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Combining empirical models and the process-based model 3-PG to predict *Eucalyptus nitens* plantations growth in Spain

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ABSTRACT

Empirical, statistically based models were used to describe the growth and development of *Eucalyptus nitens* plantations for a range of site productivities and the standard biomass and pulp silvicultural regime currently applied in Northern Spain. The results obtained, along with data gathered from a network of 68 plots, 48 trees felled for biomass estimations and 73 trees sampled for foliar area estimation were used to parameterize the 3-PG model for this species in Northern Spain. Most parameters associated with allometric relationships and partitioning (i.e. bark and branch fraction, basic density, age modifier and mortality) were derived from local data, and the remaining parameters were obtained from published studies on *E. nitens* or default values previously used for *E. globulus*. The parameterized model was validated with data from three trials measured from age 3 years until age 8–14 years, and performed better than the empirical model in terms of total stand under bark volume, mean diameter at breast height, basal area and foliar biomass. The process-based model was then used to forecast changes in plantations subjected to a clearwood regime, initializing the model at age 3 years, considering 3 prunings, 2 thinnings and lengthening the rotation to 18 years. This integrated regime was able to provide biomass for bioenergy, pulp or fibreboard wood and also solid wood, with thinning operations assisting the financial viability, and was a potentially good alternative for productive sites.

1. Introduction

Eucalyptus nitens is one of the most promising hardwoods for plantations in cool temperate regions of the world. The total planted area has been estimated at 340,000 ha, distributed throughout Australia (Tasmania and Victoria), Chile, New Zealand, South Africa and Spain (Muñoz et al., 2005). In Spain the plantations have spread out to the north, and now cover approximately 30,000 ha in the regions of Galicia and Cantabria. As a frost resistant species, the species was first planted in 1992 in frost prone areas, above 500 m, but the promising growth results and its relatively low susceptibility to damage by *Gonipterus* and *Mycosphaerella* soon led to establishment of plantations at lower altitudes, where *E. globulus* was previously used (Pérez et al., 2006; Pérez-Cruzado and Rodríguez-Soalleiro, 2011). The Barrington Tops provenance was used between 1992 and 1996, and the McAlister provenance thereafter (Astorga, pers. comm.).

Plantations are managed by intensive regimes, including mechanical soil preparation, fertilization at establishment and planting of 1000–1500 containerized seedlings per ha. Brush weeding is applied frequently before canopy closure, and clearcutting is carried out at age 10–12 years. The timber is commonly used as a raw material in the manufacturing of medium density fibreboard (Pérez-Cruzado, 2009). Nevertheless, Spanish pulp factories are beginning to use the timber, although the basic density of the wood is lower than that in *E. globulus* (Pérez et al., 2006). Logging residues and small diameter logs are also used for energy purposes, through the use of bundles and further chipping once the bundles are air dried. A poor coppicing ability has been reported for the species (Little and Gardner, 2003), although good examples of resprouting have been found in Northern Spain. Declining pulp prices worldwide and the need for product diversification are leading to the increased popularity of plantations of this species managed for solid wood products (Medhurst et al., 2001). There is an increasing interest in Spain in silvicultural regimes aimed at obtaining clearwood through pruning and thinning, and lengthening the rotation age to 18–25 years (Nutto and Touza-Vázquez, 2004).

Plantation yield prediction has been dominated by empirical modelling, but process-based models of forest growth and production have increasingly become part of the forest management

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decision making process. These models have been used to study different situations, including the response to management of established plantations, in terms of yield prediction (Battaglia et al., 2007). The site index approach defines invariant growth trajectories for top height, an assumption known from practical experience to be false. The SI concept is in fact a logically circular concept, which limits the flexibility of the empirical models and their capacity to simulate the results of environmental stresses or departures from the climatic conditions during the periods of plot measurement (Fontes et al., 2006). These problems can be overcome by the use of process-based models, which provide estimates that depend directly on site conditions.

The 3-PG model of forest growth (Landsberg and Waring, 1997) is the most used process-based forest model (Landsberg et al., 2003; Almeida et al., 2004; Sands and Landsberg, 2002; Battaglia et al., 2007). It has been parameterized for several species of eucalypts and conifers and used for research and teaching purposes, as well as in the management systems of forest companies. A user-friendly version is available (Sands, 2002) and the information required to run the model is readily obtained from national meteorological agencies or site assessment studies. A study has already applied the Sands and Landsberg (2002) parameterization of 3-PG for *E. globulus* to test the performance of this model in Northern Spain (Rodríguez-Suárez et al., 2010).

The aims of the present study were: (i) to parameterize the 3-PG model for *E. nitens* plantations in the site conditions of Northern Spain, (ii) to compare 3-PG with an empirical based model for current silvicultural regimes applied in three trials, measured at age 3–8 years (one trial), and 3–14 years (two trials), and (iii) to apply the 3-PG to an alternative silvicultural regime aimed at production of clear wood, for two representative sites of high and low productivity in Northern Spain, based on current knowledge of the species response to pruning and thinning treatments. This regime will be evaluated in terms of growth and production.

2. Materials and methods

2.1. Empirical models and productivity levels

Empirical individual-tree and stand models are available for *E. nitens* in Northern Spain (Pérez-Cruzado, 2009). These models have been obtained for the observed range of site productivity and silvicultural treatments applied in the region, which in most cases involves maximizing chip and biomass production. The structure of the empirical models is based on a site index system $H_2 = f_1(H_1, t_1, t_2)$, relating top height (H) to age (t), where $H_2 = SI$ (site index) for t_2 = reference age, which has been chosen as 6 years in Spain (Fig. 1). This system was used in the present study to classify the productivity levels of each permanent trial (PT) used to compare the empirical model and 3-PG and the temporary plots (TP) used to propose an alternative silvicultural regime.

A second equation in the empirical models is a static model to predict quadratic mean diameter (d_g). Because neither the TP nor the PT have been thinned, d_g may be directly related to stand density (N) and top height ($d_g = f_2(H, N)$). This equation is based on the relationship between average tree size, density and a productivity indicator. The change in tree density (N) was thus only dependent on mortality, and stem reduction closely followed a modified Candy (1997) mortality model ($N_2 = f_3(N_1, t_1, t_2, SI)$.

These three equations enable calculation of the changes in three stand state variables (H, basal area, G and N), from which several derived variables can be obtained, in particular the stand biomass components: wood biomass (W_w), bark biomass (W_b), branches biomass (W_{br}) and foliage biomass (W_f). These functions were fitted simultaneously to produce the system of equations shown in Table 1. The under-bark volume was obtained from the wood biomass, considering an average value of basic density. The equations were used to initialize the process-based model at age 3 years and to calculate stand production in terms of wood or biomass.

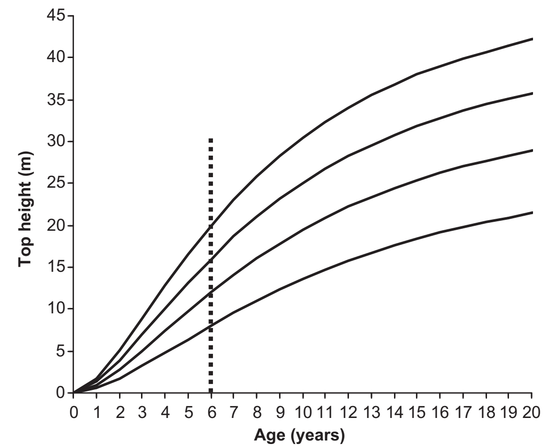

Fig. 1. Site index system for *Eucalyptus nitens* in Northern Spain, showing the changes in top height for the productivity range observed in the area.

2.2. Experimental data for calibrating 3-PG

A simple process-based model (3-PG) was used to predict the stand evolution as an alternative to empirical models (Landsberg and Waring, 1997). 3-PG is driven by intercepted radiation, with radiation-use efficiency for carbon fixation affected by temperature, vapour pressure deficit, available soil water, stand age and site fertility (Sands and Landsberg, 2002). The model calculates monthly net carbon fixation, stand growth, biomass (considering three compartments, foliage, stems and branches) and water use from monthly values for solar radiation, modified by several soil, climate and management factors. The 3-PG version used in this study was 3-PGpjs2.5, which is implemented as a Microsoft Excel spreadsheet with a user-interface that facilitates data entry and interpretation of results (Sands, 2002).

The use of 3-PG required prior parameterization for *E. nitens*, which was performed with different data sets:

(i) A sample of 48 trees covering the full range of diameter and height classes existing in Spanish plantations was felled and the following variables were recorded: diameter at breast height (cm), tree age, stem biomass (considering wood, bark and branches together) and foliage biomass. The trees were felled and cut into 0.5 m logs until a thin-end diameter of 7 cm. Wood density was calculated from the wood dry biomass and the volume calculated by applying the Smalian equation to each log. Basic density data were available for these 48 trees and an additional sample of 14 trees.

Table 1
Equations fitted to estimate aboveground stand biomass components. W_w is wood biomass, W_b is bark biomass, W_{br} is branch biomass and W_f is foliage biomass (oven dry, kg ha^{-1}). Sub index i in each parameter refers to the corresponding component in each file.

Model	Parameter estimates				Adj. R^2
	b_{1i}	b_{2i}	b_{3i}	b_{4i}	
$W_w = b_{11} \cdot dg^{b_{21}} \cdot H_0^{b_{31}} \cdot N^{b_{41}}$	11×10^{-6}	2.2067	0.8808	0.9631	0.9984
$W_b = b_{12} \cdot dg^{b_{22}} \cdot H_0^{b_{32}} \cdot N^{b_{42}}$	13×10^{-6}	2.3318	0.0463	1.0031	0.9993
$W_{br} = b_{13} \cdot dg^{b_{23}} \cdot H_0^{b_{33}} \cdot N^{b_{43}}$	18×10^{-6}	2.3522	0.0914	0.9648	0.9909
$W_f = b_{14} \cdot dg^{b_{24}} \cdot H_0^{b_{34}} \cdot N^{b_{44}}$	5.03×10^{-6}	2.3607	0.0510	1.0035	0.9992

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(ii) A set of 68 plots in which diameter and height of all trees were recorded, and stand variables, including site index, were calculated. The plots, in which the trees were aged 1–18 years, were either circular, of radius 10 m, or square plots of 20 × 20 m. It was possible to apply the empirical model to them to calculate the predicted annual increment and relate this value to the maximum volume increment for the same site index, thus evaluating the age modifier of 3-PG. The plots were also used to adapt the mortality model, and to evaluate the fraction of mean single-tree biomass lost per dead tree, assuming no foliage biomass is lost because of mortality.

(iii) The average value of the specific leaf area for young leaves was determined from a set of 73 trees in which foliar samples were obtained in a pruning trial for the species. The trees were pruned to 2–4 m, and a composite sample of fresh leaves was weighed, scanned and oven-dried to constant weight, for calculation of the dry weight. The leaf area was calculated after digitalization of the scanned images. A single composite value was used per tree.

The models required to obtain the 3-PG parameter values were fitted with the NLIN procedure of SAS (SAS Institute, 2004).

No attempts were made to evaluate the allocation of net primary production (NPP) to roots, but biomass allocation to foliage (η_F) and stems (η_S) was determined by considering the derivatives of the allometric functions for mean single-tree foliage and stem biomass and considering the ratio $p_{FS} = \eta_F/\eta_S$ to be an allometric function of diameter at breast height (Sands and Landsberg, 2002). A detailed analysis of allometric relations and their applicability to different ages and sites is available for Tasmania (Medhurst et al., 1999), and was considered for comparisons. A temperature modifier of quantum efficiency was used, considering the minimum, optimum and maximum temperatures for net photosynthetic production. Rodríguez et al. (2009) applied values of 2, 20 and 32 °C for this species in Chile and Battaglia et al. (1996, 1998) reported the higher ability of *E. nitens* than of *E. globulus* to maintain high photosynthetic rates at low temperatures. Although Battaglia et al. (1996) showed a platykurtic response of net photosynthesis to temperature for *E. nitens*, it seems reasonable to consider a lower optimum temperature than the value applied to parameterize 3-PG to *E. globulus* (16 °C, Sands and Landsberg, 2002; Fontes et al., 2006).

Litterfall should vary in response to local conditions, and so the monthly litterfall rates γ_F should ideally be site dependent (Sands and Landsberg, 2002), but as no information was available on litterfall, the default value for very young stands was applied, and the maximum litter fall rate was derived from the study of Moroni and Smethurst (2003). The default values used by Sands and Landsberg (2002) for parameters related to stomatal conductance were considered, applying a sensitivity analysis to the maximum canopy conductance, because stomatal conductance and growth are more sensitive to water stress in *E. nitens* than *E. globulus* (White et al., 1999).

Several sources of information were used to determine other parameters, but especially the references related to specific studies in Tasmania. Default values for *E. globulus* were considered if no more specific information was available (Sands and Landsberg, 2002), and affected mostly to parameters reported to have a low sensitivity for volume or leaf area estimations (Esprey et al., 2004).

2.3. Site data

To test whether the parameterization proposed can accurately predict growth, three PT of the species with continuous measurements were employed. In addition, two TP representative of high and low levels of productivity for simulating clear wood regimes were identified and the soil and climatic data required to run 3-PG were recorded.

Climatic data were obtained from series of the last 30 years (www.meteogalicia.es), and solar radiation or average number of frost days was derived from the same weather stations (but for 5-year series). Monthly average values were used as input data in the model (Table 2). All five plots were in the latitude range 42.6–43.4°N. The three PT were established in June, 1992, with a spacing of 1283 trees per ha, and all diameter and heights were measured annually till age 6 years, and then at age 8 (all trials) and 14 (two trials). Wood volumes inside bark were calculated from single tree equations, considering 3 years as the initializing age. The values of site index and volumes were the average values for 7–9 rectangular plots of 420–520 m^2 per trial. The three trials were similar in terms of summer temperatures, although Lalín was the most elevated (700 m) and more exposed to frost. There were clear differences in terms of soil (see Table 2) and parent material: quartziferous schists at Lalín, granites at Antas and slate at Xermade.

The two TP are representative of the area where most commercial plantations are located, and the sites were rather similar in terms of summer precipitation, annual precipitation and elevation (600 m), although total annual radiation was 38.4% higher in the most productive site. There were also fewer frost days for Guitiriz. The clearest differences were in soil depth and, correspondingly, the maximum available soil water. The texture of both soils was similar, as was the parent material (schists).

Available soil water capacity was calculated from soil depth, soil organic matter and soil texture, using the model proposed by Domingo-Santos et al. (2006). The fertility rate of 3-PG, which varies between 0 and 1, was evaluated according to the information on parent material, soil depth, soil pH, C:N ratio of organic matter, soil nutrient concentrations and texture, considering reference values for the optimum soil conditions for growth in the area (Table 3). The forests soils in the region are highly acidic and usually shallow, with fertility directly related to the organic mater content and its mineralization rate or to the Al content (Álvarez et al., 2002). Foliar levels of P, Ca and Mg are usually low in *E. globulus* planted in shallow and stony soils (Merino et al., 2005). We used the approach of

Table 2
Climate data for the sites used to parameterize and validate the 3-PG model. PT are permanent plots. TP are temporary plots. T_{av} is the average temperature for the three summer and three winter months, S-W radiation is total annual short wave incoming radiation, MASW is maximum available soil water and FR is the fertility rate.

Site	Treatment type	Site index (m)	Age measurement (years)	T_{av} summer (°C)	T_{av} winter (°C)	Annual frost (days)	Precipitation (mm)	S-W radiation MJ m^{-2}year^{-1}	Soil depth (cm)	MASW	FR
Xermade	PT	14	3, 4, 5, 6, 8, 14	16	6.3	14	2100	4480	50	145	0.5
Antas	PT	12	3, 4, 5, 6, 8, 14	17	6.2	20	1180	4770	85	170	0.5
Lalín	PT	10	3, 4, 5, 6, 8	16.2	5.5	64	1360	4770	15	30	0.15
Guitiriz	TP	17	7	17.8	6.2	16	1090	4460	120	300	0.7
Begonte	TP	11	14	16.5	6.1	21	1110	3220	30	50	0.3

Table 3
Soil parameters for the upper 30 cm layer used to propose a fertility rate for the three permanent trials of *Eucalyptus nitens*. FL is fertility limitation, WL is water limitation, O is oxygen, M is management and T is topography. MASW is maximum available soil water.

Soil property	Optimum	Xermade	Antas	*Lalín*	*Guitiriz*	*Begonte*
pH (water)	5.5	4.4	4.3	4.4	5.1	4.9
OM (%)	10	10	9.8	5.6	4.6	7.9
C/N	10	13.5	11.4	15.4	10.2	12.5
N (%)	0.5	0.43	0.5	0.21	0.26	0.38
P (kg ha^{-1})	200	13	36	9	36	85
K (kg ha^{-1})	400	230	450	170	480	89
Mg (kg ha^{-1})	300	76	324	164	247	28
Ca (kg ha^{-1})	650	279	830	100	357	53
Soil depth (cm)	100	50	85	20	80	40
FL	1	0.42	0.68	0.33		
Sand (%)	60	79	80	72	62	57
Lime (%)	25	14.7	16	16	28	38
Clay (%)	15	6.3	4	12	10	5
Parent material	–	Slate	Granites	Slate	Schist	Schist
WL		0.8	0.6	0.4	1	1
OL	1	1	1	0.8	1	0.3
ML	1	0.6	0.6	0.4	0.6	0.4
TL	1	0.6	0.6	0.2	1	0.9
Initial FR	1	0.61	0.67	0.39	0.76	0.54
Tuned FR		0.62	0.66	0.40		
MASW (mm)		145	170	30	150	70

Almeida et al. (2010), which takes into account the main factors that limit nutrient availability (Eq. (1)):

$$FR = 0.4\,FL + 0.2\,WL + 0.1\,OL + 0.2\,ML + 0.1\,TL \quad (1)$$

where FL is fertility limitation, WL is water limitation, O oxygen, M management and T topography. The limitation (L) may be null (1.0), slight (0.8), moderate (0.6), strong (0.4) and very strong (0.2). A complete soil analysis including available content of nutrients and soil expert assessment was used to establish the initial FR values for the three PT and the two TP. In all plots, fertilizer was initially added to the planting hole, and had a short-lived effect. During calibration, FR was allowed to vary within ±0.1 units from the field estimation values (Fontes et al., 2006).

2.4. Silvicultural regimes and model evaluation

Details of the silvicultural alternatives were obtained by a literature review of pruning and thinning experiments in the species (Medhurst et al., 2001; Gerrand et al., 1997), as well as from the result of local trials. The first regime is usually applied to produce chipwood and bioenergy, i.e., as in the plots inventoried, whereas the alternative regime is used to produce mainly solid wood at the end of the rotation.

(1) Fiber alternative, with no thinning or pruning. This regime was used for the three PT to validate the 3-PG calibration, tune the FR and evaluate the differences between the empirical and the process-based model. The observed data were used to initialize both the empirical model and 3-PG at age 3 years, and the models were then run until the age of the last measurement. The accuracy of the 3-PG model in relation to the empirical model was evaluated with the root of the mean square residue (RMSE) and the model efficiency (ME). The mean residue (MRES) was used to evaluate bias (Stape et al., 2004).
(2) Integrated scheme. Planting 1400 seedlings, pruning to 2 m at age 2–3 years (for the high and low productivity levels, respectively), to 4 m at age 3–4 years of selected 700 stems per ha, thinning of no pruned stems at age 3–4 and increase of pruned height to 6 m at age 4–5 years. Further thinning at age 6–8 years, leaving 350 trees per ha, rotation age 18 years. The low productivity site (Begonte) was pruned or thinned later on than for Guitiriz, as the age ranges showed. Early pruning was assumed to be necessary to always remove live branches.

The 3-PG was the only model applied to simulate the changes in the stand for alternative 2, as the empirical model is unable to predict growth after thinning. After initializing the stand data at age 3 years, the 3-PG model was run for different stages, applying a reduction in foliage and stem mass after pruning or thinning, considering the percentage of trees removed or pruned and a ratio of reduction derived from the pruned height in relation to crown length or a ratio between average biomass of trees removed to average biomass of trees before thinning equal to 0.6.

Log assortments were calculated from an inside bark taper function, considering the volume of logs up to a height of 6 m as clear wood. The 3-PG output mean stand diameter (B) was used to calculate the percentage of clear wood.

3. Results

3.1. Model calibration

The target of the parameterization process was to establish as many parameters specific to *E. nitens* as possible with the information available. This enabled the parameterization of the allometric relationships and partitioning, specific leaf area of juvenile trees, bark and branch fraction, basic density, age modifier and mortality. Most parameters reported to have a high ranking in sensitivity for stand volume or leaf area by Esprey et al. (2004) were given species-specific values. Overall, 21 out of 45 parameters were fitted or observed, as follows:

(1) the parameters related to allometry and partitioning were derived from the following set of equations:

$$W_s = 0.092\,B^{2.4493} \quad \text{Adj. } R^2 = 0.84 \quad n = 48 \quad (2)$$

$$W_f = \frac{W_s}{100}\left(\frac{49.5696}{B} + 2.9648\right) \quad \text{Adj. } R^2 = 0.65 \quad n = 48 \quad (3)$$

$$B = 27.1098\,(1 - e^{-0.2346t})^{3.7046} \quad \text{Adj. } R^2 = 0.72 \quad n = 68 \quad (4)$$

where W_f is the foliage biomass (kg tree^{-1}), W_s the stem biomass (kg tree^{-1}), B the breast height diameter (cm) and t age (years).

Eq. (2) directly provided the parameters a_S and n_S (Table 4, Fig. 2). The values of the ratio between derivatives of Eqs. (3) and (2) at $B = 2$ and 20 cm and the need to compensate for the litterfall at these moments provided the estimates of $p_2 = 0.17$ and $p_{20} = 0.12$ (Table 4).

(2) The average value of the specific leaf area for young leaves (SLA_0) was 12.47 m^2 kg^{-1}, with SD = 3.7. The distribution of the values was leptokurtic, with a maximum value of 24.5 m^2 kg^{-1} and a minimum of 6.9 m^2 kg^{-1}. The observed age of leaf change is around 4 years (Table 4).

(3) The bark and branch fraction in the stem shows a decreasing trend with age, which was modelled with Eq. (5) and

Table 4
List of 3-PG parameters and values applied to *Eucalyptus nitens*. Default values are those used by Sands and Landsberg (2002) for *Eucalyptus globulus*. In the Parameterization column, *En* refers to *E. nitens* and *Eg* to *E. globulus*.

Meaning	Symbol (units)	Site or species specific	Parameterization	Value
Allometric relationships and partitioning				
Ratio foliage:stem partitioning at B = 2 cm	p_2	Species	Fitted *En*	0.17
Ratio foliage:stem partitioning at B = 20 cm	p_{20}	Species	Fitted *En*	0.12
Constant in stem mass and diameter relationship	a_S	Species	Fitted *En*	0.092
Power in stem mass and diameter relationship	n_S	Species	Fitted *En*	2.45
Maximum fraction of NPP to roots	η_{Rx}	Species	Default *Eg*	0.80
Minimum fraction of NPP to roots	η_{Rn}	Species	Resh et al. (2003) *En*	0.10
Temperature and frost modifier				
Minimum temperature for growth	T_{min} (°C)	Species	Rodríguez et al. (2009) *En*	2
Optimum temperature for growth	T_{opt} (°C)	Species	Proposed *En*	15
Maximum temperature for growth	T_{max} (°C)	Species	Rodríguez et al. (2009) *En*	32
Days of production lost for each frost day	d_F (days)	Species	Fontes et al. (2006) for *Eg*	1
Litter fall and root turnover				
Maximum litter fall rate	γ_{Fx} (per month)	Both	Moroni and Smethurst (2003) *En*	0.022
Litter fall rate for very young stands	γ_{F0} (per month)	Both	Default *Eg*	0.001
Age at which litter fall rate = ½ (γ_{Fx} + γ_{F0})	$t_{\gamma F}$ (month)	Both	Default *Eg*	12
Average monthly root turnover	γ_R (per month)	Both	Default *Eg*	0.015
Conductance				
Maximum canopy conductance	g_{Cx} (m s^{-1})	Species	Default *Eg*	0.02
Maximum stomatal conductance	g_{Sx} (m s^{-1})	Species	Default *Eg*	0.006
Defines stomatal responses to VPD	k_g (k Pa^{-1})	Species	Default *Eg*	0.05
Canopy boundary layer conductance	g_B (m s^{-1})	Both	Default *Eg*	0.2
Fertility effects				
Value of m when FR = 0	m_0	Species	Default *Eg*	0
Value of f_N when FR = 0	f_{N0}	Species	Landsberg et al. (2003) for *Eg*	0.6
Soil water modifier				
Moisture ratio deficit which gives f_θ = 0.5	c_θ	Site	Sandy loam texture	0.6
Power of moisture ratio deficit in f_θ	n_θ	Site	Sandy loam texture	7
Age modifier				
Maximum age used to define relative age	years	Species	Observed *En*	20
Power of relative age in f_{age}	n_{age}	Species	Fitted *En*	5.7
Relative age to give f_{age} = 1/2	r_{age}	Species	Fitted *En*	0.86
Specific leaf area				
Specific leaf area at age 0	SLA_0 (m^2 kg^{-1})	Species	Fitted *En*	12.5
Specific leaf area for mature leaves	SLA_1 (m^2 kg^{-1})	Species	Medhurst and Beadle (2001) *En*	4.2
Age at which $SLA = (SLA_0 + SLA_1)/2$	t_{SLA} (years)	Species	Observed *En*	4
Stem mortality and self-thinning				
Mortality rate for large age	γ_{Nx} (% year^{-1})	Site (*SI* 17, 11)	Fitted *En*	1.8, 0.6
Seedling mortality rate	γ_{N0} (% year^{-1})	Site (*SI* 17, 11)	Fitted *En*	0.7, 0.25
Age at which mortality rate has median value	$t_{\gamma N}$ (year)	Site (*SI* 17, 11)	Fitted *En*	9, 9
Shape of mortality response	$n_{\gamma N}$	Species	Default *Eg*	1
Maximum tree stem mass for 1000 trees ha^{-1}	w_{Sx1000}	Species	Fitted *En*	285
Fraction mean single-tree biomass lost per dead tree	m_F, m_R, m_S	Species	Observed *En*	0.32
Branch and bark fraction				
Branch and bark fraction at age 0	p_{B0}	Species	Fitted *En*	0.71
Branch and bark fraction for mature stands	p_{B1}	Species	Fitted *En*	0.2
Age at which $p_B = (p_{B0} + p_{B1})/2$	t_{pB} (years)	Species	Fitted *En*	3.66
Basic density				
Minimum basic density for young trees	ρ_{min} (Mg m^{-3})	Species	Fitted *En*	0.32
Maximum basic density for older trees	ρ_{max} (Mg m^{-3})	Species	Observed *En*	0.51
Age at which rho = $(\rho_{min} + \rho_{max})/2$	t_ρ (years)	Species	Fitted *En*	7.16
Production and light interception				
Maximum canopy quantum efficiency	α_{Cx} (mol mol^{-1})	Species	Proposed *En*	0.07
Ratio NPP/GPP	Y	No	Default *Eg*	0.47
Extinction coefficient for absorption of PAR	k	Species	Default *Eg*	0.5
Age at canopy cover	t_C (years)	Both	Observed *En*	3
Maximum proportion of rainfall evaporated from canopy	I_{Cx}	Species	Huber and Iroumé (2001) *En*	0.32
LAI for maximum rainfall interception	L_{IC}	Species	Default *Eg*	2

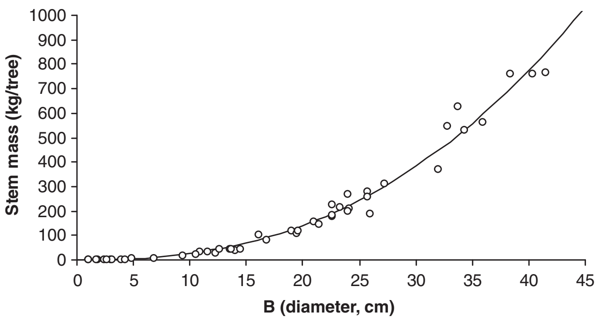

Fig. 2. Relationship between stem mass and breast height diameter.

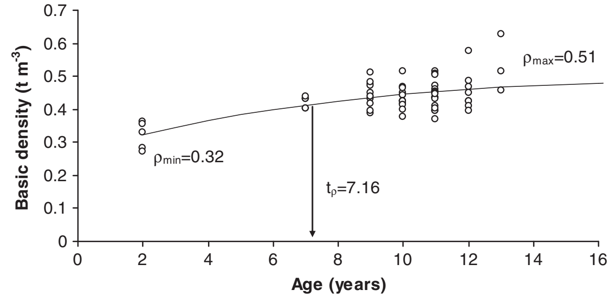

Fig. 4. Relationship between basic density and age. Observed values of 62 trees are represented by open circles and the fitted equation by a line. The values of the 3-PG parameters obtained from the relation are shown.

allowed to set three parameters: $p_{B0} = 0.71$, $p_{B1} = 0.20$ and $t_{pB} = 3.66$ (Fig. 3):

$$p_{BB} = 0.2 + 0.51\, e^{-0.1887\, t} \quad \text{Adj.}R^2 = 0.66 \quad n = 48 \tag{5}$$

(4) Three parameters were obtained from the relationship between basic density and age through Eq. (6). The young trees were considered those of age 2 years, whereas the basic density of older trees was considered asymptotic (Fig. 4).

$$BD = 0.51 - 0.1873\, e^{-0.1319(t-2)} \quad \text{Adj.}R^2 = 0.40 \quad n = 62 \tag{6}$$

(5) A model of age modifier was obtained, considering a maximum age of 20 years, according to the range of plot ages. For each plot, the observed value of the age modifier was obtained from the ratio of actual current annual increment (CAI) to maximum CAI for the same site index and initial density. The age modifier was set at 1 for plots where age <age of maximum CAI. The inverse-potential model proposed by Sands (2002) was fitted (Eq. (7), see Fig. 5).

$$f_{age}(t) = \frac{1}{1 + (t/0.859\,20)^{5.706}} \quad \text{Adj.}R^2 = 0.92 \quad n = 68 \tag{7}$$

(6) The parameters for the density independent mortality model were obtained after application of the Candy (1997) model to site indices of 17 and 11, to obtain the changes in the mortality rate (% year^{-1}) and thus the mortality rate for older age, for seedlings and the age at which the mortality rate has median value. Those parameters were considered site-specific, as the mortality rate was very different for each site index. A default value of 1 for the shape of the mortality response was considered.

In the case of the density dependent mortality model, the maximum tree stem mass for a density of 1000 trees per ha was obtained by plotting density in relation to average tree biomass for

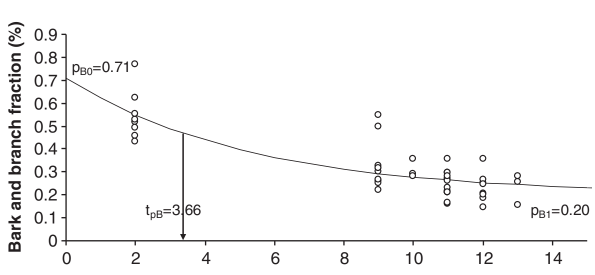

Fig. 3. Relationship between bark and branch fraction and age. Observed values are represented by open circles and the fitted equation by a line. The values of the 3-PG parameters obtained from the relation are shown.

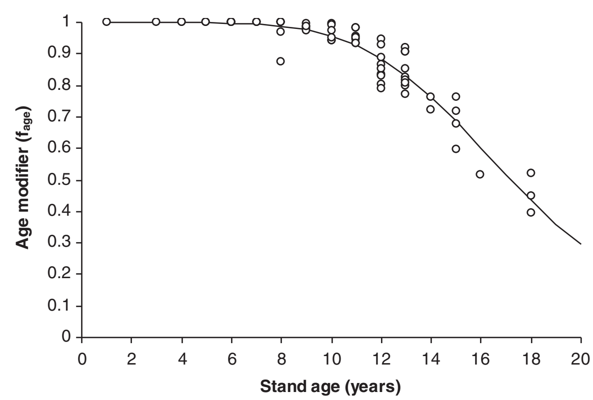

Fig. 5. Relationship between the age modifier of 3-PG and age. The values calculated for 68 plots are represented by open circles and the fitted equation by a line.

the overstocked plots. A maximum value of 285 kg was obtained (data not shown). The fraction of mean single-tree biomass lost per dead tree was the average observed in the network of 68 plots: 0.32 (Table 4).

3.2. Model testing and validation

The performance of the 3-PG model was compared with data from the permanent trials and the predictions of the empirical model. In this process, the initial values of FR were those derived from field measurements, but they were allowed to vary by ±0.1 U during the final model validation, because the exact values cannot be known (Fontes et al., 2006). The empirical model and model 3-PG are compared in Figs. 6–8, considering four model outputs (under bark volume, mean diameter, basal area and foliar biomass) and the observed changes in the three permanent trials. The observed quadratic mean diameter was considered for comparison with the predicted value of 3-PG. There was a close similarity of the growth trajectories predicted by 3-PG and the volume data in the case of Lalín and Xermade, whereas 3-PG tended to slightly overestimate the values for ages up to 10, and to slightly underestimate values thereafter in the Antas trial. The 3-PG predictions of mean diameter and basal area were close to the observed values, although they tended to produce underestimations because of the positive values of MRES in the three plots. The variable most difficult to predict was foliar biomass, which tended to be slightly overestimated, although the ME of 3-PG was always higher than 0.87 (Table 5). Overall, the 3-PG model performed better than the empirical model in all the cases. The bias was smaller in the case of 3-PG, and the empirical model tended to overestimate

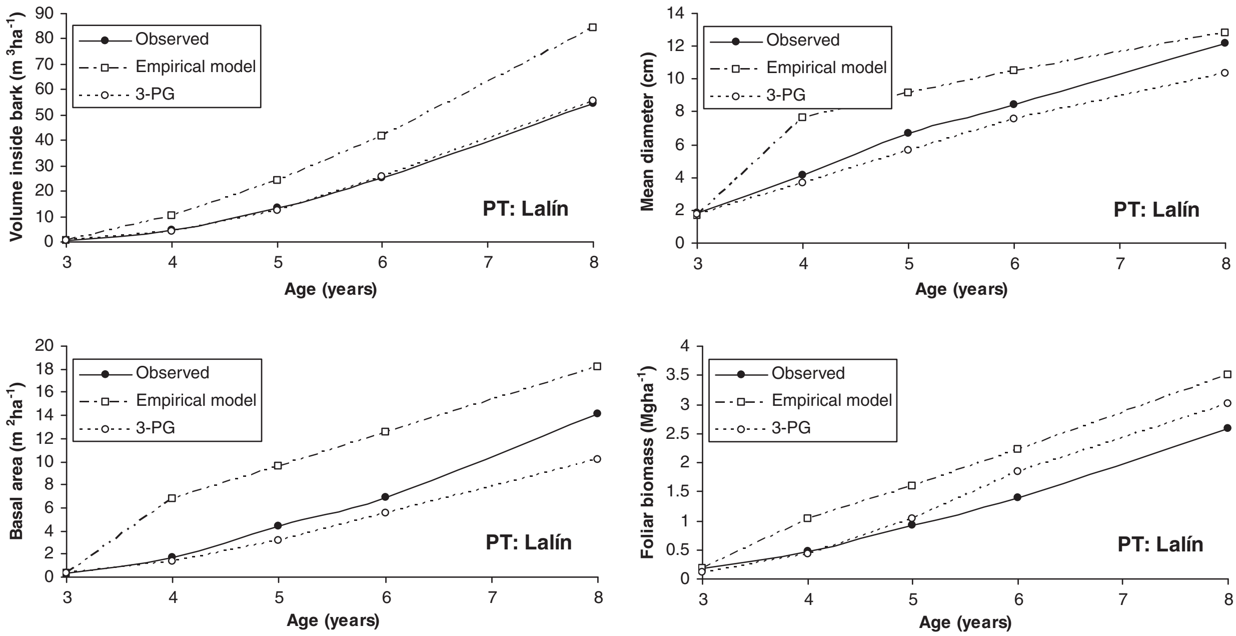

Fig. 6. Observed changes in the inside bark volume, mean diameter, basal area and foliar biomass in the permanent trial Lalín in relation to the predictions of 3-PG and the empirically based model.

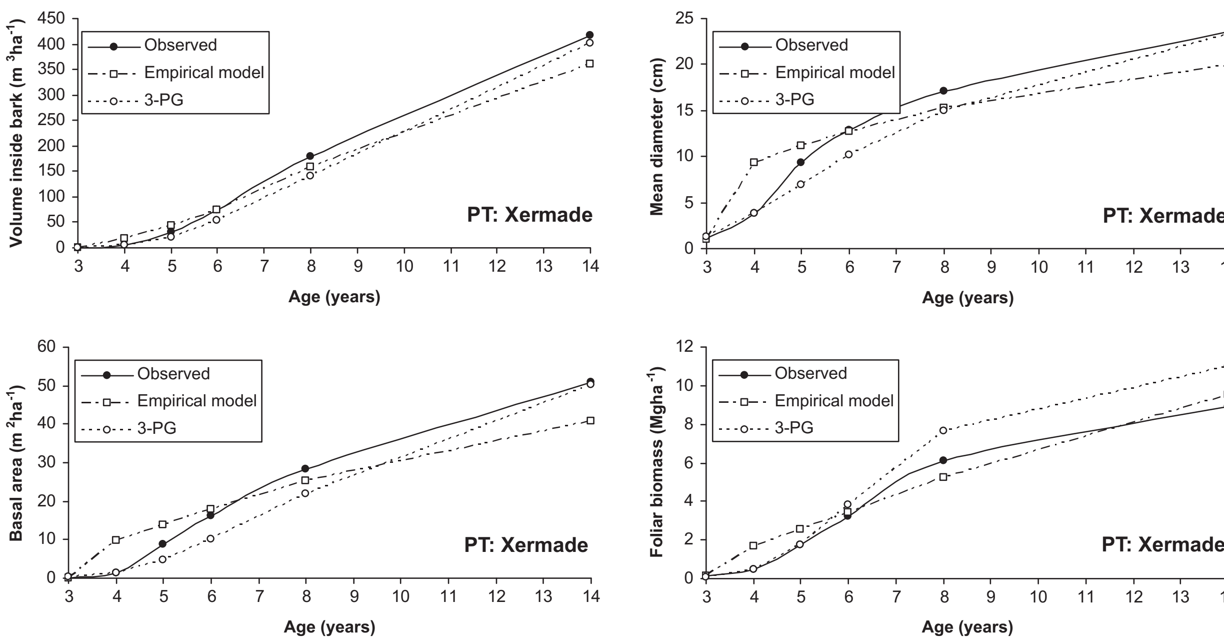

Fig. 7. Observed changes in the inside bark volume, mean diameter, basal area and foliar biomass in the permanent trial Xermade in relation to the predictions of 3-PG and the empirically based model.

the values of the four variables for ages less than 6 years, as suggested by the MRES values (Table 5). The empirical model failed completely in forecasting the growth of the plot with poorer growth conditions. The precision of 3-PG was higher in most cases.

It may be argued that the changes in stand parameters simulated with the empirical model are determined once the initializing values of density at age 3 years and site index are established, whereas in the case of 3-PG the fertility rate can be fine-tuned (see Landsberg et al., 2001). The fine tuning process involved marginal changes to the previously established FR values (Table 3). As the predictions obtained for four output variables were reasonable in the three trials of study, we can consider that the parameterization of 3-PG is sound enough to apply the model to alternative silvicultural regimes, such as the solid wood regime.

3.3. Sensitivity analysis

A sensitivity analysis was carried out for six 3-PG parameters considered to be the most important for explaining growth differences, or which were given different values for previous parameterization to *E. globulus*: maximum canopy quantum efficiency (α_{Cx}), the value of f_N when FR = 0 (f_{N0}), the minimum allocation to

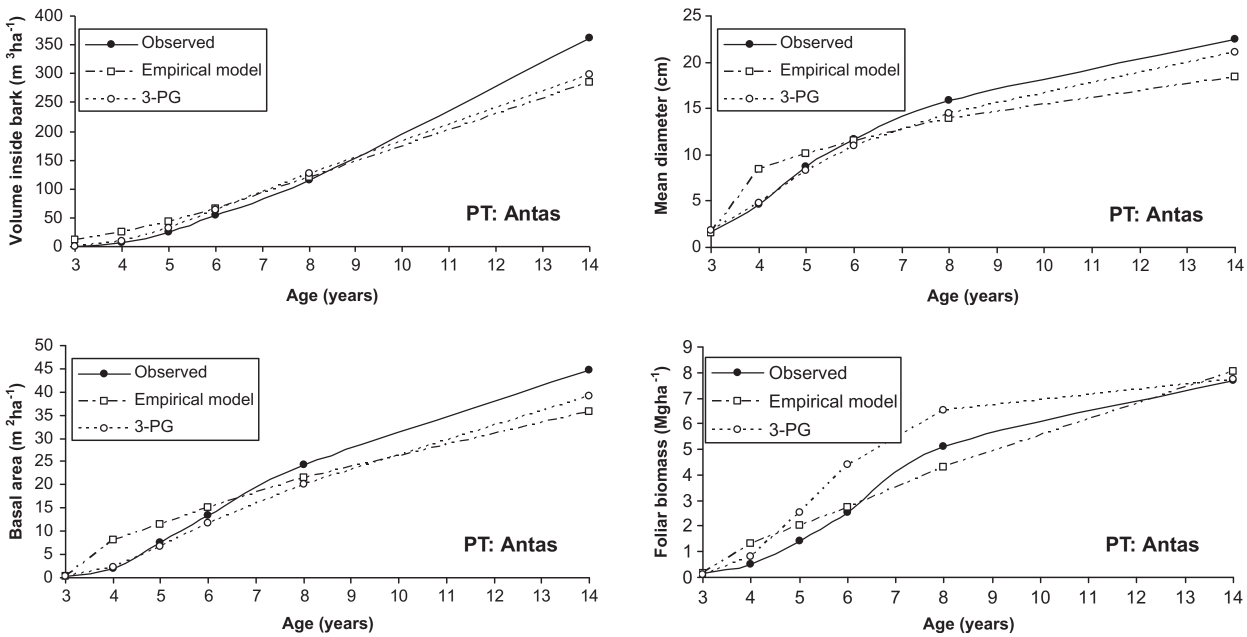

Fig. 8. Observed changes in the inside bark volume, mean diameter, basal area and foliar biomass in the permanent trial Antas in relation to the predictions of 3-PG and the empirically based model.

Table 5
Values of mean residue (MRES) and root mean square errors (RMSE), both evaluated in absolute and relative terms for the 3-PG and the empirical based model.

Trial	Variable	Mean	3-PG model			Empirical model		
			MRES	RMSE	ME	MRES	RMSE	ME
Lalín	V_{ub} (m^3 ha^{-1})	19.67	0.12	0.65	0.99	−12.64	16.23	0.44
	B (cm)	6.03	0.88	1.05	0.93	−1.69	2.13	0.71
	G (m^2 ha^{-1})	5.50	1.41	1.96	0.87	−3.98	4.48	0.32
	W_f (Mg ha^{-1})	1.11	−0.17	0.28	0.91	−0.59	0.67	0.50
Xermade	V_{ub} (m^3 ha^{-1})	118.1	14.38	19.52	0.98	8.67	26.07	0.97
	B (cm)	10.4	1.19	1.68	0.96	−0.26	2.86	0.88
	G (m^2 ha^{-1})	17.6	2.86	3.94	0.96	−0.39	5.93	0.91
	W_f (Mg ha^{-1})	3.4	−0.70	1.08	0.90	−0.33	0.72	0.96
Antas	V_{ub} (m^3 ha^{-1})	93.6	5.47	27.24	0.96	2.31	34.24	0.94
	B (cm)	10.0	0.63	0.91	0.98	0.18	2.49	0.89
	G (m^2 ha^{-1})	15.3	1.99	2.95	0.97	−0.02	4.88	0.92
	W_f (Mg ha^{-1})	2.9	−0.78	1.06	0.87	−0.18	0.55	0.96

roots (η_{Rn}), the maximum canopy conductance (g_{Cx}) and the stem allometric parameters (a_S and n_S).

The effects of −20 and +20% changes in the selected parameters on predicted estimates are shown in Fig. 9. Basal area (G) and mean diameter at breast height (B) are the outputs most affected by these changes, particularly in the case of the power parameter: reducing n_s by 20% can affect G by 307% and B by 72%. Foliar biomass (W_f) was also affected. The 3-PG outputs showed sensitivity to maximum canopy conductance (Fig. 9), except in the case of B. The biomass pools and G were highly sensitive to maximum canopy quantum efficiency. The sensitivity of most outputs to the minimum site nutrition growth modifier was also high. Only the two biomass components analyzed were slightly sensitive to partitioning to roots or canopy conductance.

The results from this sensitivity analysis indicate the need for further exploration of differences in allometry derived from changes in provenances, breeding materials and site conditions. The sensitivity found to α_{Cx}, η_{Rx} or g_{Cx} is consistent with that found in previous studies (Almeida et al., 2004) and demonstrates the interest in determining species-specific values for these parameters, rather than the default values considered for *E. globulus*.

3.4. Simulation of a solid wood regime for two representative plots

Once the model was shown to be adequately parameterized, it was used to simulate the changes in stand parameters for the solid wood silvicultural regime in the temporary plots representative of high and low productivity levels (Guitiriz and Begonte, see Table 2). The 3-PG model was applied in different stages, considering separately the reduction in stand biomass due to pruning and thinning activities. The predictions until age 18 years are shown in Fig. 10. The observed values in the two plots and the expected evolution from 3-PG without pruning or thinning are also represented to show the probable reduction in productivity derived from the thinning. The observed values are clearly higher than the trajectories forecast by 3-PG for the solid wood regime, because the measured tree densities were much higher (1089 trees ha^{-1} in Guitiriz and 1178 trees ha^{-1} in Begonte). For each of the three harvest applied (two thinning and the clearcutting), the assortment of forest products was calculated (Table 6). The average diameter at clearcutting (B from 3-PG, cm) was 41 for the high productivity site but only 33 for the low productivity plot. Application of a taper function available for the species provided the estimated average diameter at

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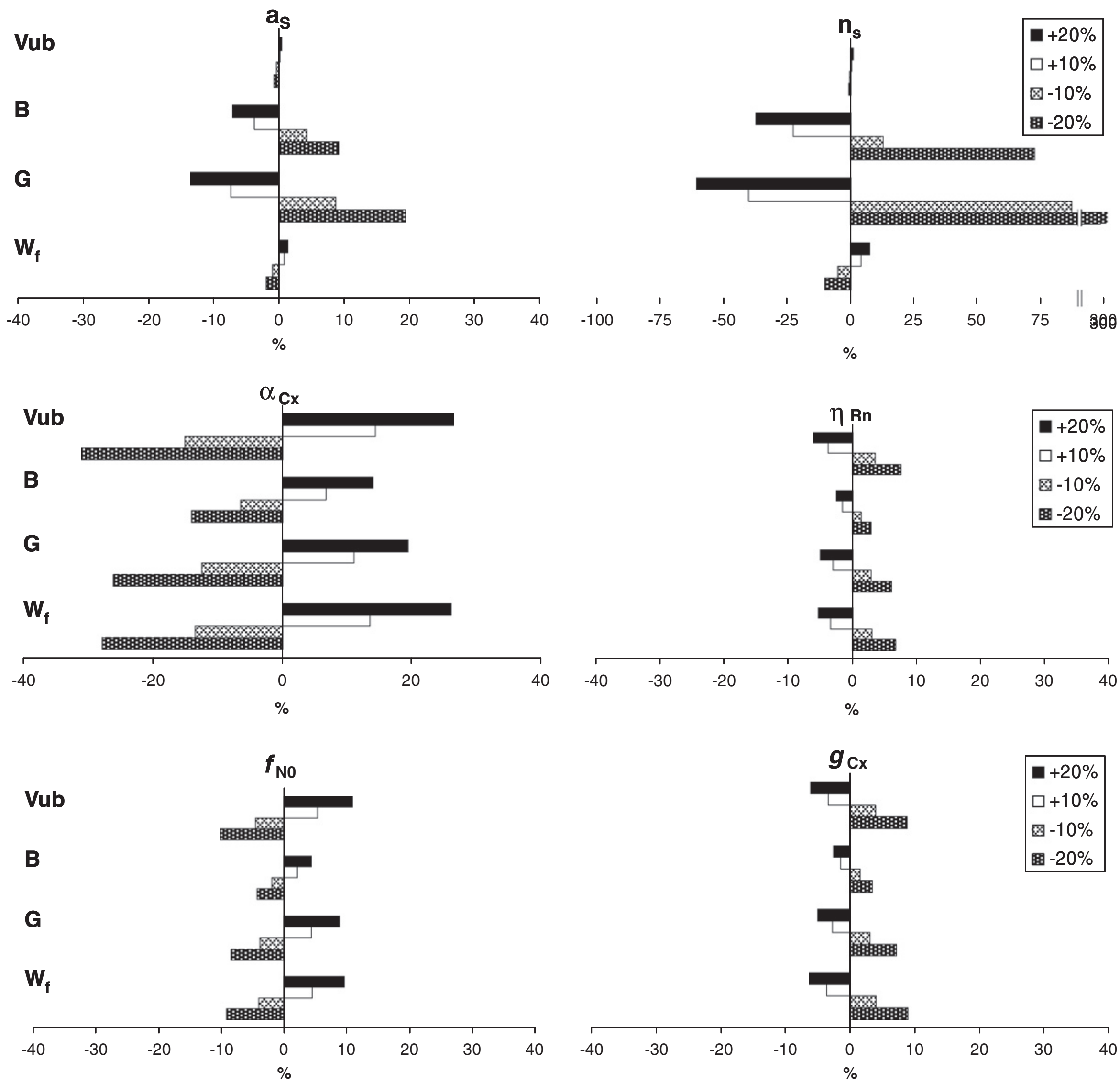

Fig. 9. Estimated sensitivity of selected 3-PG outputs to the parameters: stem constant (a_S), stem power (n_S), maximum canopy quantum efficiency (α_{Cx}) minimum biomass partitioning to roots (η_{Rn}), minimum site nutrition growth modifier (f_{N0}) and maximum canopy conductance (g_{Cx}). The bars show the effects of +20,+10, −10 and −20% variation in each parameter in inside bark volume (V_{ub}), breast height diameter (B), basal area (G) and foliage biomass (W_f).

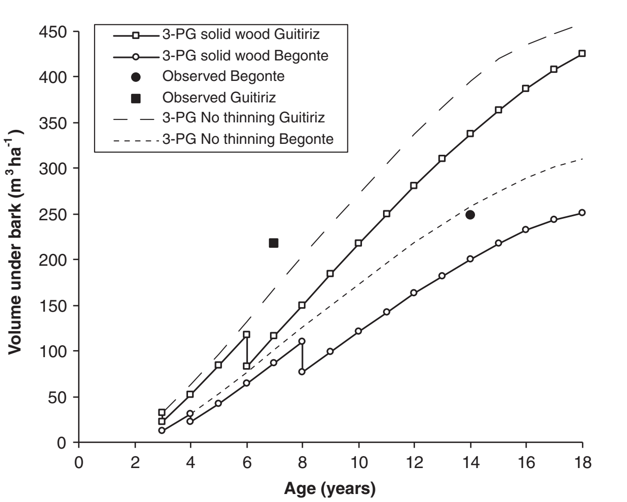

Fig. 10. Changes in the inside bark simulated with 3-PG for two productivity levels.

6 m: 33 cm and 24 cm, respectively. These results show the suitability of clearwood systems in highly productive plantations and the possibility of combining three different products throughout the rotation in an integrated scheme. The values of MAI derived from Table 6 and are 33.5 and 21.1 $m^3\ ha^{-1}\ year^{-1}$ for the two productivity levels.

4. Discussion

4.1. 3-PG calibration

Procedures for calibrating 3-PG and the ability of the model to fit a wide range of forest growth data sets were established by Landsberg et al. (2003). The parameterization carried out in this study was limited to information obtained from plots in which allometric relations, biomass, mortality, timber growth and timber density assessment were the main target, and it was not possible to propose a specific value for each of the 3-PG parameters. The validation was made with data from a limited number of permanent trials in the area of Northern Spain where most of the

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Table 6
Assortment of forest products obtained from the harvests simulated by the 3-PG model for two productivity levels. V_{ub} pulp refers to inside bark volume obtained from unpruned logs or at thinning. V_{ub} clean is inside bark volume obtained from pruned logs at clearcut.

	Site index 17				Site index 11			
	Age (years)	Biomass (t ha^{-1})	V_{ub} pulp (m^3 ha^{-1})	V_{ub} clean (m^3 ha^{-1})	Age (years)	Biomass (t ha^{-1})	V_{ub} pulp (m^3 ha^{-1})	V_{ub} clean (m^3 ha^{-1})
First thinning	3	6.9	–	–	4	6.4	–	–
Second thinning	6	8.3	35.3	–	8	7.0	33	–
Clearcut	18	42	240.3	184.8	18	24.8	145.7	105.8
Total		57.2	275.7	184.8		38.2	178.7	105.8

plantations of this species are located. The use of four output variables of 3-PG for this validation process show the ability of the model to forecast growth at least with a similar precision as the empirical models currently in use.

The values assigned to the parameters of biomass allocation and partitioning should be considered specific to Northern Spain and the constant and power in the stem biomass and diameter relationship should even be tested in other areas not covered in this study, such as Cantabria. The allometry of *E. nitens* has been studied, particularly in Tasmania (Medhurst et al., 1999; Pinkard and Battaglia, 2001), often with the goal of obtaining useful relationships to predict leaf area. Previous studies on *E. globulus* show that biomass partitioning and allometry are the main drivers of the poor performance of 3-PG when applied with the original Australian parameters and so a specific calibration for Portugal was necessary (Fontes et al., 2006). The sensitivity analysis carried out in the present study shows the dramatic effect of the power parameter n_S on basal area and breast height diameter predictions.

The average value of SLA_0 in Spain is higher than reported values for healthy leaves of *E. nitens* seedlings in Tasmania (8.3 m^2 kg^{-1}, Pinkard et al., 2006). A decreasing trend has been reported, with values of 4.75–4.93 in 7-year-old stands (Pinkard and Neilsen, 2003) and the value used in this study, calculated as the weighted average of the values observed by Medhurst and Beadle (2001) in 8-year-old stands. The equation proposed in the present study for the changes in basic density with age provide lower values than those observed for 9-year-old stands in Tasmania (0.49 Mg m^{-3}, Raymond and Muneri, 2001).

Nutrition is clearly an important variable for forest growth, and even if a numerical procedure was applied to calculate FR (Almeida et al., 2010), it seems reasonable to consider FR as a tuneable parameter (Fontes et al., 2006). Although some studies have considered the FR to be correlated with SI (Dye et al., 2004), we assigned the values exclusively according to soil expert knowledge, by comparison with the optimum values, which are known to provide growth conditions not limited by nutrition.

The maximum photosynthetic rate α_{Cx} = 0.07 mol C (mol quanta)$^{-1}$ considered in this study is the maximum value proposed by Landsberg et al. (2003) as realistic and applicable to fast growing eucalypts species. The sensitivity analysis shows important changes in the predictions derived from modifications of this parameter. This value is consistent with the parameterization for *E. globulus* (Sands and Landsberg, 2002; Fontes et al., 2006) and the higher rate for net assimilation for *E. nitens* reported by Battaglia et al. (1996) in relation to *E. globulus*.

4.2. Predictions of E. nitens growth after thinning

The 3-PG has been already applied to predict the development of thinned stands and it has been shown that, under usual thinning regimes, a variety of thinning intensities can be adequately described by a simple multiplicative model relating the proportion of volume and foliage mass removed to the corresponding proportion of stem number (Landsberg et al., 2005). This provides the necessary information about the reduction in all state variables at each thinning to run the model between thinning events, as carried out in this study.

Even so, there may be some limitations derived from the dramatic change in leaf area resulting from a high intensity of thinning. The discontinuous canopy resulting from thinning affects the radiation available to individual trees and may alter the structure of tree crowns and the stand as a whole (Medhurst and Beadle, 2001). These authors found that the relative rate of increase in LAI was much greater in stands of lower stocking (more intensively thinned), suggesting a higher proportion of assimilated carbon being allocated to canopy development in these widely spaced stands. Moreover, the Beer–Lambert law for estimating light attenuation is more appropriate for closed canopies, and heavily thinned stands are unlikely to return to full canopy closure (Medhurst et al., 2001).

The growth response to thinning has been quantified for *E. nitens* in Tasmania (Gerrand et al., 1997) and also in Chile (Muñoz et al., 2005). The latter authors found the volume yield at 14 years in plots thinned to 400 stems per ha was 56–75% of that in non-thinned stands. On the other hand, for thinned plots at age 18 years and productivity similar to the *SI* 17 m, the Chilean growth simulator EUCASIM (2010) estimated 72–85% of the yield of unthinned plots. This means that *E. nitens* has a good ability to recover growth after thinning, even for intense fellings (Gerrand et al., 1997), and the predictions obtained by applying 3-PG are probably underestimates. The response to thinning may be attributed to the effects of increase in *SLA* after thinning, a reduction in the attenuation of light in the crown and increases in the photosynthetic capacity of old and mature foliage in the lower and middle crown zones (Medhurst and Beadle, 2005). This suggests the need to refine some of the 3-PG parameters (k, SLA_1, α_{Cx}) to apply the model after thinning, which was not possible with the information available in the present study.

Another limitation of the 3-PG model is that it produces the mean stand diameter *B* as output, although it is the stem size distribution that is the most important feature in the commercial value of timber. Landsberg et al. (2005) fitted regressions relating the parameters of the Weibull distribution to *B* and obtained results that were good enough to provide preliminary indications of likely product quality. This may be a further step in improving the predictions made in the present study.

The present study provides a set of values for the parameters to include in 3-PG in order to predict *E. nitens* stand growth and development. The model can be used to simulate the stand evolution for various silvicultural systems or using observed climate data instead of the average climate values used in this study.

The results obtained in the simulations indicate that the silvicultural regimes described are likely to produce clear wood, particularly in highly productive areas. The existence of a market for biomass makes the thinning to waste operations proposed in other studies unnecessary (Candy, 1997), showing the possibility of integrating biomass and solid wood production in the same stand. Medhurst et al. (2001) recommended a final density in the range of 200–300 trees per ha, which would improve the growth during a rotation of 20–25 years, thus largely preventing under-utilization of site resources. Washusen et al. (2009) found that trees of equivalent size grown under different competitive regimes did not differ substantially in their performance in sawmill processing.

5. Conclusions

The parameterization of the process-based model 3-PG proposed for *E. nitens* plantations in Northern Spain provided accurate and unbiased predictions of the inside bark volume for three permanent trials of the species. The predictive ability for mean diameter, basal area and foliar biomass was better than that provided by the empirical model available. An alternative silvicultural regime aiming to obtain clearwood as the main product, integrating the production of pulpwood and biomass for bioenergy was simulated using the model 3-PG, which can be used to quantify the timber and biomass yield for this regime and for the conventional pulpwood regime currently applied.

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