.95	27.3	3.0	0.93
$\hat{G}$	16.3			23.4			25.6			27.6		

Note: The trees were 13.3 years old. Spacings and the resulting stem populations (stocking density) are given in the top row. RMSE, root mean square error; ME, modeling efficiency. The other variables are as in Table 2. Values in parentheses are trees per hectare.

Fig. 2. Observed versus predicted values from the validation on permanent sample plots (○ and the top regression equation) and after an adjustment of maximum available soil water and fertility rating (◆, second regression and trend line). For Figs. 2*b* and 2*c*, the fitted lines are forced through the origin as the intercepts were not significantly different from zero ($p > 0.05$).



situations. Additionally, this procedure provides a test of the accuracy of the field estimates of FR and MaxASW; if good results were obtained with those estimates and if those results could not be significantly improved by altering the values of those input variables, it could be concluded that the field estimates were accurate.

Table 4. Mean ME values for the 3-PG model after the three steps followed (*i*) initial test against the irrigation and fertilization (IF) and spacing trial data with Australian published parameter values; (*ii*) calibration based on the IF and spacing trial data; and (*iii*) test against PSP data using calibrated parameters, with and without adjustment of the FR and MaxASW values to improve the fit.

			Test against PSP data	
Parameter	Test against IF and spacing trial data	Calibration with IF and spacing trial data	Without adjustment	With adjustment
W_s	0.75	0.95	0.89	0.94
W_f	–0.49	0.94	0.85	0.94
V	0.47	0.96	0.89	0.91
G	0.92	0.97	0.91	0.92

Note: See Table 2 for definitions of variables.

Table 5. List of the values of the 3-PG parameters for Portugal that are different from those given by Sands and Landsberg (2002).

			3-PG parameter values	
Values	3-PG symbol	Units	Portuguese	Sands and Landsberg (2002)
Foliage:stem partitioning ratio at d = 2 cm	pFS2	—	0.3	1
Foliage:stem partitioning ratio at d = 20 cm	pFS20	—	0.09	0.15
Constant in stem mass – diameter relationship	a_s		0.056 (0.065)	0.095
Power in stem mass – diameter relationship	n_s		2.7	2.4
Maximum fraction of net primary productivity to roots	pRx	—	0.5	0.8
Minimum fraction of net primary productivity to roots	pRn	—	0.25 (0.15)	0.25
Minimum temperature for growth	Tmin	°C	6	8.5
Optimum temperature for growth	Topt	°C	16	16
Maximum temperature for growth	Tmax	°C	40	40
Mean monthly root turnover rate	Rttover	1/month	0.01	0.015
Maximum litterfall rate	gammaFx	1/month	0.013 (0.018)	0.027
Age at which litterfall rate has median value	tgammaF	month	6	12
Days production lost per frost day	kF	days	1	0

Note: Values in parentheses were used for the spacing trial with the exception of treatment 9 in that trial, which had the same stocking as the Furadouro trial.

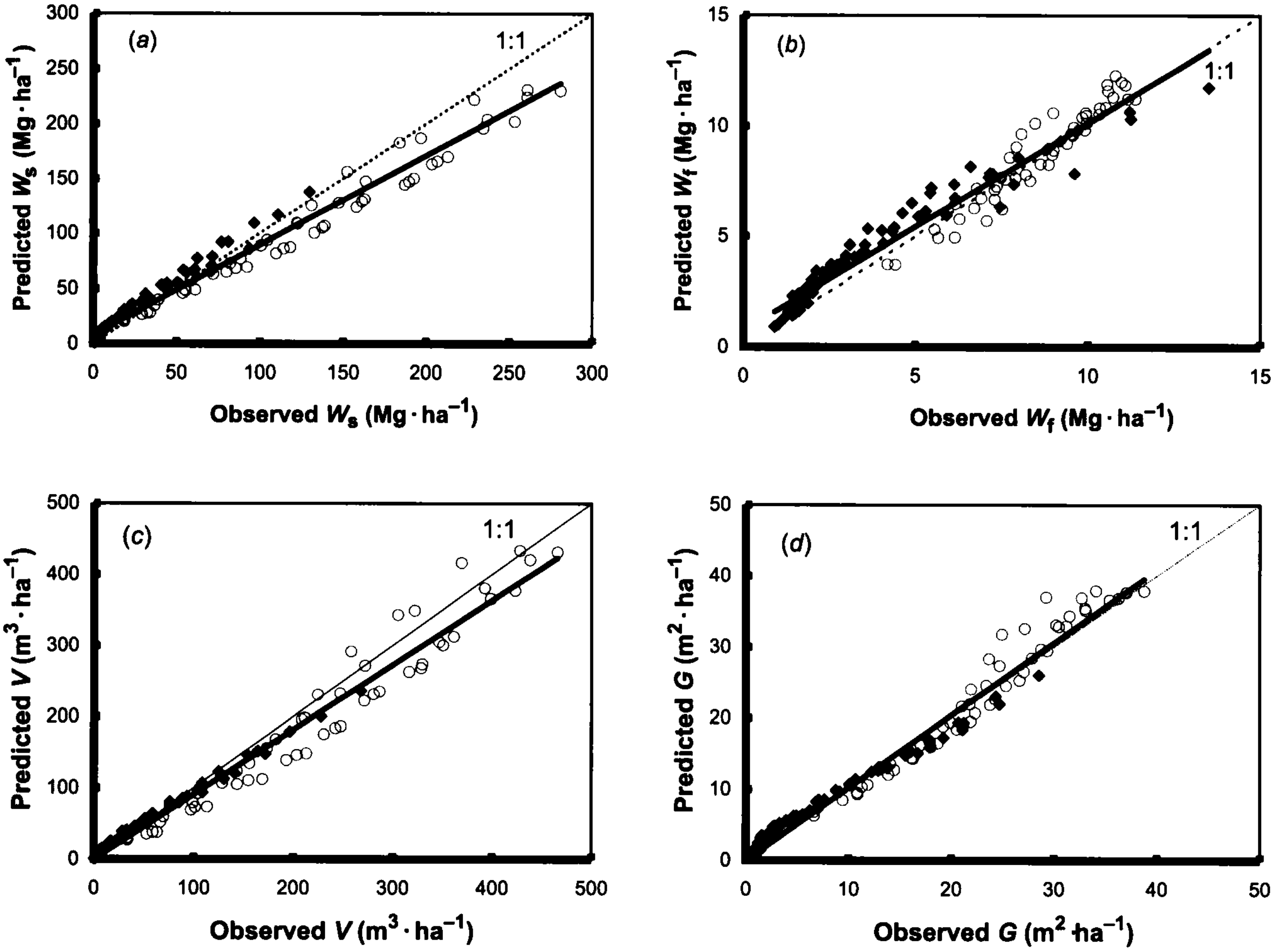
Results

The results of the initial analysis of the data from Furadouro using 3-PG with the parameters from Sands and Landsberg (2002), the parameters for specific leaf area and wood density, and allometric relationships fitted to Portuguese data showed (Table 2) that the model provided good estimates for stem mass and basal area (ME between 0.9 and 0.98), poor estimates for leaf mass (ME negative), and reasonable estimates for volume (ME between 0.73 and 0.89). Results from the spacing trial (Table 3) were not as good, particularly at the higher stocking densities. However, the leaf mass estimate, for the conventional stocking density, was better than the estimates for Furadouro.

Most of the parameter values resulting from the tuning and calibration procedure carried out after the initial tests against the Furadouro and spacing trial data were very similar to those given by Sands and Landsberg (2002) for *E. globulus* in Tasmania. However, the optimum values for the Portuguese data for the NPP partitioning parameters were quite different, and the values of these parameters that gave the best fit to different stocking data also differed (Table 5). At higher stocking densities, it was necessary to change the allometric equation, which is to be expected because of the effects of stocking density on tree form. There was also an increase of the rate of litterfall at higher stocking. It was found that the optimum allocations to roots at Furadouro and in the spacing trial were slightly different (Table 5), which can be explained by differences between the soils of the two sites. At Furadouro, the soil is deeper, less stony, and lower in nutrients than the soil at the spacing trial. These different values were not considered in the development of the optimum parameter set used in the tests against PSP data, which applies to trees planted at standard spacings (3 m × 3 m or 4 m × 2 m, i.e., about 1100–1200 trees·ha^{-1}). The implications of all these differences are explored in the Discussion.

The optimum set of parameters obtained from the calibration process was used to simulate stem mass, foliage mass, stand volume, and basal area for all treatments in the Furadouro and spacing trials. The predicted values are plotted against observed values in Fig. 3, the 1:1 lines are shown. For a perfect result, the slopes of the fitted lines would be one, and the r^2 value would also be one. The results show close approximations to these criteria; departures from them are almost certainly attributable to the fact that

Fig. 3. Values predicted by 3-PG versus observed values for the Furadouro experiment (◆) and the spacing trial (○): (*a*) stem mass; (*b*) foliage mass; (*c*) stand volume; and (*d*) basal area. For Figs. 3*c* and 3*d*, the fitted lines were forced through the origin because the intercepts were not significantly different from zero ($p > 0.05$).



there is natural variation in the observed data, possibly caused by factors that are not accounted for by the 3-PG model or possibly by random factors.

Predicted variable values for the PSPs, before and after adjustment of FR and MaxASW, are plotted against observed data in Fig. 2; as in Fig. 3, the lines are forced through zero, the 1:1 lines are shown, and the r^2 values and slopes are given on the graphs. We note from the slopes of the lines in Fig. 2 that the model slightly underestimates stem biomass in the PSPs but slightly overestimates volume. This can be explained by the conversion from mass to volume carried out in the model using eq. 1, the estimate for wood density, and the discount for the fraction of branch and bark. As mentioned before, the test in which 3-PG was used to simulate data from the PSPs was followed by adjustment of the field estimates of the FR and MaxASW. For the reasons outlined earlier (uncertainly in the field estimates) FR values were allowed to vary ±0.1 unit and MaxASW within ±50 mm to evaluate the impact on the fit to PSP data. No other tuning or calibration was carried out. The mean values of the original field-based estimates of FR and MaxASW for the PSPs were 0.39 and 140 mm, respectively; the means after adjustment were 0.40 and 142 mm, respectively. The relationships shown in Fig. 2 indicate that the model performed well, even without adjustment, but performance was improved by the adjustments (see also Table 4).

The data in Table 4 illustrate the improvements in ME brought about by the sequential test, calibration, and validation procedures outlined above. The ME values for the sequential test and calibration are based on the IF experiment and the spacing trial. Note that the adjustment of the FR and MaxASW values brought about a slight improvement. Overall, the model does an excellent job.

Manipulation of Sands and Landsberg (2002) equations A8, A9, and A10 also allows us to solve for the coefficients of the allometric equation describing foliage mass in terms of stem diameter. Note that this will not be the same as eq. 1, which describes foliage mass in terms of d at any time t ($d(t)$), because that equation does not account for leaves that have already fallen (as litterfall) from the trees. The equation is

$$[7] \quad \sum_{i=0}^{t} w_f^*(i) = w_f(t) + \sum_{i=0}^{t} \text{litterfall}(i) = a_f^* d(t)^{n_f^*}$$

This provides a means of checking litterfall values by subtracting the value of $w_f(t)$ from $\sum_t^{i=0} w_f$. This should be (approximately) equal to the cumulative litterfall up to time

Fig. 4. Change in observed (●) and predicted leaf biomass (□), including accumulated litterfall, with changes in diameter at breast height from the Furadouro trial. Predicted values based on Sands and Landsberg (2002; △) are also shown.

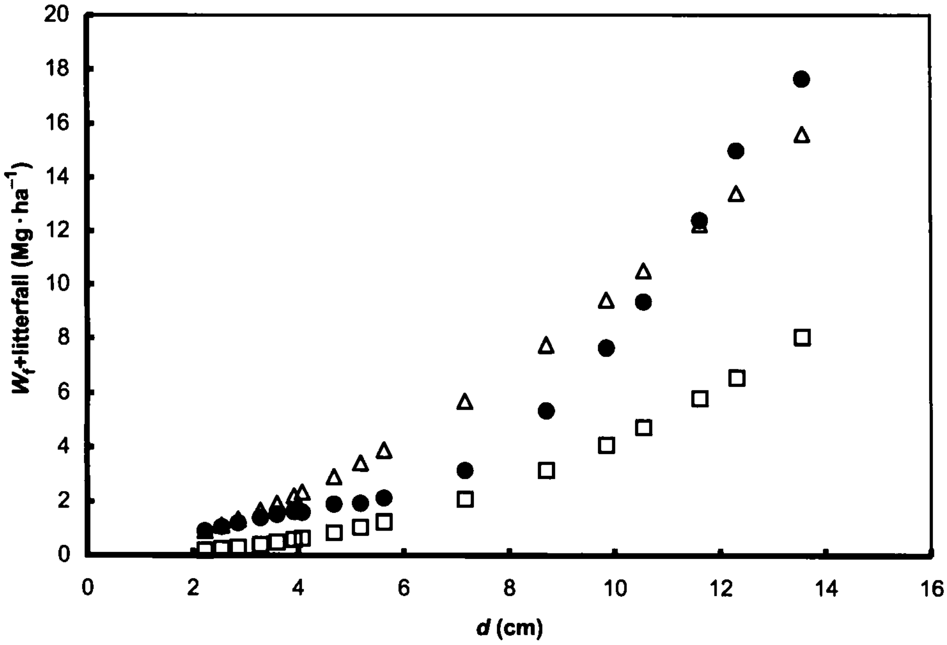
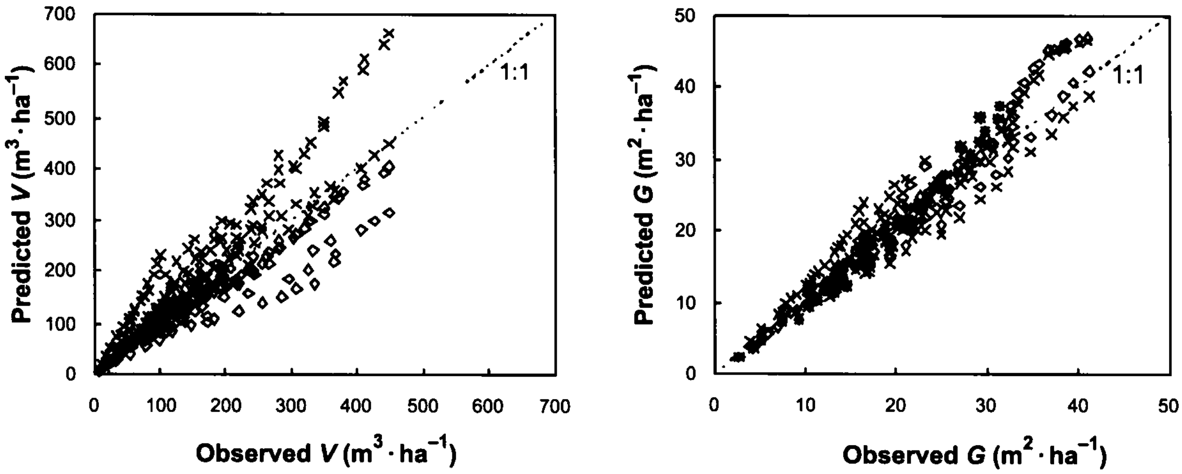


Fig. 5. Observed versus predicted values from stand volume under bark and basal area per hectare of the PSPs using the 3-PG (×) and GLOBULUS 2.1 (◇) models.



t. The comparison of the observed values of leaf biomass with litterfall and the values calculated using the coefficients from the Furadouro data and from Sands and Landsberg (2002) gives an interesting result; the coefficients given by Sands and Landsberg show better correspondence with the observed values of litterfall from Furadouro than do the coefficients that emerged from the present analysis (Fig. 4).

The results from 3-PG model predictions in relation to the PSPs for two main variables of interest for foresters, stand volume, and basal area, and the estimates from empirical model GLOBULUS 2.1 (Tomé et al. 2001) are graphically compared in Fig. 5. There is an overestimation of 3-PG volume estimates for the older PSPs, namely the A009 with 25 years and the AV03 with 18 years, which might be due to the calibration being based in younger data from the IF trial with 6 years. On the other hand, there is an underestimation of GLOBULUS 2.1 volume estimates for the PSPs with highest SI located in the Centre-littoral regions, A001, A004, and B051, although it gives good estimates for the highest productivity PSP located in the North-littoral, QP09.

Discussion

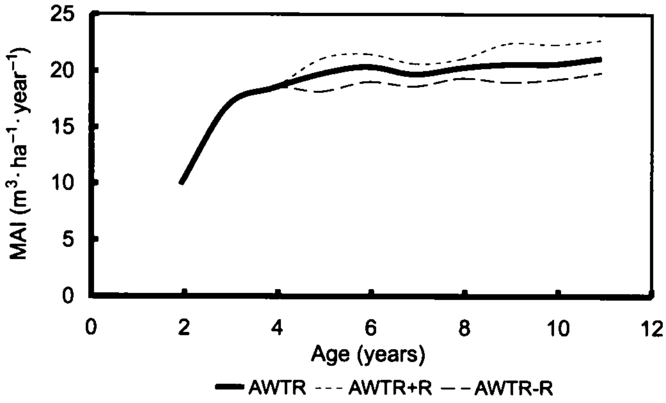
The initial evaluation of 3-PG using published parameter values was a true test because the data against which the model was tested were completely independent of model development or calibration. The test involved evaluating the predicted growth of *E. globulus* at very different nutrition and available water conditions and at a range of stocking densities. The model predicted the values at harvest of stem mass, stand volume, and basal area with useful accuracy for the IF trial data. Foliage mass was not well predicted, except for the 3 m × 3 m treatment in the spacing trial.

The differences shown in Fig. 4 are not surprising; the litterfall predictions are derived from highly nonlinear equations (see Sands and Landsberg (2002), eqs. A11 and A12) in which small variations in the values of parameters can have large effects. Litterfall is difficult to measure accurately and varies with time and conditions. In terms of mass, it is a relatively small component of the model (compare accumulated litterfall of, for example, 10 Mg·ha^{-1} with stem mass of 250 Mg·ha^{-1}); its main importance lies in the fact that it must be calculated accurately enough to allow good estimates of leaf area index (LAI), a key variable in the model, because it determines absorbed photosynthetically active radiation (APAR). The divergence between observed litterfall and that predicted by the coefficients derived from the Furadouro analysis, which was too low, suggests that there must have been a slight compensating error in biomass allocation in the model. Because predicted litterfall was too low, allocation to foliage must have been slightly too low; otherwise, LAI would have been consistently high, which would introduce major errors. In absolute terms, the allocation errors were small; this warrants further investigation, but it is doubtful that this model can be calibrated accurately enough to rectify them. (See the study by Dye et al. (2004), which provides detailed evaluation of the main variables in 3-PG. They provide monthly litterfall measurements from eucalyptus plantations for a year, for two sites and several treatments.)

As would be expected, the calibration of the model led to significant improvement in the match between observed and predicted values for the IF and spacing trials; it also revealed that, to obtain good fits for high stocking densities, it was essential to alter the coefficients in the allometric equation (eq. 1), which is not surprising because these coefficients reflect the form of the trees: those grown at high stocking rates have a different form than those grown at lower rates. It was also necessary to alter litterfall to get good predictions of foliage mass at high stocking; again this is not surprising, because crowded trees do not hold their lower foliage as long as more widely spaced trees. The subsequent test of model performance against PSP data, using the optimum parameter set for the normal range of spacings, was very stringent because those data were not used for calibration or tuning. The exercise indicates that it would be possible to get good estimates of forest productivity across a wide range of field sites and situations in the field in Portugal using a single set of parameters for sites that range from SI = 14 to SI = 32. For significantly higher or lower productivity sites, it will be necessary to vary some parameter values.

The implications of this result are that, from a commercial point of view, 3-PG can be used to get good estimates of forest productivity using the parameter values given by Sands and Landsberg (2002) with the alterations presented in Table 5. However, there are indications in the data examined that, if high accuracy is required of the predictions for a particular area, it would be beneficial if the model were calibrated for that area using some form of stratification on the basis of SI or soil type. It would be advisable for a commercial company to maintain a number of check or calibration plots in representative areas of its forest estate. The advantage doing this would be that relatively few measurements would be needed, and there would be no need for analysis of large data bases and the development of conventional mensuration-based models. Standard stem diameter measurements in those plots and occasional destructive sampling to determine the coefficients of eq. 1 and to obtain information about wood density, the proportion of branches, and stem volumes would provide ample information for this process-based model.

Fig. 6. Mean annual increment (MAI) calculated for a hypothetical stand in the Furadouro area using mean weather data (AWTR), below-average rainfall (AWTR–R), and above-average rainfall (AWTR+R).



Another major advantage of using 3-PG in commercial planning and management is that the model can be used to assess the probable yield loss from periods of drought (Almeida et al. 2004*b*; Dye et al. 2004). This is illustrated in Fig. 6, where observed weather data from a site with FR = 0.8 in the Furadouro region has been used to calculate volume maximum mean annual increment (MAI) for a hypothetical stand over 11 years. The increment was then calculated with the actual weather data with two simulated drought periods by subtracting 200 mm·year^{-1} of rainfall between April and October in years 4 and 8, when the observed rainfall was 852 mm and 724 mm, respectively. Years with above-average rainfall were also simulated by adding 200 mm·year^{-1} between May and September in the same 2 years. These changes, which are well within the normal range, caused a difference of about 3 m^3·ha^{-1}·year^{-1}, that is, a reduction of about 15%, which is significant in commercial terms.

The model can also be used to assess the effects of silvicultural practices, such as decisions about levels of fertilization.

The major differences between the parameter values published by Sands and Landsberg (2002) and the optimum set developed for Portugal are the foliage : stem biomass allocation ratios at stem diameters of 2 and 20 cm (see Table 5). Equations A8, A9, and A10 from Sands and Landsberg (2002) can be used to assess the implications of these differences in terms of the time course of biomass allocation in the Portuguese and Australian stands.[3]

[3] The software package 3-PGS (available from http://www.ffp.csiro.au/fap/3pg/download_details.asp) includes a "Tools" file that allows these calculations to be done easily and immediately.

Fig. 7. Time course of biomass allocation to stems (eta_s) and foliage (eta_f) for the Portuguese Furadouro (thin solid line), Quinta do Paço (broken line), and Australian stands (thick solid line).

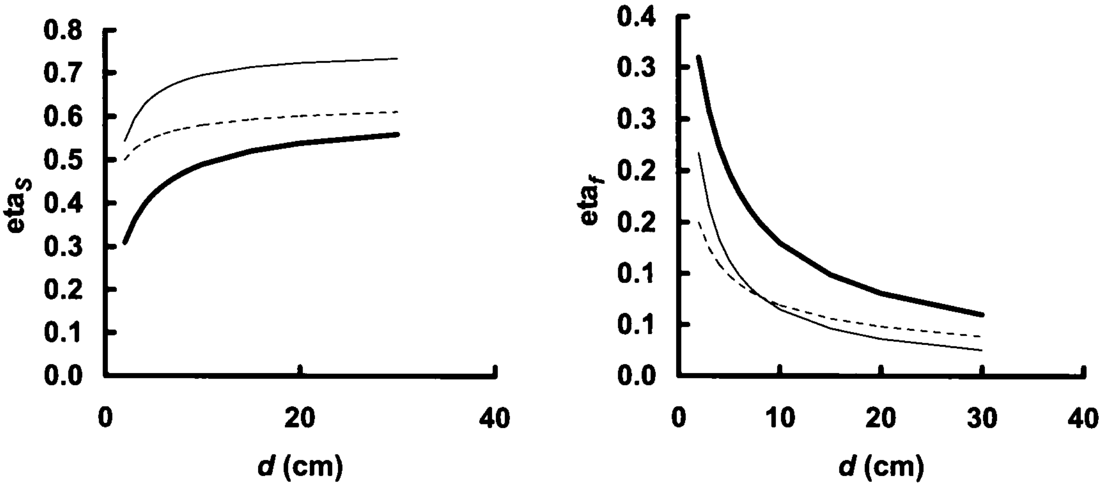


Figure 7 compares the proportion of stem and foliage biomasses in Portugal and Australia with the data from Australia calculated with the allocation for roots calculated previously based on an FR average for Australia (0.5 units). This figure shows that the proportion of NPP allocated to stems by *E. globulus* in Portugal is higher than in Australia, although the higher values occur, as could be expected, for the spacing trial. Inversely, the proportion of NPP allocated to the leaves is higher in Australia than in Portugal.

The comparison of the empirical model GLOBULUS 2.1 (Tomé et al. 2001) and 3-PG model for two main variables of interest for foresters, stand volume and basal area, have shown that 3-PG has almost as good estimates to this empirical model.

Conclusions

It has been shown that a process-based model, in this case the 3-PG model of Landsberg and Waring (1997), can be calibrated to give accurate descriptions of the growth patterns of plantation-grown eucalyptus, confirming previous findings that the model could accurately describe the growth of eucalyptus and a range of other species (Landsberg et al. 2001*b*, 2003; Almeida et al. 2004*a*; Stape et al. 2004). Almost identical sets of parameter values emerged from the analysis of a trial in which growth patterns were quite radically changed by fertilization and irrigation treatments that would not normally be used in commercial production and from a spacing trial in another part of the country with no environmental manipulation. This indicates that the physiology of the trees and the processes that govern their growth and biomass allocation are strongly conservative and that the major factors influencing growth (local radiation, temperature, rainfall or irrigation mediated through MaxASW, and soil fertility) are the factors that determine site productivity and account for virtually all the variation in growth and productivity. Therefore, geographical information systems can be used with soil and weather data layers to estimate wide-scale productivity, examine the effects of events such as droughts, assist in management decisions, assess potential productivity, and assess the probable benefits of fertilizer applications and effects of thinning.

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