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Long-term trends in dominant-height growth of black pine using dynamic models

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ABSTRACT

Black pine (*Pinus nigra* Arn.) is a pan-Mediterranean species of high ecological importance and one of the most important timber species in the area. We compare several site dependent height–age models for the species in three regions along its natural distribution area in Spain. The best model was a generalized algebraic difference approach (GADA) polymorphic model with variable asymptotes (Cieszewski, C.J., Bailey, R.L., 2000. Generalized algebraic difference approach: theory based derivation of dynamic site equations with polymorphism and variable asymptotes. *For. Sci.* 46, 116–126). There was no significant increase in error when a reduced model common to the three regions was tested instead of a full model with region-specific parameters. To study possible biases of the proposed model along the trees' lifespan we carried out a LOWESS analysis of residuals in time. We detected deviations in the model residuals, and a patent growth reduction in the 1960s and 1970s, which might be related to climate and/or changing stand characteristics. Departures from estimated mean past growth should be monitored in the future to adapt models to a changing environment.

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1. Introduction

Forest productivity is a complex biological concept that cannot be described directly with mathematical expressions. In Forestry, it has usually been estimated indirectly using dominant-height growth in site index models. Carmean (1975) defined site index as the biomass production in forest stands of a species at a certain site. Site index models are commonly used and are amongst the most important tools for the management of even-aged stands. They are closely linked with many variables that determine the quality of the site, such as climate and soil characteristics. These models may also be used to investigate growth trends caused by different factors and predict future stand development and yields (Vanclay, 1994).

Pinus nigra Arn. (black pine) is a Mediterranean pine species with a broad distribution area, from the Iberian Peninsula in the west to Turkey in the east, with its northern limit in Austria. It is generally associated with basic substrata and it is present in many different ecological assemblages. In the Iberian Peninsula, *Pinus nigra* ssp. *salzmannii* occupies an area of 1.4 million hectares (Fig. 1). About one-third of this area is comprised of pure black pine stands and the rest are mixed stands mostly with other pines (*P. sylvestris* L., *P. pinaster* Ait., and *P. halepensis* Mill.). Most of this area is located

on mountain ranges in the eastern half of the Iberian Peninsula coinciding with basic soils on calcareous substrate (Sánchez-Palomares et al., 1990). These forests are not only very important sources of timber production, but are also of increasingly recreational importance. They play a major role in soil protection and are a key species in many biologically diverse habitats.

The importance of black pine timber production has motivated the study of stand productivity in the forestry literature in the past. Several site index curves have been developed for black pine in different regions of Spain (Pita Carpenter, 1965; Gómez Loranca, 1996; Bautista et al., 2001; Palahí and Grau, 2003). Pita Carpenter (1965) developed a model with a multi-regional scale whereas the rest are local models fitted for specific regions. The different methodologies, equations, and data used to fit these models might be responsible for the diverse growth patterns depicted by them (data not shown). It would be easier to make productivity comparisons between sites if a single model were used for several or all regions, instead of a different equation for each region.

Site index, as a surrogate of productivity, is assumed to remain constant over time for a given stand as long as the influencing factors (e.g. species, climate, soil) also remain constant or with little variation. However, if these factors change, productivity at a site can be reduced or increased. These site index variations might appear as trends in residuals of site-dependent height–age models if the fluctuating variables are not included to fit the models. Therefore, site-dependent height–age models can be used to detect trends in dominant height because they indirectly represent the development of site productivity and might show whether the

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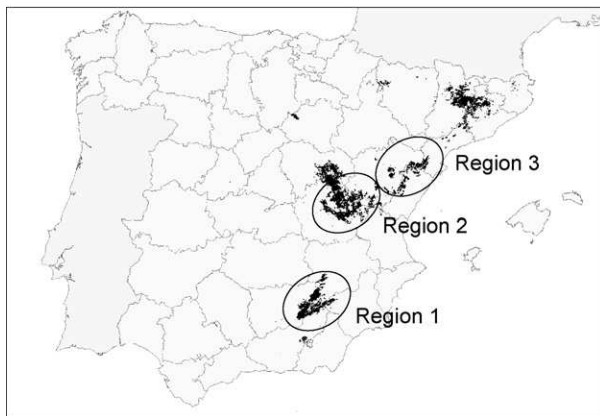


Fig. 1. Map of the natural distribution area of *Pinus nigra* in the Iberian Peninsula showing the three studied regions.

growing conditions are changing over time (Goelz and Burk, 1998). To investigate long-term trends of tree growth, dominant height is a better indicator of site productivity than tree-rings because radial growth can be influenced by many factors (such as competition or stand dynamics) which are not thought to affect dominant height (Goelz and Burk, 1998). Chronologies of height increments are a good method to identify and quantify growth trends, but the laborious technique required has reduced its use in dendroecology (Pensa et al., 2005).

Trends in dominant height of trees have been studied by analyzing the trends of residuals from dominant-height models (Duplat and Tran-Ha, 1997; Goelz and Burk, 1998). The models used by Goelz and Burk (1998) failed to fulfill the necessary requisite of base-age-invariance (Bailey and Cieszewski, 2000), which makes them unsuitable for investigating trends in dominant height. However, the rest of the methodology of Goelz and Burk (1998) remains valid for these purposes. In analyzing trends in residuals, it has been observed that *Quercus petraea* Liebl. in France (Duplat and Tran-Ha, 1997), *Picea rubens* Sarg. and *Abies fraseri*

(Pursh) Poir. in North Carolina (Goelz et al., 1999) experienced no long-term trends, but a slight decline in height growth after 1950–1960. If trends are consistent over time, it might indicate an increase or decrease in the productivity of the site for the given species and time period.

The objectives of our study were: (i) to analyze the regional variability in dominant-height growth patterns for black pine in three of the most productive regions of the Iberian Peninsula (Elena Rosselló and Sánchez Palomares, 1991); (ii) to test the possibility of using a single model for all the studied regions; and (iii) to check for possible trends in dominant-height growth using the chosen models through the analysis of residuals in time.

2. Materials and methods

2.1. Study area and data

We focused on three areas in this study, corresponding to three of the most productive regions of black pine in the Iberian Peninsula (Fig. 1). Region 1 is located in the southeastern part of Spain, on the Cazorla mountain range. Region 2 is located in ‘Serranía de Cuenca’ in central-eastern Spain. Region 3 is located on the north-east quadrant of the Iberian Peninsula on the mountains that surround the southern margin of the Ebro valley.

This study is based on stem analyses data from 94 trees in pure even-aged black pine stands (Table 1). Dominant trees [considered as the 100 largest diameter trees per hectare (Assmann, 1970)] were selected from stands near INIA (Spanish National Institute of Agricultural Research) permanent sample plots (PSPs) located in the three mentioned regions and established in 1964. That year, in 33 of the 50 PSPs, two dominant trees were felled from each plot (except in one plot where only one tree was felled) resulting in 65 trees in total. The rest of the stem analyses (37) were taken some years later (Gutiérrez-Oliva et al., 2006) from the same regions, but not from the vicinity of the PSPs.

For each felled tree, total height was measured and discs were taken at 0.5 m from the stump and at several different distances thereafter. Number of growth rings was counted in each disc. Since

Table 1
Average stand variables by region for the permanent sample plots in the eight inventories considered and for the stem analysis

Region	Variable	Inventory								Stem analysis
		1	2	3	4	5	6	7	8	
1	N	21	21	19	17	13	9	9	9	30
	Age*	90 (32–160)	95 (37–165)	96 (42–170)	94 (47–175)	81 (52–145)	90 (59–152)	97 (66–159)	106 (75–168)	118 (33–206)
	BA/ha (m ² /ha)	38.22 (11.90)	42.06 (13.22)	43.48 (12.04)	42.63 (5.78)	48.63 (6.28)	56.08 (8.25)	58.50 (14.55)	62.59 (17.04)	
	Trees/ha	1130 (989)	1130 (989)	906 (605)	787 (451)	896 (431)	828 (461)	799 (479)	745 (433)	
	Dg (cm)	12.3 (3.8)	12.8 (3.9)	13.8 (3.7)	14.6 (3.9)	14.3 (3.7)	16.1 (3.7)	16.8 (3.9)	17.8 (3.6)	
	Ho (m)	16.89 (4.50)	17.99 (4.32)	19.00 (4.32)	19.84 (4.33)	19.53 (3.92)	22.33 (3.69)	23.43 (3.66)	24.28 (3.53)	17.67 (5.7)
	Hm (m)	12.23 (4.77)	13.31 (4.67)	15.25 (4.62)	16.62 (4.51)	16.91 (3.82)	19.53 (3.41)	20.52 (3.24)	21.48 (3.83)	
2	N	20	20	20	17	16	15	15	15	46
	Age*	62 (31–131)	67 (36–136)	72 (41–141)	67 (46–118)	73 (52–123)	73 (56–100)	81 (64–108)	90 (73–117)	85 (33–175)
	BA/ha (m ² /ha)	40.66 (10.36)	43.32 (10.43)	41.27 (9.70)	41.43 (8.24)	44.89 (8.82)	45.26 (12.27)	47.61 (13.35)	50.00 (15.67)	
	Trees/ha	2042 (856)	2023 (861)	1467 (583)	1549 (531)	1479 (481)	1272 (532)	1115 (398)	1026 (434)	
	Dg (cm)	8.7 (3.0)	9.0 (3.1)	10.1 (3.0)	9.7 (2.3)	10.2 (2.3)	11.1 (2.5)	12.0 (2.5)	12.9 (2.5)	
	Ho (m)	15.13 (4.45)	15.99 (4.57)	16.74 (4.64)	16.35 (3.74)	17.44 (3.51)	18.47 (3.44)	20.30 (4.35)	21.00 (4.24)	14.84 (5.7)
	Hm (m)	11.35 (4.18)	12.11 (4.30)	13.55 (4.51)	13.40 (4.05)	14.63 (3.91)	15.92 (4.03)	17.55 (4.17)	18.70 (4.40)	
3	N	9	9	9	6	6	6	6	5	26
	Age*	83 (45–114)	88 (50–119)	93 (55–124)	92 (60–129)	97 (65–134)	102 (70–139)	111 (80–149)	163 (86–155)	133 (45–245)
	BA/ha (m ² /ha)	33.92 (11.23)	36.32 (12.03)	34.43 (10.32)	38.45 (7.07)	41.69 (8.69)	42.31 (8.63)	46.53 (11.65)	51.06 (11.61)	
	Trees/ha	1137 (747)	1137 (747)	815 (410)	884 (424)	884 (424)	877 (425)	866 (423)	912 (388)	
	Dg (cm)	10.4 (2.3)	10.8 (2.4)	12.1 (2.7)	12.4 (2.6)	12.9 (2.5)	13.1 (2.4)	13.7 (2.4)	13.9 (2.5)	
	Ho (m)	13.11 (3.33)	13.76 (3.02)	14.20 (3.32)	14.47 (1.53)	14.92 (1.50)	15.34 (1.52)	16.81 (2.28)	17.04 (2.74)	16.02 (3.5)
	Hm (m)	10.13 (4.17)	10.65 (3.70)	12.01 (3.62)	12.31 (2.48)	12.81 (2.49)	13.25 (2.50)	14.18 (2.76)	14.71 (3.10)	

Standard deviation is shown between parentheses except in *Age where range is given. BA, basal area; Dg, quadratic mean diameter; Ho, dominant height; Hm, mean height.

the length of the sections does not necessarily match total annual height growth, Carmean's (1972) method with Newberry's (1991) modification was used to correct height/age pairs. These corrections remove the bias created when we assume that the height of the section is the maximum height attained at a given age.

Dominance of trees in a stand may vary over the lifespan of the stand so the fact that a tree may be considered dominant at a certain time does not necessarily imply that it has always been or will continue to be dominant at another time (Zeide and Zakrzewski, 1993; Cherubini et al., 1998). For this reason, when height–age curves were plotted, all trees that showed signs of suppression at any given time of their lives were removed from the study. After rejecting 8 of the 102 stem analyses (1 from region 1, 2 from region 2, and 5 from region 3), a total of 94 stems were used to fit the models.

Since quality of fit does not necessarily imply the same quality in prediction, it is important to compare models on a separate validation data set (Vanclay, 1994). We conducted an assessment of the goodness of fit of the models on an independent validation data set, which consisted of repeated dominant-height measures in the same black pine PSPs where trees were felled for stem analyses (Table 1). The PSPs are rectangular, have a variable number of trees and plot areas ranged from 650 m² to 2500 m². They were inventoried at 5–9-year intervals from 1963 to 1964 until 2006. In each inventory and each plot, the diameters of all trees and the height of a sample of 40 trees were measured, 30 of these proportionally to the diameter distribution for mean height estimation and 10 dominant trees for top height estimation.

2.2. Statistical analysis

Among all tested dynamic site equations, the three that showed the best results and significant parameters are shown in Table 2. These three models [hereafter referred as M1, M2 and M3] were derived using the Generalized Algebraic Difference Approach (GADA) by Cieszewski and Bailey (2000) and Cieszewski (2004) from different base growth equations commonly used for the development of site index curves and dominant-height growth modeling (i.e. Zeide, 1993; Kiviste et al., 2002). These models fulfilled the desirable properties of dynamic site models, which are: (i) sigmoid growth pattern; (ii) asymptotic behavior; (iii) logical behavior (zero origin and always increasing); (iv) theoretical basis; (v) base-age invariance; and (vi) polymorphism. For the GADA, it is generally needed that two parameters (the parameter related to the asymptote and one of the shape parameters) are functions of site productivity to allow for simultaneous polymorphism and variable asymptotes. Productivity is assumed to be dependent on an unobservable variable *X* which can neither be measured nor defined (Cieszewski and Bailey, 2000; Cieszewski, 2002, 2004). GADA methodology usually produces better models than the Algebraic Difference Approach (ADA) (e.g. Cieszewski, 2002; Barrio Anta et al., 2006) which is a particular case of GADA. While GADA assures base-age invariance of the derived algebraic forms, the base-age invariance of the model parameter estimates

was assured by fitting them using the dummy variable approach (Cieszewski et al., 2000).

Two types of models (full and reduced) were fitted in two different steps. First, in the full model, functions are independently fitted to data from each of the three regions. This way, the full model consists of a different set of parameters for each region, including a dummy variable to differentiate regions, so that $Y = \sum V_i \cdot f_i$ where f_i is the growth function $f(x, \beta_i)$ for region *i*, and V_i is a dummy variable whose value is 1 if data is from region *i* and 0 otherwise. Using this model we could compare the dominant-height growth patterns among all the regions. Second, we fitted a reduced model to all data together. Later, when a differential function was selected, we compared regional growth patterns and goodness of fit statistics between the full and reduced models to check whether the differences justify the use of separate models for each region or if it would be possible to use a single model for all regions. In fitting the models, the Marquardt (1963) iterative method was used because it is the most useful method when working with highly correlated parameter estimates (Fang and Bailey, 1998; Kelley, 1999). We used PROC MODEL in the SAS/STAT software (SAS Institute Inc., 2004) to fit all models.

The fact that data originates from stem analysis creates autocorrelation among observations within the same tree. Parameter estimates are not biased by this autocorrelation, but estimators of standard errors are (Gregoire et al., 1995), which invalidates the standard hypothesis testing. To remove autocorrelation during model fitting, a second-order autoregressive AR(2) structure was considered. The general expression of a difference model with AR(2) is

$$H_{ij} = f(H_j, T_i, T_j, b) + e_{ij} \quad \text{with } e_{ij} = \rho_1 \cdot e_{i-1} + \rho_2 \cdot e_{i-2} \quad (1)$$

where H_{ij} represents height prediction at age T_i by using H_j, T_j, T_i as predictor variables; β is the vector of model parameters; e_{ij} is the residual for observation *i* as predicted from *j*; ρ_1, ρ_2 are the first and second autocorrelation parameters. Residuals were plotted against predicted values and homoscedasticity was visually checked.

A three-step procedure was used for model comparison and selection. The first step involved fitting the full model to the data set and comparing performance criteria as well as curve shapes. In the second step, goodness of fit statistics using the models and the validation data sets were calculated and compared. Finally, factors such as logical interpretation, desirable characteristics, and biological realism were taken into account. In all the analyses a significance level of $\alpha = 0.001$ was used except when indicated. The statistics used to compare models were:

- Residual mean square error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (\text{est}_i - \text{obs}_i)^2}{n - p}}$$

where *est* is the estimated height values; *obs* is the observed height values; *n* is the number of observations; *p* is the number of

Table 2
Base and dynamic equations used to model dominant-height growth of *Pinus nigra*

Reference and base equation	Site related parameters	Solution for <i>X</i>	Reference and dynamic equation	Model
Lundqvist, 1957	$a = \exp(X)$	$X_0 = 0.5 (\ln(y_1) + F_0)$	Cieszewski and Bailey (2000)	M1
$y = a \exp(-bt^{-c})$	$b = b_1/X$	$F_0 = \sqrt{-(\ln(y_1))^2 + 4b_1 t_1}$	$y_2 = \exp(X_0) \exp\left(-\left(\frac{b_1}{X_0}\right) t_2\right)$	
von Bertalanffy, 1957;	$a = \exp(X)$	$X_0 = 0.5 \cdot (\ln(y_1) - c_1 F_0 + \sqrt{(c_1 F_0 - \ln(y_1))^2 - 4F_0})$	Cieszewski (2004)	M2
Richards (1959):	$c = c_1 + (1/X)$	$F_0 = \ln(1 - \exp(-bt_1))$	$y_2 = \exp(X_0) \cdot (1 - \exp(\Xi_2))^{(c_1 + 1/X_0)}$	
$y = a(1 - \exp(-bt))^c$	$a = \exp(X)$	$X_0 = 0.5 \cdot (\ln(y_1) + \sqrt{(\ln(y_1))^2 - 4c_2 F_0})$	Cieszewski (2004)	M3
	$c = c_2/X$	$F_0 = \ln(1 - \exp(-bt_1))$	$y_2 = \exp(X_0) \cdot (1 - \exp(\Xi_2))^{(c_2/X_0)}$	

parameters, when calculating RMSE for a fitted model, and $p = 1$ when calculating RMSE for an age or dominant-height class. Relative RMSE was calculated by dividing the previous expression by the mean observed dominant height:

$$\text{RMSE (\%)} = \left(\frac{\text{RMSE}}{\text{obs}} \right) \times 100$$

- Coefficient of determination (R^2 in the 'estimation phase') or efficiency (EF in the 'prediction phase'):

$$R^2 \approx \text{EF} = 1 - \frac{\sum_{i=1}^n (\text{est}_i - \text{obs}_i)^2}{\sum_{i=1}^n (\text{obs}_i - \overline{\text{obs}})^2}$$

- Mean residual (bias):

$$\text{Bias} = \frac{\sum_{i=1}^n (\text{est}_i - \text{obs}_i)}{n}$$

- Akaike's information criterion differences (AICd) (Burnham and Anderson, 1998):

$$\text{AICd} = n \ln \hat{\sigma}^2 + 2k - \min(n \ln \hat{\sigma}^2 + 2k)$$

where

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^n (\text{obs}_i - \overline{\text{obs}})^2}{n}$$

Once a differential equation was chosen to describe dominant-height growth, a comparison was made between the full and the reduced models (based on that equation) in order to analyze possible differences between them. In these comparisons the χ^2 test proposed by Lakkis and Jones (Khattree and Naik, 1999) was used to detect simultaneous homogeneity among parameters. For this test it is necessary to define the full and the reduced model. It has been widely used for analyzing differences between forest stands from different geographic regions (i.e. Pilsbury et al., 1995; Calama et al., 2003; Álvarez-González et al., 2005). Practical implications such as ease for inter-regional comparisons were also taken into account to choose between the full and the reduced model.

The Lakkis and Jones test uses the L statistic (Khattree and Naik, 1999), defined as $L = (SS_r/SS_f)^{n/2}$ where SS_r and SS_f are the sum of squares' errors for the reduced and the full models, and n the total number of data. The sum of squares error (SS) was defined as, $SS = \sum_{j=1}^m \left(\sum_{i=1}^n (\text{est}_i - \text{obs}_i)^2 / n \right)$ where n is the total number of observations for each tree; m is the total number of plots; j is the plot number; est_i and obs_i are the estimated and observed heights of tree i , respectively. If homogeneity exists between the parameter vectors from the full and reduced models, the distribution of the statistic $-2 \cdot \text{LL}$ (log-likelihood) converges to a Pearson χ^2 distribution with ν degrees of freedom, with $\nu = \text{df}_r - \text{df}_f$ (df_r is the number of degrees of freedom in the reduced model and df_f in the full model).

In order to detect possible differences in the distribution of errors from full and reduced models, RMSE and Bias were plotted against 20-year predictor-age and prediction interval classes. Prediction interval was defined as the difference between predictor-age and the age at which dominant height was estimated.

2.3. Analysis of residuals through time

Average residuals from fitting site index models to individual stem analysis were plotted against chronological decades in which the growth (and thus the residual) was produced (Goelz and Burk, 1998; Duplat and Tran-Ha, 1997). The sub-sample of stem-analysis

taken in 1964 near the PSPs and the data from the eight inventories of the PSPs was used. As the age of the sampled trees varied from 30 to 183 years, year did not correspond to age across the data set. Because of the variation in tree age and the fact that many different base ages were used for the fittings, the biological age and base age of the trees did not influence trends in the calculated residuals.

The reduced model was used for this analysis to avoid possible trends in residuals coming from different sets of parameters in each region. In addition, potential inter-regional differences could be assessed by using the reduced model. Heights were predicted using the immediately previous height-age observation, to reduce the prediction interval lengths and hence the prediction errors. Using LOWESS (locally weighted least squares), a line was drawn to fit the residuals as a function of time (Cleveland, 1979). LOWESS is a robust time series smoother that produces a regression line which is less affected by outliers and non-equispaced data than classical least squares regression.

3. Results

3.1. Model selection

In the estimation phase all models were unbiased both when independently adjusted to each of the three regions and to the three regions together (data not shown). The lowest values of RMSE and the highest R^2 for the three regions were obtained with model M1 (Cieszewski and Bailey, 2000), a GADA formulation based on the Korf growth equation (Table 3). Similar values of RMSE and R^2 were obtained with all models showing that all of them behaved very well in the estimation phase. Dominant heights at 350 years were within the species height range [up to around 50 m according to Ruíz de la Torre, 1979] except for models M1 and M2 in region 3.

With different parameters for each region (full model), models were validated using the validation data set and estimated dominant heights were compared to observed heights. Goodness of fit statistics were also calculated to compare models. In this step, model M1 showed the best overall statistics, although other models performed better in certain regions and statistics. Model M3 showed lower RMSE, bias and higher efficiency than M1 for region 3. Models were also unbiased in the validation phase (Fig. 2a; Table 4). In this case all the efficiencies were higher than 80% (Table 4).

The most appropriate reference age was set at 80 years as a compromise between the number of samples used in the estimation phase (too low after 80 years) and the relative error obtained (Fig. 2b). This reference age is slightly lower than the rotation age (100–120 years) commonly used in these stands. The curves generated by the selected model M1 for site indices of 26, 22, 18, 14, and 10 m at a reference age of 80 years were compared for the three regions (Fig. 3). Regions 1 and 2 showed a very similar pattern in dominant-height growth. The pattern in region 3 differed from the other two regions in that it showed lower dominant heights at younger ages and higher heights after the reference age of 80 years.

When parameter homogeneity was assumed for all three regions (reduced model), the Lakkis and Jones test did not show significant differences between the full and reduced models ($L = 0.5354$; $p = 0.8699$) and therefore we selected the reduced model. Model M1 behaved well when applied to the complete validation data set. In this case, the mean residual value was 0.0036 m (not significant for $\alpha = 0.001$) and the efficiency was 98%. Bias was thus lower than that obtained when M1 was independently applied to separate regions. Because the pattern in region 3 differed more than the patterns in the other two regions, we

Table 3
Parameter estimates and estimation goodness of fit statistics for the candidate models

Model	Region		Estimate	S.E.	<i>t</i>	<i>p</i> > <i>t</i>	RMSE	Adj <i>R</i> ²	AICd	(<i>H</i> ₃₅₀)
M1	1	<i>b</i> 1	39.615	2.576	15.38	<0.0001	0.9638	0.9791	0.00	49.9
		<i>c</i>	0.397	0.057	6.92	<0.0001				
M2	1	<i>c</i> 1	0.907	0.079	11.48	<0.0001	1.0155	0.9768	19.02	45.5
		<i>b</i>	0.012	0.001	8.82	<0.0001				
M3	1	<i>c</i> 2	4.168	0.254	16.44	<0.0001	0.9928	0.9778	10.80	42.8
		<i>b</i>	0.012	0.001	9.47	<0.0001				
M1	2	<i>b</i> 1	64.266	15.292	4.20	<0.0001	0.4026	0.9941	0.00	70.4
		<i>c</i>	0.223	0.059	3.81	0.0002				
M2	2	<i>c</i> 1	0.926	0.083	11.12	<0.0001	0.4128	0.9938	11.88	71.5
		<i>b</i>	0.005	0.002	2.77	0.0060				
M3	2	<i>c</i> 2	4.000	0.269	14.89	<0.0001	0.4165	0.9937	16.09	53.1
		<i>b</i>	0.007	0.002	4.08	<0.0001				
M1	3	<i>b</i> 1	47.200	1.880	25.11	<0.0001	0.695	0.9857	0.00	56.0
		<i>c</i>	0.374	0.043	8.75	<0.0001				
M2	3	<i>c</i> 1	1.008	0.054	18.66	<0.0001	0.7062	0.9853	8.86	47.3
		<i>b</i>	0.012	0.001	11.94	<0.0001				
M3	3	<i>c</i> 2	4.567	0.176	25.91	<0.0001	0.7023	0.9854	5.79	44.6
		<i>b</i>	0.012	0.001	12.67	<0.0001				
M1	1&2&3*	<i>b</i> 1	43.735	1.175	37.23	<0.0001	0.6938	0.9863	0.00	53.4
		<i>c</i>	0.380	0.027	13.99	<0.0001				
M2	1&2&3*	<i>c</i> 1	0.967	0.040	24.04	<0.0001	0.7640	0.9834	134.24	49.7
		<i>b</i>	0.011	0.001	15.59	<0.0001				
M3	1&2&3*	<i>c</i> 2	4.368	0.127	34.5	<0.0001	0.7592	0.9836	125.59	45.2
		<i>b</i>	0.012	0.001	17.84	<0.0001				

Dominant height (*H*₃₅₀) is calculated in m for class I at 350 years as an estimate of maximum growth rather than the asymptote. S.E. = standard error; RMSE = root mean square error; AICd = Akaike's information criterion differences. *, reduced model.

analysed the errors obtained when applying the reduced model to the validation data set from this region. Efficiency was 91.3% and mean error (0.0164 m) was not significantly different from zero ($\alpha = 0.05$). Predictions for young trees below 70 years old produced the largest relative RMSE (>7%), whereas for oldest ages RMSE was below 6% for both models (Fig. 4). Prediction error was below 10% for lags shorter than 40 years (Fig. 4). The reduced model produced homoscedastic residuals (Fig. 5).

When applying the reduced model to the stem analysis data (estimation data set), predictions of site index were consistent over time, except for the youngest ages below 50 years (Fig. 6). This is in agreement with decreasing relative RMSE as prediction age increases and more erratic tree growth at the youngest ages. The mathematical expression of the reduced model (M1) was

$$H = \exp(X_0) \exp\left(-\frac{43.73549}{X_0} \cdot t^{-0.38048}\right)$$

where

$$X_0 = 0.5(\ln H_0 + \sqrt{(-\ln H_0^2 + 4 \cdot 43.73549 \cdot t^{-0.38048})})$$

Site index curves (Fig. 7) were produced using 80 years as a reference age through the age-height points (80, 26), (80, 22), (80, 18), (80, 14), and (80, 10). These curves closely described the dominant-height growth of trees in the estimation and validation data set (Fig. 7).

3.2. Analysis of residual trends over time

Fig. 8 shows the LOWESS line fitted to residuals and plotted against the calendar year at the end of the corresponding time period (decade for the stem analysis data and the year of inventory

for PSP data) when the growth was produced (i.e. 1951–1960 is plotted at 1960). After 1900, the residuals of regions 2 and 3 started to increase in synchrony, whereas for region 1 residuals were already increasing. All regions showed two periods of increasing residuals (from 1900 to 1940–1950 and from 1980 to 1990–2000) and two periods of decreasing residuals (from 1940–1950 to 1980 and from 2000 to 2006). It is important to note that trends of both data sets (stem analysis and repeated inventory of PSPs) showed a similar behaviour in the common period of 1970s. Overall, residuals were positive from the beginning of the 20th century until the 1960–1970s where they became negative until almost the end of the measurement period in 2006. The positive residuals showed that mean observed growth was greater than predicted, thus all regions showed superior growth during the first 60–70 years of the 20th century and below expected mean growth for the last 30–40 years.

Table 4
Goodness of fit statistics for the model validation

Model	Region	<i>N</i>	RMSE (m)	Bias (m)	EF
M1	1	111	0.6003	0.1322	0.98
M2	1	111	0.6446	0.0310	0.98
M3	1	111	0.6073	0.0691	0.98
M1	2	48	0.8010	−0.1026	0.88
M2	2	48	0.9599	−0.1741	0.83
M3	2	48	0.7598	−0.0634	0.89
M1	3	129	0.8482	−0.1064	0.96
M2	3	129	1.0836	−0.1905	0.94
M3	3	129	0.9911	−0.1519	0.95
M1	1&2&3	288	0.6781	0.0036	0.98
M2	1&2&3	288	0.9293	−0.1210	0.96
M3	1&2&3	288	0.8055	−0.0602	0.97

RMSE = root mean square error; EF = efficiency.

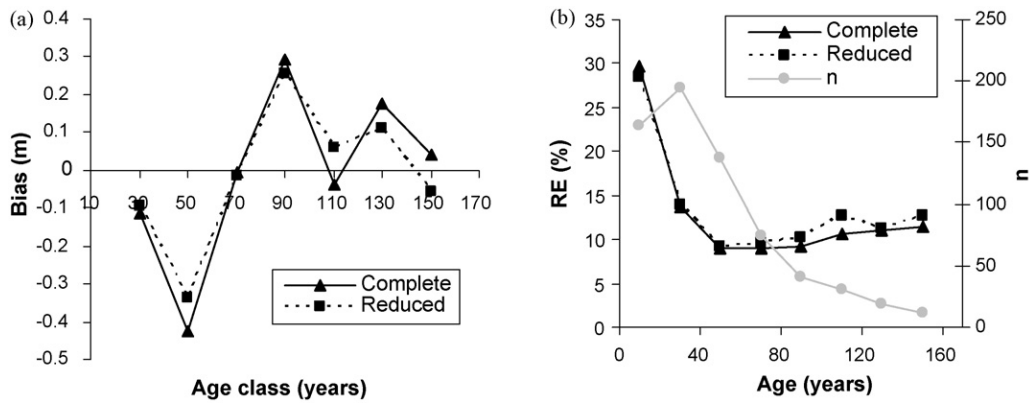


Fig. 2. (a) Bias variability with age class using the reduced model and PSP inventory data. (b) Mean relative error in dominant height predictions by reference age for the full model and the reduced model, and sample size using stem analysis data.

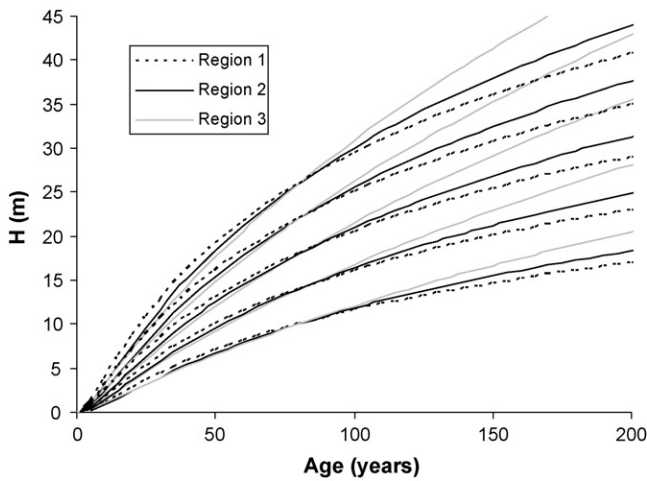


Fig. 3. Comparison of the site index curves of 26, 22, 18, 14, and 10 m at a reference age of 80 years independently fitted to each of the three regions studied.

4. Discussion

We have compared three GADA formulations derived from three base-growth equations by Cieszewski and Bailey (2000), and Cieszewski (2004) to model dominant-height growth of *P. nigra*.

Model M1 (Cieszewski and Bailey, 2000) behaved best both in the estimation phase (using data from stem analysis) and when validated with an independent data set from PSP inventories. Several site height–age models derived from the Korf growth function has also been found to best describe different aspects of tree growth in Mediterranean species, such as the dominant-height growth of *Pinus pinea* L. (Calama et al., 2003), diameter growth of *Quercus ilex* L. (Gea-Izquierdo et al., 2008) or basal area growth of *Pinus pinaster* (Barrio Anta et al., 2006).

Once model M1 had been selected, we conducted a regional comparison of dominant-height growth patterns (Fig. 3). It was observed that the patterns in regions 1 and 2 were very similar, while those in region 3 differed from the other two. This could be caused by the dataset used, as we had a small number of stem analysis for model estimation in region 3, especially for the higher site qualities and for ages older than 80 years. The lack of data in this last region could also be the cause of unexpectedly high asymptotes. However, the χ^2 test showed no significant differences among all regions, meaning that the reduced model (with a single set of parameters for all the regions) performed as well as the full model (different set of parameters of all regions). This was also supported by the similarity in the bias and RMSE distributions of the full and reduced models (Fig. 2a; Fig. 4). In both cases, bias is higher for the youngest age classes and decreases for older classes, although fluctuating from positive to negative. More pronounced patterns were found for RMSEs that steadily decreased for higher

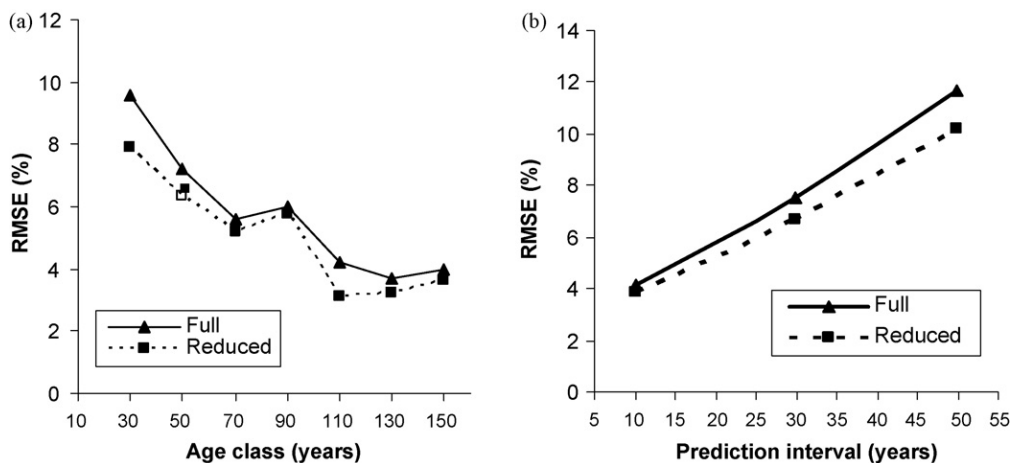


Fig. 4. Relative mean root square error (RMSE) by age class and prediction interval using the full and reduced model and PSP inventory data.

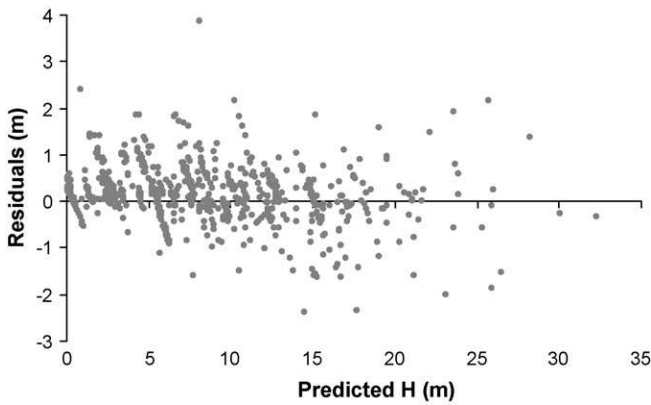


Fig. 5. Residual against predicted dominant height (H) for the reduced model and stem analysis data set.

prediction-age classes and lower prediction intervals. The reduced model showed slightly smaller relative RMSE for both prediction age and interval length. This could be caused by a compensating effect between regions. Information from some regions may have improved the performance of the reduced model for other regions where samples in certain ranges of height and/or age are underrepresented or lacking (Goelz and Burk, 1998).

Dominant-height growth models are developed assuming that climate stays constant and that silvicultural treatments have little effect on dominant height. This might not be true in a climate change scenario (Gamache and Payette, 2004) and/or for all stand densities and species (MacFarlane et al., 2000). Since dominant-height growth models account for the effect of age and productivity, it seems reasonable to use such models to subtract these effects from the height growth curves of trees or stands while leaving the influence of other factors. The models used in this work are all base-age invariant and thus suitable for the study of trends in residuals over time. An almost synchronous trend of residuals was observed for all regions with superior growth (higher than predicted) before the 1960s and low growth from 1970 onward with a short period of higher-than-predicted growth around 1990. Similar height growth trends have been shown in different regions of France for *Q. petraea* (age between 102 and 216 years) during the 1960s and 1970s (Duplat and Tran-Ha, 1997) and for trees of several North American species in the same age range as the trees we used (e.g. Van Deusen, 1992; Goelz et al., 1999).

These trends in residuals were most likely caused by variables that change over time and that could have accounted for some of

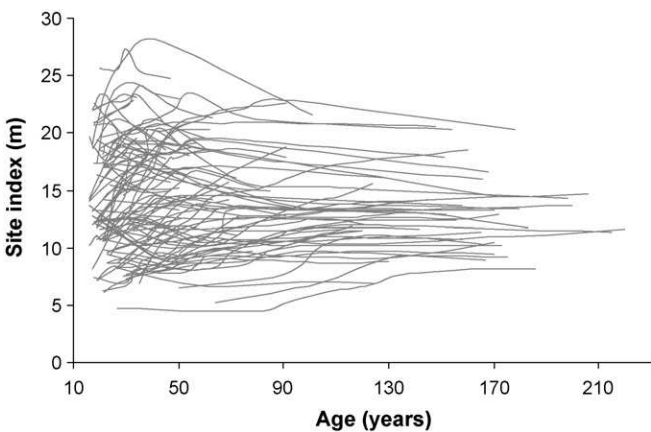


Fig. 6. Site index predictions against age using the reduced model and the stem analysis data set.

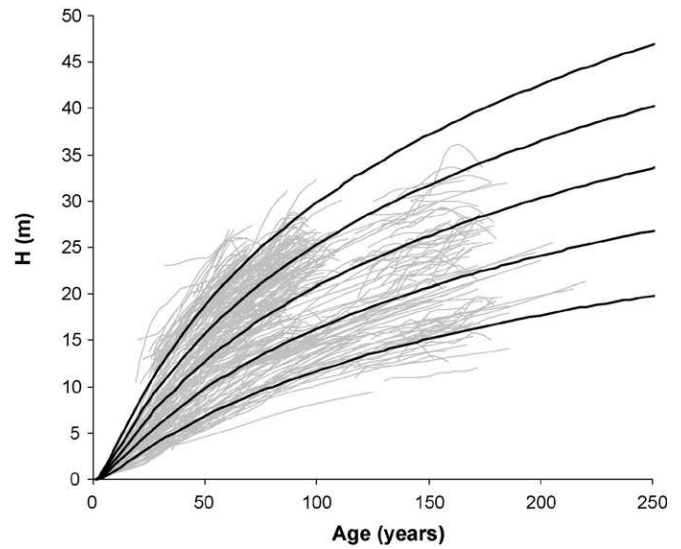


Fig. 7. Site index curves for the reduced model at 80 years and 26, 22, 18, 14, and 10 m (black lines) overlaid with the estimation and validation data sets (grey lines).

this variability in growth had they been included in the model (Goelz and Burk, 1998). In this case, the residuals would have shown a random distribution over time without any evident trends. Lebourgeois et al. (2000) compared young and old plots of black pine growing side by side in France and concluded that dominant trees of plots established after 1950 were growing faster than plots planted before that year. Thus site index had increased for the same site, which in part contradicted the general assumption that site index remains constant in time for a certain species at a certain site (Assmann, 1970; Carmean, 1975; MacFarlane et al., 2000). The causes for the observed deviations from the proposed models can be many. Even though atmospheric pollution could lead to a growth decrease (e.g. Schulze, 1989), this explanation can probably be ruled out because all stands used in this study are distant from industrial and heavy polluted areas. A decrease in precipitation and/or increase in water stress could decrease height growth, as it is known to reduce the radial growth of *P. nigra* (Lebourgeois et al., 2000; Martín-Benito et al., 2008) and other Mediterranean pine species (i.e. Sarris et al., 2007). A trend of decreasing precipitation for the study area number 1 has been observed after 1960 (Rodrigo et al., 1999), which could lead to decreasing height growth (negative residuals) after that year (Fig. 8). In addition, Rodrigo et al. (1999) also found a above-average precipitation period between 1920 and 1940 where we have shown increasing trend in residuals. Therefore, it appears that

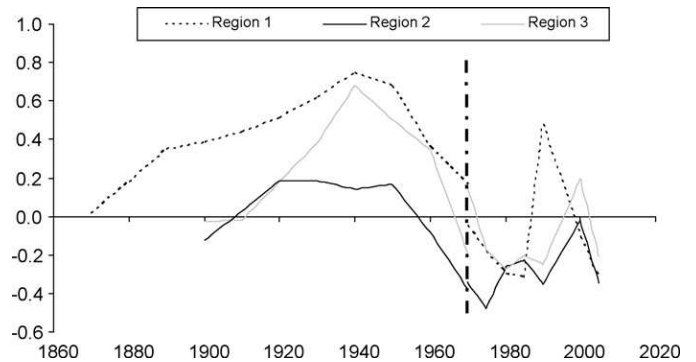


Fig. 8. Evolution of LOWESS line fitted to residuals from the reduced model for the three regions. The vertical line marks the year 1964 when stem analysis data ends and PSP inventories start. See text for details.

the growth trends found in this study are based on changes in precipitation during the 20th century. However, a direct relationship between height growth and climate cannot be completely proven with the available data. It must be noted that these results were derived assuming that the growth of dominant trees analyzed in 1964 and thereafter describes well the dominant-height growth of the stands. As discussed, stand dynamics can confound site index interpretations because it may not be completely correct to assume that dominant height is unaffected by stand density. Therefore changes in stand density could also be the cause of the observed trends (Van Deusen, 1992; MacFarlane et al., 2000).

5. Conclusions

After comparing different models using data from the most productive regions of *P. nigra* in Spain, we propose a single site-dependent height–age model for black pine in the three studied regions. This model offers great practical advantages because inter- and intraregional comparisons of silvicultural treatments, productivities, and experiences can be made without using different models, which can create inconsistencies. Although bias was very small and not significant both in the estimation and validation phases, all height–age models discussed are likely to be biased in some way since long-term trends were observed in the residuals. The apparent reduction in growth after 1960–1970 requires careful interpretation as many factors such as stand aging or change of inventory protocols may have confounding effects. Whether the observed trends were caused by climate, pollution, stand dynamics or any other factors cannot be inferred from our results. If these trends are true and realistic, they might exist in most similar empirical height models found in the literature.

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