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Resource communication. Individual-tree growth model for radiata pine plantations in northwestern Spain

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Abstract

Individual-tree basal area and height increment models were developed with data from 130 permanent plots of *Pinus radiata* D. Don located in Galicia (northwestern Spain). Mixed-models techniques were used for model fitting. Covariates acting at tree and stand level were included as fixed effects. Estimated values of stand variables obtained from aggregation of individual-tree predictions were used in model evaluation. The developed models accounted for 54% of the variability in basal area increment and 36% of the variability in height increment, with mean errors of 16 cm^2 and 0.36 m, respectively. These models, along with an existing individual-tree mortality model, constitute a whole individual-tree growth model that can be used to simulate forest management alternatives, helping in forest managers' decision making.

Key words: mixed-effects modeling; *Pinus radiata*; Galicia.

Resumen

Comunicación de recurso. Modelo de crecimiento de árbol individual para plantaciones de pino radiata en el noroeste de España

En este estudio se han desarrollado modelos de incremento en sección normal y altura de árbol individual, utilizando datos de 130 parcelas de *Pinus radiata* D. Don localizadas en Galicia. La técnica de modelos mixtos se utilizó en el ajuste de los modelos. Se incluyeron covariables que actúan a nivel de árbol y a nivel de rodal como efectos fijos en los modelos. En la evaluación de los modelos se utilizaron estimaciones de variables de rodal obtenidas por agregación de las predicciones de árbol individual. Los modelos desarrollados explicaron el 54% de la variabilidad en el incremento en sección normal y el 36% de la variabilidad en el incremento en altura, con errores medios de 16 cm^2 y 0.36 m, respectivamente. Estos modelos, junto al modelo de mortalidad de árbol individual existente, forman un modelo de crecimiento de árbol individual que puede utilizarse para simular alternativas de gestión forestal, ayudando a la toma de decisiones de los gestores forestales.

Palabras clave: modelo de efectos mixtos, *Pinus radiata* D. Don; Galicia.

Introduction

Radiata pine (*Pinus radiata* D. Don) is the most commonly used exotic conifer in reforestations in Spain, especially in northern Spain, where it covers approximately 270,000 ha (DGCN, 1998). In Galicia (northwestern Spain) it is estimated to cover 90,000 ha (Xunta de Galicia, 2001). Related studies mainly refer to stand growth and yield and to ecological and silvicultural aspects. Yield tables (Sánchez *et al.*, 2003) and a dynamic stand growth model (Castedo-Dorado *et al.*, 2007) have been developed for Galicia.

Individual-tree growth models provide more detailed information than other modeling approaches (Gadow and Hui, 1999; García, 2003) and usually perform better than stand growth models for short term projections (Burkhart, 2003).

The objective of the present study was to develop distance-independent individual-tree basal area and height increment models for even-aged radiata pine

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plantations in Galicia (northwestern Spain) to be combined with an existing mortality model and form a whole individual-tree growth model.

Methodology

Data

130 plots located in Galicia, representing the existing range of ages, stand densities and sites, were used (stand basal area –*G*– ranging from 6.6 to 70.6 m^2ha^{-1}, stems per hectare –*N*– ranging from 192 to 3,936, dominant height –*H*– ranging from 6.8 to 35.2 m, and age –*t*– ranging from 8 to 47 years). Diameter at breast height (*d*, cm, 1.3 m above ground) was measured in all the trees in each plot and total tree height (*h*, m) was measured in 30 randomly selected trees and in the dominant trees (the proportion of the 100 thickest trees per ha). 79 plots were measured in two occasions (1996 and 1999) and 51 plots were measured in three occasions (1996, 1999 and 2005). As the re-measurement interval was variable (with either 3 or 6 years between successive inventories), the method of calculating the average annual growth was used to calculate the independent variables (annual basal area and height increments).

Models

Zeide (1993) showed that many growth equations can be decomposed into two components when they are consider in the differential form, leading to simple basic models. These basic models were proposed for fitting to the database.

The inclusion of stand and tree variables and competition indices in these basic forms was tested using linear transformations and OLS techniques. Those alternatives with a variance inflation factor larger than 10 were rejected (Myers, 1990).

Because of the specific correlation structure of the experimental data (trees grouped in plots), the basic assumption about non-correlated residuals did not hold. To compensate for this, a nonlinear mixed model —including both fixed and random components— was applied.

The first-order method of Beal and Sheiner (1982), available in the NLMIXED procedure of SAS/STAT® (SAS Institute Inc. 2009) was used for model fitting.

Different combinations of model parameters were tested to be mixed. Heterocedasticity was analyzed by means of visual analysis of studentized residuals. If necessary, weighted regression was used.

The weak autocorrelation in the remeasured data was ignored because the impact of variance underestimation is likely to be masked by fitting each individual tree as an independent observation (Temesgen and Gadow, 2004).

Model comparison

Three statistical criteria were used for model comparison: root mean square error (RMSE), the model efficiency (*EF*), similar to the coefficient of determination for linear regression, and Akaike's information criterion (AIC, Akaike, 1974).Plots of observed against predicted increments and plots of residuals against predicted increments were also used for model comparison and selection.

Validation was not carried out because an independent dataset was not available, and other validation methods seldom provide any additional information compared with the fitting statistics (Kozak and Kozak 2003). Anyway, the developed equations where used together with the individual-tree mortality equation for the species in the region (Crecente-Campo *et al.*, 2009) to make simulations using the fitting data. As the accuracy of the system (i.e., the individual-tree growth model) is more important than the accuracy of the individual equations, real values of stems per hectare (*N*) and stand basal area (*G*, m^2ha^{-1}), and the diameter and height distributions in the second and three inventories were compared with the predicted values. The Kolmogorov-Smirnov test was used to compare real and predicted diameter distributions. Different *cut-off* values were tested to convert mortality estimations to live/dead trees (Crecente-Campo *et al.*, 2009).

Results and discussion

The models that performed best were:

$$ig = \alpha_0\, d^{\alpha_1}\, G^{\alpha_2} \exp\left(\alpha_3\, t + \alpha_4\, BALMOD + \alpha_5\, BAR\right) \quad [1]$$

$$ih = \alpha_0\, h^{\alpha_1}\, d^{\alpha_2}\, SI^{\alpha_3} \exp\left(\alpha_4\, t + \alpha_5\, R_{BA-D}\right) \quad [2]$$

where *ig* is the annual basal area increment (cm^2), *BALMOD* is the competition index developed by Schröder and Gadow (1999), *BAR* is a basal area ratio ($100 \cdot g/G$, where *g* is the basal area of the tree –m^2), *ih* is the annual height increment (m), *SI* is the site

Table 1. Parameter estimates and goodness-of-fit statistics for the individual-tree basal area and height increment models

Model	Fixed effects			Variance components			RMSE	EF
	Parm.	Estimate	Std. Err.	Parm.	Estimate	Std. Err.		
Basal area	α_0	0.2822	0.0288	σ^2	210.0	2.9	14.82	0.6196
	α_1	2.845	0.064	$\sigma^2_{b_0}$	0.01470	0.00121	(16.21*)	(0.5448*)
	α_2	–0.8608	0.0546	$\sigma^2_{b_4}$	0.006326	0.001178		
	α_3	–0.05018	0.00257	$\sigma^2_{b_5}$	1.676	0.242		
	α_4	–0.04286	0.01142	$\sigma^2_{b_0b_4}$	–0.004530	0.000950		
	α_5	–1.471	0.0170	$\sigma^2_{b_0b_5}$	–0.1444	0.0119		
				$\sigma^2_{b_4b_5}$	0.03648	0.01112		
Height	α_0	0.05284	0.01268	σ^2	0.1011	0.0021	0.3123	0.5157
	α_1	–0.5727	0.07344	$\sigma^2_{b_1}$	0.2644	0.0041	(0.3575*)	(0.3647*)
	α_2	0.5482	0.05977	$\sigma^2_{b_2}$	0.2198	0.0032		
	α_3	1.080	0.087	$\sigma^2_{b_1b_2}$	–0.2375	0.0017		
	α_4	–0.03272	0.00353					
	α_5	–50.01	5.46					

b_i: random parameter related with the fixed α_i parameter; σ^2: error variance of the model; σ^2_{bi}: variance associated with the random parameter b_i; σ_{bibj}: covariance between random parameters b_i and b_j. *These statistics were calculated with only the fix part of the models.

index (Diéguez-Aranda *et al.*, 2005), R_{BA-D} is a basal area ratio, raised to the power of a diameter ratio ($[g/G]^{d/Dg}$, where Dg is quadratic mean diameter –cm) and α_i are fixed parameters, common to the population.

The results for the best mixed-effects models are shown in Table 1. All parameters were significant at the 0.01 level. The plots of residuals against predicted values showed homogeneous variance patterns. An attempt was made to relate the random parameters to stand variables but no significant relationships were found.

Wykoff (1990) and Monserud and Sterba (1996) found that most of the variance explained in basal area increment was due to size factors (diameter, crown ratio), and then competition variables, primarily basal area in larger trees (*BAL*). The total variance explained was between 20% and 63%, from which only 2-6% was explained by site factors. The same was found in this study.

The height increment model showed poorer results. Similarly, Hasenauer and Monserud (1997) could only explain 14% of the observed variation. Tanaka (1988) explained so little variation in height increment ($R^2 < 0.01$) that a purely stochastic height increment model was developed instead. Other studies developed non-linear height-diameter models to obtain height estimations (e.g., Mabvurira and Miina, 2002; Palahí *et al.*, 2003), instead of developing a height increment model. Other authors (e.g., Nord-Larsen, 2006; Burkhart *et al.*, 2003) obtained similar results than in this study, explaining 37% and 46% of the observed variation, respectively.

The ability of the models developed here to handle thinning effects is associated with the variation in stand variables and competition indices that the removal of some trees causes. Past research has shown that a true thinning effect was rarely significant (e.g., Pukkala, 1989), and was then only a minor effect (Monserud and Sterba, 1996).

The fixed parts of Eqs. (1) and (2) are proposed for individual-tree basal area and height annual increment estimations of radiata pine stands in Galicia, with the parameter estimates shown in Table 1. These models plus the existing individual-tree mortality model (Crecente-Campo *et al.*, 2009) conform a whole individual-tree growth model that can be used to forecast forest management alternatives, giving accurate results (Table 2) for the entire rotation age

Table 2. Statistics obtained with the individual-tree growth model for stand basal area (*G*) and trees per hectare (*N*) projection using several *cut-off* values

cut-off	*n*	*RMSE G*	*RMSE N*
0.80	9	2.413	98.21
0.81	9	2.399	95.56
0.82	12	2.387	92.77
0.83	17	2.363	88.62
0.84	17	2.341	85.56
0.85	25	2.337	84.77
0.86	27	2.315	82.07
0.87	33	2.308	82.06
0.88	35	2.313	84.29
0.89	39	2.316	89.15
0.90	43	2.331	97.34

n: number of plots (out of 130) that failed to pass the Kolmogorov-Smirnov test.

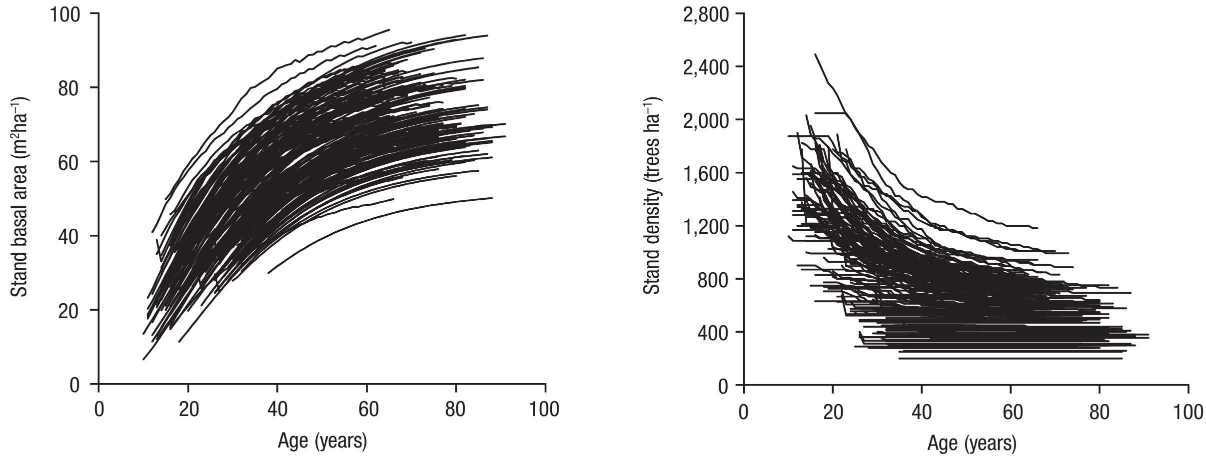

Figure 1. Simulation of the changes in stand basal area and tems per hectare by use of the whole individual-tree growth model for radiate pine stands in Galicia.

of the species in the region, i.e., 25-45 years depending on site quality. From application, a fixed *cut-off* value of 0.84 gives a good compromise between *G* and *N* estimations and the number of plots that passed the Kolmogorov-Smirnov test (Table 2). Results for 50 years of projection using a *cut-off* of 0.84 are shown (Fig. 1) in order to show the biological realism of the model.

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