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

César Pérez-Cruzado [a], Fernando Muñoz-Sáez [b], Fernando Basurco [c], Guillermo Riesco [a], Roque Rodríguez-Soalleiro [a,*]

[a] Unit of Sustainable Forest Management, University of Santiago, E-27002 Lugo, Spain
[b] University de Concepción, Victoria 631, Casilla 160 – C Chile
[c] CIT Ence, Lourizán, E-36153-Pontevedra, Spain

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A B S T R A C T

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

* Corresponding author. Tel.: +34 982 285900x23107; fax: +34 982 285926.
E-mail address: roque.rodriguez@usc.es (R. Rodríguez-Soalleiro).

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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.

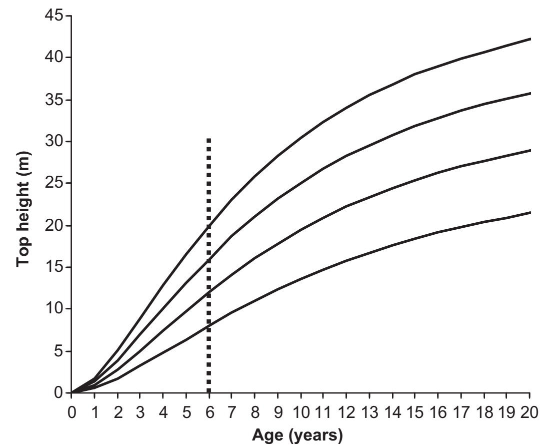

Fig. 1. Site index system for *Eucalyptus nitens* in Northern Spain, showing the changes in top height for the productivity range observed in the area.

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