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Individual-tree diameter growth model for rebollo oak (*Quercus pyrenaica* Willd.) coppices

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Abstract

In this study, a distance-independent mixed model was developed for predicting the diameter growth of individual trees in Mediterranean oak (*Quercus pyrenaica* Willd.) coppices located in northwest Spain. The data used to build the model came from 41 permanent plots belonging to the Spanish National Forest Inventory with the dependent variable being 10-year diameter increment over bark for trees larger than 7.5 cm at breast height. The basic field data required for predictions had been divided into four main groups: size of the tree, stand variables, competition indices and biogeoclimatic variables. The most significant independent variables were the individual-tree diameter, the basal area of trees larger than the subject tree, dominant height, site index and biogeoclimatic stratum. The model was defined as a mixed linear model with random plot effect, achieving an efficiency of 44.38%. The accuracy of the model was tested against the modelling data and against independent data from the same stands. Mixed model calibration of diameter increment was carried out with the independent data using a different sample of complementary observations of the dependent variable. The calibrated model was an improvement on the trivial model, which assumes constancy in diameter increment for a short projection period, especially the pattern of residuals with respect to predicted diameter and the independent variables.

Keywords: Individual-tree model; Mixed model; Diameter growth; *Quercus pyrenaica*

1. Introduction

The species *Quercus pyrenaica* Willd., commonly known as rebollo oak or pyrenean oak, is widely distributed across the Iberian Peninsula, but is mainly found in the mountain ranges of the north-west (Fig. 1) (Costa et al., 1996). According to the Second Spanish National Forest Inventory (DGCN, 1996), the total surface area covered by this Mediterranean oak in Spain is 659,000 ha. Owing to its widespread distribution, great variability exists among stands in terms of silvicultural and ecological conditions. The traditional treatments applied in these stands (usually coppice management) have been progressively abandoned due to the decrease in use of firewood and charcoal as an energy source and to rural emigration to the cities. Furthermore, *Q. pyrenaica* stands have been frequently affected by forest fires. As a result of these determining factors, stands today are generally coppice and somewhat diverse, ranging from diminished stands with low densities to open-woodlands with large diameters, although well-stocked coppices represent around 43% of stands (DGCN, 1996). To avoid putting the existence of these coppices at risk in the long term, it is necessary to establish a sustainable forest management plan for each kind of stand. Moreover, the increasing interest in using these stands for either direct production (such as wine barrels) or indirect production (such as silvopastoral uses, recreation, environmental preservation) justifies the urgent need to guarantee a sustainable management of rebollo oak stands (Cañellas et al., 2004).

The availability of information on diameter increment and growth patterns for individual trees is an important asset in forest management which allows the selection of tree species for logging or protection as well as the estimation of cutting cycles and the prescription of silvicultural treatments. Diameter increment measurements are also required to feed statistical models of forest dynamics both for modelling and simulation (Pereira da Silva et al., 2002). In this way, growth models can

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Fig. 1. Distribution of *Quercus pyrenaica* Willd., biogeoclimatic strata and sample plots in studied area.

facilitate the search for solutions in the management of rebollo oak stands, especially in the case of coppices where the growth pattern often justifies investment in silvicultural treatments.

Individual-tree growth models enable a more detailed description of the stand structure and its dynamics than stand-level models (Vanclay, 1994a; Chojnacky, 1997; Mabvurira and Miina, 2002). They also allow silvicultural treatments to be simulated and permit comparison with alternative thinning regimes (Mabvurira and Miina, 2002). These kinds of models would seem suitable for rebollo oak coppices given their high structural variability. Furthermore, this approach usually performs better than stand models for short-term predictions (Burkhart, 2003), being especially useful when the models are going to be used with national forest inventories.

Many tree diameter growth models have been fitted on the basis of national forest inventory data (Wykoff, 1990; Monserud and Sterba, 1996; Lessard et al., 2001; Andreassen and Tomter, 2003). This kind of data set permits the use of a large amount of data although the sampling methodology was not specifically designed to develop growth and yield models and may lead to large errors when measuring radial increment (Trasobares et al., 2004). Nevertheless, assuming that measurement errors are random, the large sample should compensate for this deficiency (Monserud and Sterba, 1996).

Modelling data sets for individual-tree growth have a hierarchical stochastic structure. This type of structure occurs when multiple measurements are taken from individual sampling units, and measurements are combined across sampling units (West et al., 1984; Fox et al., 2001), so there is a violation of the OLS regression assumption of independent residuals and results in biased estimates of the standard error of parameter estimation (West et al., 1984; Schabenberger and Gregoire, 1995). The modelling data are mutually correlated (trees within plots) and, thus, cannot be regarded as an independent sample of the basic tree population (West, 1981; West et al., 1984; Fox et al., 2001).

The evolution of the mixed modelling methodology provided a statistical method capable of explicitly modelling hierarchical stochastic structure (Biging, 1985; Lappi, 1986; Hökkä et al., 1997; Fox et al., 2001; Calama and Montero, 2005). Linear mixed models are composed of a fixed functional part, common to the complete population, and random components acting at each sampling level. The explanatory variables in the fixed part were either measured or estimated tree variables, stand variables and site attributes, and they are selected based on statistical properties and biological principles (Zhao et al., 2004). These explanatory variables do not explain the total variation in tree growth, so the mixed models allow the different sources of stochastic variability to be identified (Calama and Montero, 2005).

Ojansuu (1993) states that the application of a stochastic model such as this would be limited to new data, although this limitation can be removed by regressing nested stochastic parameters for external stand-level variables. Lappi (1991) and Calama and Montero (2005) proposed a calibration based on predicting the random components using best linear unbiased predictors (BLUP). This last predictor is calculated using a sample of complementary observations of the dependent variable.

The objective of this study was to develop a diameter growth model for *Q. pyrenaica* Willd. coppices growing in northwest Spain, that allows the development and evaluation of growth functions for later improvement of existing stand-based long-term forest management planning packages. A mixed modelling approach was emphasised due to the hierarchical structure of the data set, including both fixed and random components. Different calibrations using 1, 2 or 3 trees per plot were calculated to find out how many tree measurements were necessary to achieve good diameter growth estimation.

2. Materials and methods

2.1. Data set

The data were obtained from 200 plots belonging to the Spanish National Forest Inventory (SNFI) in the northwest area

Table 1
Characteristics of the strata

Ecoregion	Stratum	Area (km^2)	Tm	Ppm	Altm
2	1	40,505	11.7	517	818
	2	22,157	10.5	600	939
	3	17,566	9.2	905	1245

Tm, mean temperature (°C); Ppm, mean precipitation (mm); Altm, mean altitude above sea level (m).

Table 2
Plot radius for different classes of tree dbh

Dbh	Plot radius (m)
$75 \leq$ dbh < 125 mm	5
$125 \leq$ dbh < 225 mm	10
$225 \leq$ dbh < 425 mm	15
dbh ≥ 425 mm	25

of Spain (Castilla y León region), which had been used and complementary measured to study the autoecology and the growth of rebollo oak in Castilla y León region. According to Elena Roselló (1997), the region is covered by two ecoregions, being the *Q. pyrenaica* stands mainly in Ecoregion 2, characterized by a Mediterranean climate with low precipitation and extreme temperatures. The author classified the ecoregion into three stratums according to altitude. The plots were selected in proportion to the three strata (Table 1), providing representative stands with a variety of stand structure and site conditions. SNFI is a systematic sample of permanent plots distributed on a square grid of 1 km, with a remeasurement interval of 10 years. The sampling method used circular plots in which the plot radius depended on the tree's diameter breast height (Table 2), so number of measured tree per plot is variable. At each inventory, the recorded data for each sample tree are: species, diameter at breast height, total height, and distance and azimuth from the plot centre.

An initial selection of suitable plots was made from all SNFI plots over the whole study area. The plots chosen were those in which *Q. pyrenaica* was the dominant species (highest basal area proportion), and where measurement data were available from the second and third SNFI. Because of the high variability in silvicultural and ecological conditions of the rebollo stands and the lack of past management information in the SNFI, a second selection was made according to stand typology classification. The differentiation was based on stand variables and structure, leaving out both impoverished stands and stands which were too open. The coppices selected were characterized by medium to high densities (stand density index over 200 trees per hectare) and regular diameter distributions.

Ecological parameters are evaluated using climatic estimation models proposed by Sánchez et al. (1999). Each parameter is calculated according to each location, including his altitude, geographic position and catchment area.

Site index is usually included as an independent variable in diameter growth models, but this requires the age of the stand to be known. Neither age nor site index are available in SNFI, so it was necessary to make some complementary measurements. For each plot, one or two dominant trees, defined as largest trees according to the diameter at breast height, were fallen for stem analysis in the same stand but outside the original plot, so that the permanent plot would not be harmed. From stem analysis, average ages and site indexes were determined plotwise, i.e. for every stand, according to Adame et al. (2006).

The validation data set was taken from 30 of the plots used to fit the model. In these plots, some trees (5–8) were randomly sampled in the same stand but outside the original plot. The ring-growth pattern was measured to the centre of the tree using a Pressler increment borer, so that the growth over a given period could be determined. These trees were also measured for diameter at breast height, total height, crown height and crown diameter in four directions (North, South, East and West).

Finally, a total of 41 plots with 618 trees from the Third SNFI (Fig. 1) were used to fit the diameter growth model for *Q. pyrenaica* coppices. The main characteristics of the study material are shown in Table 3. To test the fitted model, a total of 190 trees from the 30 plots were used (Table 4).

The TSAP software was used with a linear positioning digitiser tablet LINTAB to measure the annual ring count for each disc and increment cores.

2.2. Statistical analyses

Let $\boldsymbol{Y}_i = (Y_{i1}, \ldots, Y_{in_i})$ be the response vector for the n_i measurements of the subject i with $i = 1, \ldots, N$. The linear mixed model for the response vector $\boldsymbol{Y_i}$ is defined as (Laird and Ware, 1982):

$$\boldsymbol{Y_i} = \boldsymbol{X_i\tau} + \boldsymbol{Z_i u_i} + \boldsymbol{\varepsilon_i} \quad (1)$$

where $\boldsymbol{\tau}$ is the $t \times 1$ vector of fixed effects, $\boldsymbol{X_i}$ is an $n \times t$ design matrix which associates observations with the appropriate combinations of fixed effects, $\boldsymbol{u_i}$ is the $q \times 1$ vector of random effects, $\boldsymbol{Z_i}$ is the $n \times q$ design matrix which associates observations with the appropriate combination of random effects, and $\boldsymbol{\varepsilon_i}$ is the $n \times 1$ vector of residual errors. It is considered a homogeneous mixed model, so $\boldsymbol{u_i}$ is normally distributed with mean μ and covariance matrix $\boldsymbol{D}$. The following is assumed:

$$\begin{bmatrix} \boldsymbol{u_i} \\ \boldsymbol{\varepsilon_i} \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \boldsymbol{G}(\boldsymbol{\gamma}) & 0 \\ 0 & \boldsymbol{R}(\boldsymbol{\phi}) \end{bmatrix} \right) \quad (2)$$

where the covariance matrices $\boldsymbol{G}$ and $\boldsymbol{R}$ for the random effects and residual, are functions of parameters $\boldsymbol{\gamma}$ and $\boldsymbol{\phi}$, respectively. This can then be defined as:

$$\boldsymbol{H} = \mathrm{var}(\boldsymbol{Y}_i) = \boldsymbol{ZGZ}' + \boldsymbol{R} \quad (3)$$

Due to the hierarchical structure of the data (trees grouped into plots), the between-plot residual variation was defined as a random effect, with $\boldsymbol{Y_i}$ being the response vector (diameter growth or its transformation) for the n_i trees of plot j ($j = 1, \ldots, 41$). The generalized least-squares (GLS) technique was applied to fit the mixed linear models. The linear models were estimated using the maximum likelihood (ML) procedure of the computer software PROC MIXED in the SAS/STAT (2001).

Table 3
Mean and standard deviation (S.D.) of the main characteristics in the study material

Stratum	1	2	3
Plots	9	10	22
Trees	164	122	332
Diameter at breast height (D_1) (cm)			
Mean (min–max)	18.4 (7.5–98.6)	27.6 (7.5–80.5)	24.7 (7.5–99.3)
Median	15.3	23.7	19.0
S.D.	11.2	15.0	16.2
Total height (*HT*) (m)			
Mean (min–max)	10.6 (4.5–17.0)	9.2 (3.5–15.5)	11.2 (3.0–21.5)
Median	10.8	9.0	11.0
S.D.	2.7	2.4	3.3
Diameter increment for 10 years ($D_2 - D_1$) (cm)			
Mean (min–max)	1.53 (0.05–7.8)	2.3 (0.2–7.1)	2.59 (0.1–10.5)
Median	1.37	2.12	2.4
S.D.	0.99	1.21	1.52
Stand age (years)			
Mean (min–max)	71.9 (30.8–91.0)	70.1 (29.2–139.0)	68.3 (30.9–106.0)
Median	67.3	72.0	69.6
S.D.	12.9	26.6	15.6
Number of stems (*N*) (stems/ha)			
Mean (min–max)	1087.4 (359.1–1655.2)	424.6 (100.2–795.8)	896.3 (24.3–2164.5)
Median	1114.1	473.9	604.8
S.D.	476.4	212.0	667.3
Dominant height (H_0) (m)			
Mean (min–max)	11.6 (5.5–15.8)	9.5 (6.2–12.3)	12.5 (7.1–16.9)
Median	11.8	9.4	12.9
S.D.	2.4	1.7	2.7
Quadratic mean diameter (*DG*) (cm)			
Mean (min–max)	16.2(8.6–31.4)	23.8 (9.4–38.3)	19.3 (10.3–41.6)
Median	13.9	23.4	18.3
S.D.	5.8	9.2	7.4
Mean diameter (*DM*) (cm)			
Mean (min–max)	15.0 (8.5–24.4)	22.4 (9.3–35.4)	17.4 (10.2–41.6)
Median	13.5	23.0	15.3
S.D.	4.1	8.7	6.6
Basal area (*BA*) (m^2/ha)			
Mean (min–max)	19.2 (3.7–27.8)	15.4 (5.5–27.6)	19.2 (3.3–38.4)
Median	16.7	14.1	17.9
S.D.	6.1	7.5	9.4
Site index (*SI*) (m)			
Mean (min–max)	10.9 (7.1–15.9)	10.0 (4.3–16.7)	13.0 (8.3–17.8)
Median	12.0	9.1	13.4
S.D.	2.6	3.2	2.4

Different combinations of independent variables were tested to ascertain their importance with respect to diameter growth. The following aspects were considered for this purpose (Andreassen and Tomter, 2003): (i) desired variables (tree size, competition, site index and stand descriptions); (ii) logically interpretable sign for the estimates of these variables; and (iii) available variables in a common inventory. On the purely statistical side, the level of significance for the parameters, reduction in the values of the components of the variance–covariance matrices and the Likehood Ratio Test (LRT) were used (Calama and Montero, 2005).

Different forms of diameter growth were considered for the dependent variable: diameter increment ($D_2 - D_1$), 10-year diameter growth rate ($D\_rate = (\Delta D/D_1)$), square diameter increment ($D_2^2 - D_1^2$), and the natural logarithm of each. The tested explanatory variables can be divided into three main groups:

1. *Single-tree size variables*: diameter at breast height, D_1 (cm); and total height, *HT* (m). Natural logarithmic and inverse transformations of these variables were also tested.
2. *Stand variables*: number of stems, *N* (stems/ha); dominant height, H_0 (m); quadratic mean diameter, *DG* (cm); mean diameter, *DM* (cm); basal area, *BA* (m^2/ha); and site index, *SI* (m) according to Adame et al. (2006). Natural logarithmic and inverse transformations of these variables were also tested.

Table 4
Mean and standard deviation (S.D.) of the main characteristics in the test data

Stratum	1	2	3
N° Plots	5	4	21
N° Trees	33	23	134
Diameter at breast height (cm)			
Mean	21.7	20.8	23.3
S.D.	8.9	9.9	14.3
Diameter increment for 10 years (cm)			
Mean	0.85	0.66	1.24
S.D.	0.3	0.37	0.63

3. *Variables referring to competition/competition variables*: ratio between subject tree breast height diameter and mean squared diameter, (D_1/DG); and basal area of the trees larger than the subject tree, *BAL* (m^2/ha).
4. *Biogeoclimatic variables*: altitude (m), slope (%), insolation, texture, annual and seasonal (spring, summer, autumn and winter) rainfall (mm), average annual and seasonal (summer and winter) temperature (°C), fluctuation in temperature (difference between hottest month average temperature and coldest month average temperature in °C), potential evapotranspiration (mm), surplus (mm), deficit (mm), water index, drought period, cold period (months where average temperature <6 °C), vegetative period (months where average temperature >7 °C) and biogeoclimatic stratum (*STR*) defined by Elena Roselló (1997) (Table 1).

A logarithmic transformation of the dependent variable was made in order to linearize the relationship between the response variable and explanatory variables and to homogenize the variance (Baule, 1917; Jonsson, 1969; Hökkä et al., 1997). A transformation can bias the results because logarithmic regression theoretically estimates ‘‘medians’’ instead of the desired ‘‘means’’. Therefore, a bias correction was needed to transform the model predictions back to the original units (Flewelling and Pienaar, 1981). An empirical ratio estimator suggested by Snowdon (1991) was applied:

$$\frac{id_{10}}{\exp[\ln \hat{id}_{10}]},$$

where id_{10} is the mean of measured diameter increments for a future 10-year period and $\hat{id}_{10}$ is the mean of estimated diameter increments. Estimation of proportional bias from the ratio of the sample mean of the predicted values from the sample generally gave better corrections than the corrections using Finney's approximation (Finney, 1941) or Barkerville's method (Baskerville, 1972). Snowdon (1991) confirms that this ratio is more robust than corrections estimated from variance.

2.3. Model evaluation

Residual plots (in logarithmic and in arithmetic scales) were calculated to check any trends in residuals against different independent variables of the fixed part of the model (Hynynen, 1995; Hökkä et al., 1997; Mabvurira and Miina, 2002; Calama and Montero, 2005).

Table 5
Model performance evaluation criteria

Performance criterion	Symbol	Formula	Ideal
Absolute bias	Bias	$\sum_{i=1}^{n} \frac{obs_i - est_i}{n}$	0
Relative bias	rBias	$\frac{\sum_{i=1}^{n} (obs_i - est_i/est_i)}{n}$	0
Root mean square error	RMSE	$\left(\frac{\sum_{i=1}^{n} (obs_i - est_i)^2}{n}\right)^{1/2}$	0
Relative root mean square error	rRMSE	$\left(\frac{\sum_{i=1}^{n} [obs_i - est_i/est_i]^2}{n}\right)^{1/2}$	0
Coefficient of determination/model efficiency	R^2/Mef	$1 - \frac{\sum_{i=1}^{n} (est_i - obs_i)^2}{\sum_{i=1}^{n} (obs_i - \overline{obs})^2}$	1

est_i, *i*th estimated value; obs_i, *i*th observed value; *n*, number of observations.

To determinate the accuracy of the model predictions, the bias and precision of the models were calculated (Vanclay, 1994b). In the reliability tests for the fitting data, the means (Bias, cm; rBias, %), standard deviations of residuals (RMSE, cm; rRMSE, %) and the estimates of modelling efficiency (Mef) were achieved using the statistics shown in Table 5.

When applying the mixed model in the validation data set, only the fixed part can be used unless the random parameters can be predicted. A main advantage of mixed models is that the value for the random parameters vector $\boldsymbol{u}$, specific for a given unit, can be predicted if a complementary sample of observations taken from that sampling unit is available. These random components can be obtained by calibrating the model with the diameter increment for the trees from the validation data set. The best linear unbiased predictor (where ‘‘best’’ means minimum mean squared error), or BLUPs for the random components using complementary increments was calculated using the following expression (Searle et al., 1992)

$$\boldsymbol{u} = \boldsymbol{D}\boldsymbol{Z}^{\mathrm{T}}(\boldsymbol{R} + \boldsymbol{Z}\boldsymbol{D}\boldsymbol{Z}^{\mathrm{T}})^{-1}\boldsymbol{e} \quad (4)$$

where $\boldsymbol{u}$ is a vector of BLUPs for the random components, acting at plot level. $\boldsymbol{D}$ is a block diagonal matrix whose dimension is given by the number of random effects to be predicted. $\boldsymbol{Z}$ is the design matrix for the random components specific to the additional observations. $\boldsymbol{R}$ is the estimated matrix for the residual variance. $\boldsymbol{e}$ is a vector whose dimension is the number of observations, and whose components are the values for the marginal unconditional residuals of the model (difference between the observed increment and the predicted increment using the fixed effects marginal model).

To solve $\boldsymbol{u}$, a SAS program was developed using IML language. To evaluate the accuracy of the calibration, the standwise calibration (Lappi, 1986; Calama and Montero, 2005) was used. This type of calibration involves using the random plot components predicted from the increments of a small sample of trees per plot to predict the increment of the trees within the plot not used in the calibration. In this case, the calibration was made with 1, 2 and 3 trees per plot. For each option and plot, 500 random realizations were performed, including a different sub-sample of trees for each one.

Errors were calculated within each realization and divided into a mean value, a between-plot component (with variance SD^2_{out}) and a within plot component (with variance SD^2_{in}). Average values for each component were computed over the 500 realizations. Root mean square error was computed as the root of the sum of the squared mean error and the variance components of the error averaged for each option (Lappi, 1986). Besides the calibrated model, the model including only fixed effects and the trivial model, which assumes tree diameter increment remains constant for a 10-year period ($id_{-10} = id_{+10}$), was applied in the validation data set. Previous comparison statistics were also calculated.

3. Results

After considering different forms of diameter growth, the logarithm of tree diameter growth ($\ln(D_2 - D_1+1)$ was chosen as the dependent variable for the response model. The constant value 1 was added to each growth observation before making the logarithm transformation to obtain normally distributed residuals with constant variance (Hökkä et al., 1997; Hökkä and Groot, 1999; Calama and Montero, 2005). Several models were set up and compared with the basic data thorough an iterative process by analysing the residuals in relation to the input variables. Variables for which the associated parameter estimates were not significantly different statistically from zero were excluded from the model. After some testing, the best biological as well as statistical properties were shown with the following independent variables:

a. *Single-tree size variables*: natural logarithm of diameter of breast height ($\ln D_1$) square value of diameter at breast height (D_1^2).
b. *Stand variables*: number of stems (N); dominant height (H_0); and site index (SI).
c. *Variables referring competition/competition variables*: basal area of the trees larger than the subject tree (BAL) (m^2/ha).
d. *Biogeoclimatic variables*: biogeoclimatic stratum (STR).

The fixed parameter estimates were logical and significant at the 0.05 level. The random parameter estimate of the plot factor was significant at the 0.01 level. The empirical ratio estimator suggested by Snowdon (1991) was 1.047088161. The expression of the individual-tree diameter growth model for *Q. pyrenaica* coppices was:

$$\begin{aligned}\ln((D_{ij2} - D_{ij1}) + 1) &= 0.8351(0.2085) + 0.1273(0.05586)\ln(D_{ij1}) \\ &\quad - 0.00006(0.00002)D_{ij1}^2 - 0.01216(0.00302)BAL_{ij} \\ &\quad - 0.00016(0.00006)N_j - 0.03386(0.01222)H_{0j} \\ &\quad + 0.04917(0.01165)SI_j - 0.1991(0.07089)STR_k + u_j + \varepsilon_{ij}\end{aligned} \quad (5)$$

$$u_j \sim N(0, 0.02467)$$
$$\varepsilon_{ij} \sim N(0, 0.08966)$$

Table 6
Fit statistics for the distance-independent individual-tree diameter growth model

Performance criterion	Fitting data	
	Fixed model	Random model
Bias	−2.1164E-15	6.7419E-16
rBias	0.0025	−0.0049
RMSE	1.1396	0.9355
rRMSE	0.3572	0.2808
Mef	0.1748	0.4438

where D_{ij2} = breast height diameter over the following 10 years (cm) belong to the observation i taken in the j plot; D_{ij1} = present breast height diameter belong to the observation i taken in the j plot (cm); BAL_{ij} = present basal area of trees larger than the subject tree i in the j plot (m^2/ha); H_{0j} = present dominant height in j plot (m); SI_j = site index at an index age of 60 years in j plot (m); STR_k = stratum k whose value is 1 if the observation comes from stratum *1* and 0 if not; u_j is a random plot parameter specific to the observations taken in the j plot: and ε_{ij} are residual error terms. In brackets the standard error of the parameter is shown.

The fit statistics for the model obtained are included in Table 6. The random model (prediction obtained by Eq. (5)) shows a bias quite similar to that of the fixed model (prediction obtained by the fixed part of Eq. (5)), but better efficiency and RMSE. In the final model, there were no discernible trends in the residuals at logarithmic scale (Fig. 2) or arithmetic scale (Fig. 3) with respect to the predicted diameter growth or with respect to the regressor variables of the model. However, high predicted values show some variability trends because of the less number of data for high diameter increments greater than 4 cm (49 trees of 606 total trees) (Fig. 3a).

The results for the model including only fixed effects, trivial approach (it assumes constancy in diameter increment) and calibrated random model approach in the validation data set are shown in Table 7. The trivial model performs correctly compared with the model including only fixed effects, presenting better results for RMSE, rRMSE, Mef, SD_{out} and SD_{in}, but worse results for Bias and rBias. The residuals of the trivial approach display a biased prediction for some of the explanatory variables of the proposed model (Fig. 4b for D_1 Fig. 4c for BAL; Fig. 4d for N; Fig. 4e for H_0; Fig. 4f for SI). The performance criterion for calibrated predictions is significantly better than with the model including only fixed effects. The results are similar to those obtained with the trivial model but there is a substantial improvement for Bias, rBias and SD_{in}. The efficiency increases from 0.02 to 0.49 if just one diameter increment per plot is measured to calibrate the model. The calibration of 2 or 3 trees significantly improves Bias and rBias compared to the calibration of one tree and slightly improves the rest of the statistics.

4. Discussion

This study presents an individual-tree diameter growth model for *Q. pyrenaica* coppices in northwest Spain (Castilla-

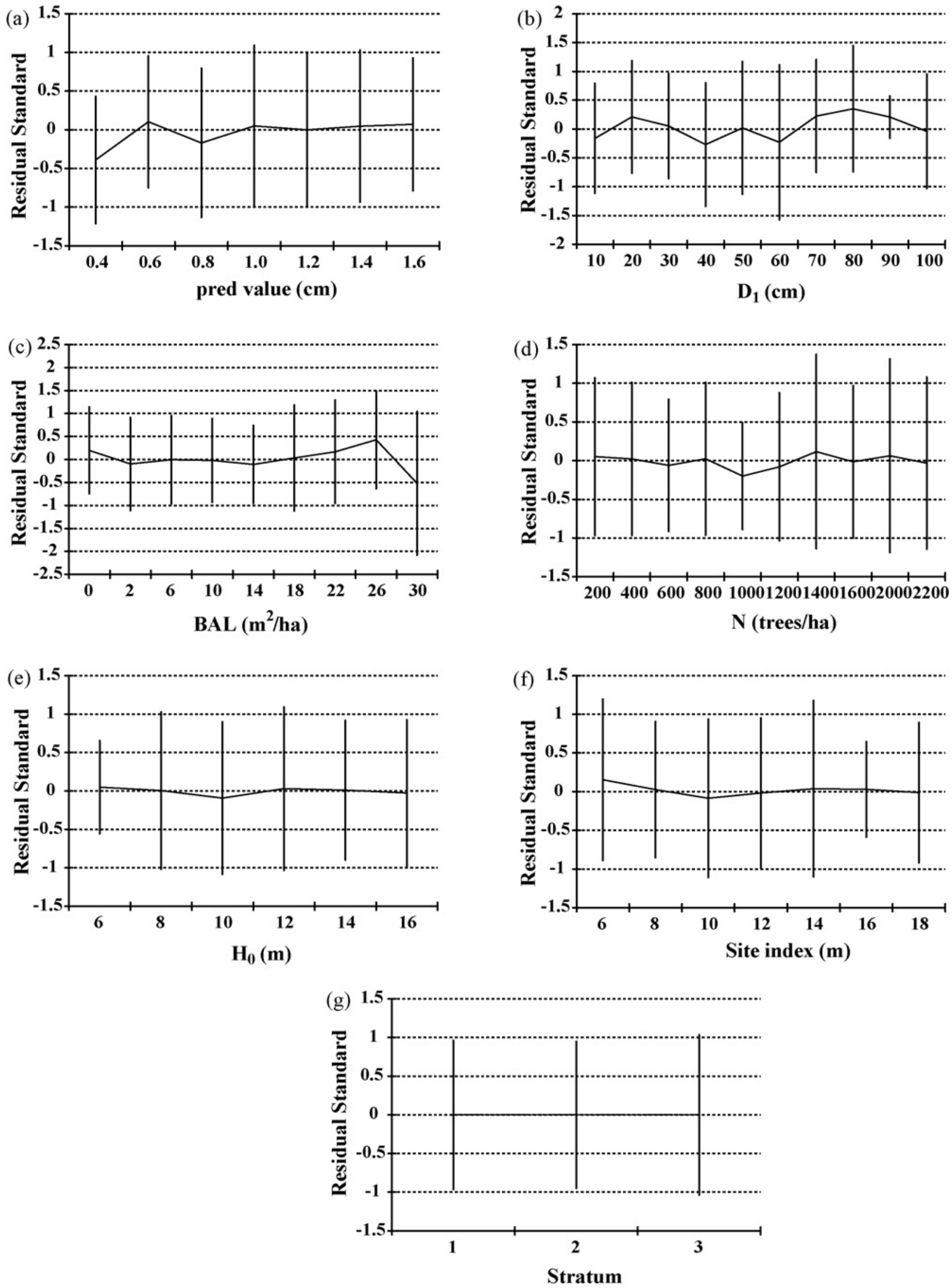

Fig. 2. Residuals (means ± S.D.) in log scale of diameter growth model (Eq. (5)) with respect to predicted diameter growth (a), diameter at breast height (D_1) (b), basal area of larger trees (*BAL*) (c), number of stems (*N*) (d), dominant height (H_0) (e), site index (*SI*) (f) and biogeoclimatic stratum (*STR*) (g).

León region), based on permanent sample plots measured twice by the Spanish National Forest Inventory. The proposed model is stochastic, where a fixed part explains the mean value for the diameter increment and unexplained residual variability is described by including random parameters. Potential predictor variables were selected based on their biological importance for tree growth rather than simply fitting statistics because if a model does not make biological sense, it will not perform well for any data set other than that used for model development (Hamilton, 1986). The predictor variables are related to tree size, stand variables, competition index and biogeoclimatic variables.

After testing different independent variables, the following were included in the model as explanatory variables constituting the fixed part: the diameter at breast height (D_1), basal area of larger trees (*BAL*), number of stems (*N*), dominant height (H_0), site index (*SI*) and biogeoclimatic stratum (*STR*) as well as a random parameter acting at plot level. Taking into account the explained variability, in descending order this would be *BAL*, *N*, *SI*, *STR*, H_0 and D_1.

The shape of the relationship between diameter at breast height (D_1) and diameter growth have the skewed unimodal form that is typical of tree growth processes (Fig. 5). The square diameter D_1^2 hastens the approach to zero for large diameters,

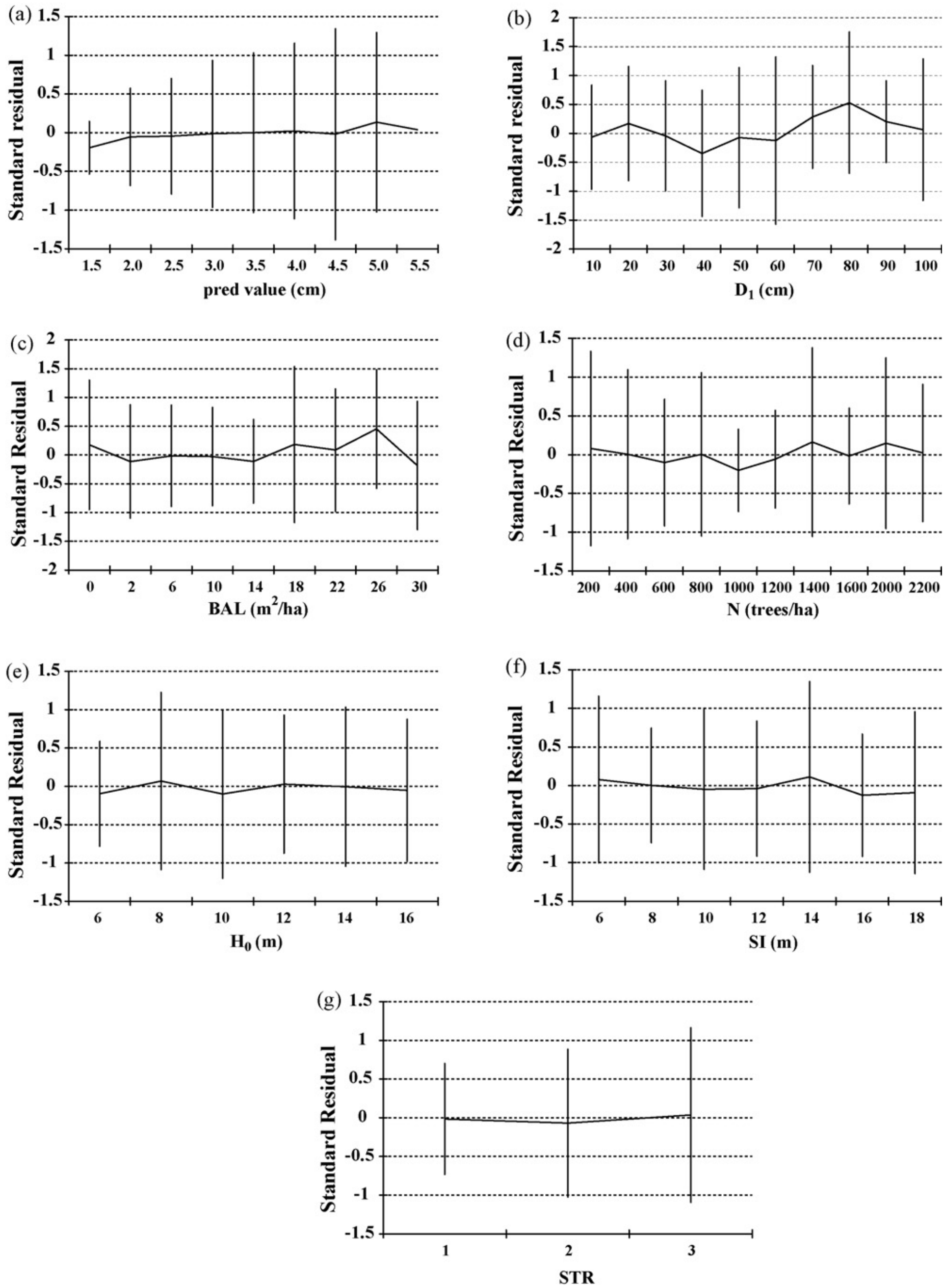

Fig. 3. Residuals (means ± S.D.) in real scale of diameter growth model (Eq. (5)) with respect to predicted diameter growth (a), diameter at breast height (D_1) (b), basal area of larger trees (*BAL*) (c), number of stems (*N*) (d), dominant height (H_0) (e), site index (*SI*) (f) and biogeoclimatic stratum (*STR*) (g).

meanwhile the variance of observed $\ln(D_1)$ is more or less constant over the observed range of logarithmic variable (Wykoff, 1990).

The basal area of larger trees (*BAL*) confirms that an increase in competition leads to a reduction in the diameter growth. The basal area of larger trees has been considered as a variable to capture competition for light (Schwinning and Weiner, 1998). The light is seen as a surrogate of one-sided competition (Yao et al., 2001), which occurs when the larger trees have a competitive advantage over smaller ones, but these smaller neighbours do not affect the growth and survival of larger trees (Cannel et al., 1984). The trees analysed are not growing in sparse stands, so this kind of competition has a significant influence on the diameter growth. Number of stems also has negative parameter, which shows a decrease in the growth rate as the stand becomes more crowded. Unless grown openly, a tree always experiences some competition from its neighbors, competing for limited physical space and resources such as light, water and soil nutrients (Yang et al., 2003). In this case, number of stems represents a two-sided competition, as all trees impose some competition on their neighbors, regardless of their size (Cannel et al., 1984). Rebollo oak stands are generally coppices, so competition is high for both water and soil nutrients. If both variables are compared, *BAL* explains more

Table 7
Comparison between fixed effect model, classic approach and calibrated model in validation data set

	Fixed model	Trivial model	Calibrated model		
			1 tree	2 trees	3 trees
Plots	30	30	30	30	30
Trees	190	190	190	190	190
Bias (S.D.)	1.4047E-15	−0.1150	−0.00036 (0.0168)	6.0481E-18 (2.8103E-17)	3.8391E-18 (2.9449E-17)
rBias (S.D.)	0.0374	−0.1240	0.0022 (0.0149)	0.0026 (0.0012)	0.0025 (0.0014)
RMSE (S.D.)	0.5899	0.4006	0.4194 (0.017)	0.4089 (0.0213)	0.4001 (0.0292)
rRMSE (S.D.)	0.3060	0.3259	0.348 (0.012)	0.3363 (0.0132)	0.3147 (0.017)
Mef (S.D.)	0.0241	0.5277	0.4959 (0.0316)	0.5172 (0.0293)	0.5569 (0.0410)
SDout (S.D.)	0.4030	0.2865	0.4207 (0.0172)	0.4105 (0.0214)	0.4022 (0.0294)
SDin (S.D.)	0.3962	0.2071	0.0521 (0.0039)	0.0524 (0.0042)	0.0496 (0.0067)

The calibrated model results are obtained as the average from 500 random realizations, including different trees in the calibration data set. S.D.: standard deviation. SD_{out}, between-plot variance; SD_{in}, within-plot variance.

variability than density because of the coppice stand structure in which high densities occur in groups. For other Mediterranean species, two-sided competition is more significant than one-sided (Calama and Montero, 2005; Sánchez-González et al., 2006).

A negative parameter for the dominant height (H_0) effect implies that the diameter growth rate of trees generally decreases as dominant height increases. This means that in two stands with the same site index, greater dominant height indicates older trees or mature stands, and consequently, smaller diameter increments than younger stands (Calama and Montero, 2005).

Site index (*SI*) is positively related to increment; therefore trees will attain greater diameter increments in better sites. This variable usually exerts a significant effect in diameter growth models (Hynynen, 1995; Gobakken and Naesset, 2002; Andreassen and Tomter, 2003).

The relationships between diameter growth and the various biogeoclimatic characteristics tested are not statistically significant in this study and are only considered indirectly in terms of biogeoclimatic stratum. This result conflicts with those of other publications on the holm oak (Mayor and Rodà, 1994) and conifers (Yeh and Wensel, 2000), in which precipitation and temperature could explain the high variation in diameter growth. This apparent contradiction might be explained if one takes into account that the climatic characteristics reflected are average values measured at the nearest weather station to the plot, meaning that microsite and annual values are not considered. According to Kangas (1998), if growth and yield predictions are made assuming average weather conditions, the real diameter growth could deviate about 25% from the expected growth in a given year. The negative parameter estimate of the dummy variable *STR* from stratum 1 as against strata 3 and 2 implies that these sites are more beneficial for growth. These strata are situated at a higher altitude with higher precipitation, lower temperatures (Table 1), and medium stand characteristics, underlining the highest dominant height and best site index (Table 3).

The previously mentioned relationships between independent variables and diameter growth can be seen in Fig. 5. All the graphs indicate that the higher the *BAL*, the smaller the diameter increment, apart from the differences in number of stems (Fig. 5a versus Fig. 5b and Fig. 5c versus Fig. 5d) and in site index (Fig. 5a versus Fig. 5c and Fig. 5b versus Fig. 5d).

The random effects at plot level were highly significant and the inclusion of the random parameter in the complete model greatly improves the fixed model. The efficiency rose from 17.5 to 44.4%, and the results were also slightly better for the rest of the performance criteria. The low efficiency of the model including only fixed effects may result from one or all of the following aspects: (i) the particular characteristics of the species, (ii) omission of silvicultural treatments and past incidents such as fires, (iii) unknown variables not included in the model (soil attributes or climatic annual characteristics). Nevertheless, the value is similar to that of other diameter growth models, reaching efficiencies of 48.72% for *Pinus pinea* L. (Calama and Montero, 2005), 36% for other broadleaves in Norway (Andreassen and Tomter, 2003) and between 43.2% and 72.3% for hardwood stands in the lower Mississippi (Zhao et al., 2004).

The differences in the performance of the mixed and fixed models is supported by the findings of Guilley et al. (2004), who observed for *Quercus petraea* that most of the between-tree variability in terms of wood density was shown to occur at the within-stand level. However, the between-plot variability could be the result of not taking into account past silvicultural treatments (Hynynen, 1995; Hökkä et al., 1997). The silvicultural practices applied in the study area vary greatly and this factor is not considered in the model. Since forest management has a considerable influence on diameter growth, the silvicultural treatments could explain a large portion of the residual variance in the diameter growth model. Cañellas et al. (2004) concluded that thinning plots of rebollo oak (testing three different treatments of 25%, 35% and 50% basal area removal) increased mean stem diameter increment in comparison to unthinned plots (from 0.99 mm yr^{-1} for unthinned plots to 2.11 mm yr^{-1} for thinned plots). Moreover, the growth of larger stems was stimulated by thinning more than that of smaller trees.

It should also be taken into account that diameter growth in fitting data is determined as the difference between diameter measurements taken at 10-year intervals by SNFI. This

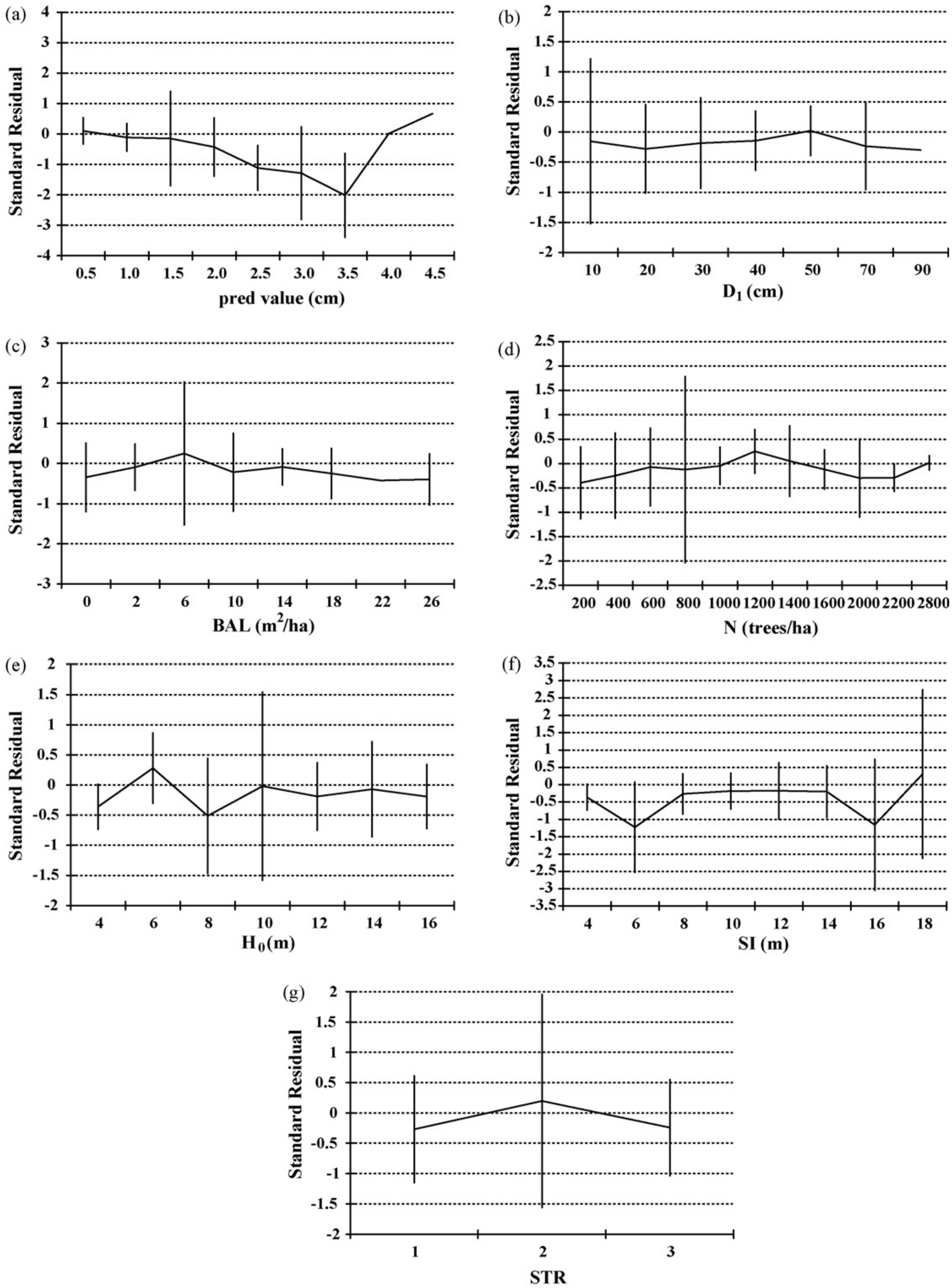

Fig. 4. Residuals (means ± S.D.) of trivial model with respect to predicted diameter growth (a), diameter at breast height (D_1) (b), basal area of larger trees (*BAL*) (c), number of stems (*N*) (d), dominant height (H_0) (e), site index (*SI*) (f) and biogeoclimatic stratum (*STR*) (g).

methodology has some disadvantages (Trasobares et al., 2004): the breast height diameter may not have been measured at exactly the same height or in the same direction on each occasion. The annual variation in diameter growth is an important source of uncertainty in future growth predictions, especially in short-term predictions (from 5 to 10 years) (Eid, 2000; Gobakken and Naesset, 2002). Furthermore, because it is not possible to know the age of every tree, some complementary age measurements are necessary to calculate the site index.

Calibration using complementary measurements leads to a great improvement in the application of the model. The accuracy of the prediction improves greatly with just one increment measurement per plot (efficiency from 0.024 to 0.4959). However, it is better to measure at least two samples

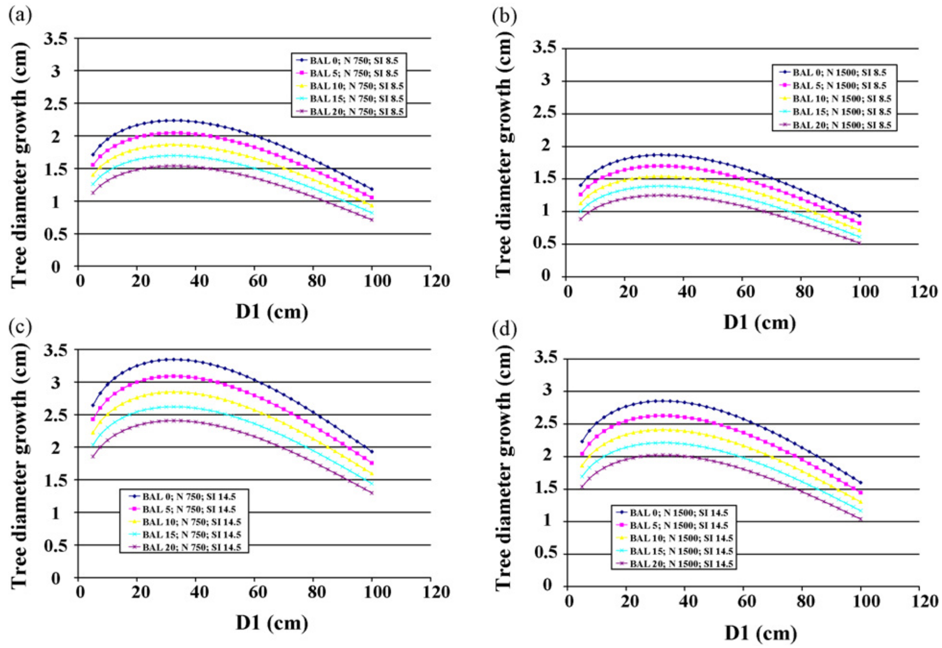

Fig. 5. Relationship between proposed model and independent variables.

because the standard deviation of the statistics will be lower than for a single-tree calibration (Table 7).

For the validation data set, the trivial model performs correctly compared with the random model and its performance is much better than that of the fixed model. This might be due to the fact that the *Quercus* genus is generally made up of slow-growing species (compared to the *Pinus* genus) and its growth is also quite constant. These slower rates of stem diameter growth are due on the one hand to the particular characteristics of the species and on the other to environmental conditions (e.g. water deficits, . . .). Even so, the residuals of the trivial model give a biased forecast (Fig. 4), leading to an overestimation if the trivial model is applied in the growth prediction of large growths.

With regard to the validation data set, the measurement process differs from that used for the fitting data set. Taking cores with a Pressler increment borer presents difficulties in this species because the growth centre is not usually in the centre of the tree, and two or more different growth centres may be found at breast height. This characteristic is somewhat inconvenient if tree age is required to estimate the site index. In future research, radial increments should be recorded by averaging two perpendicular measurements at breast height using a Pressler increment borer, or even through stem analysis.

The low-density stands are not included in the analysis, so large diameters are not proportionally represented in the study. The results of this report might be analysed in future research, applying them to open stands, which are very important in Spain from an ecological point of view as well as in terms of landscape. In this respect, Cabanettes et al. (1999) tested the possibility of adapting conventional forest growth models to widely spaced oak trees. Preliminary indications on growth trends suggested that the diameter growth curves of widely spaced trees reach a point of inflexion at a later age than those in closed forest stands, as well as having a higher asymptote.

Q. pyrenaica coppice stands present one of the biggest challenges that forestry research currently faces in Spain. Traditional uses are being progressively abandoned and they are at risk of fire and degradation. Therefore, further study into evolution and management alternatives is necessary. Forecasting diameter growth is one of the primary components of individual-tree growth models, which are essential for managing and predicting long-term growth performance. These models allow detailed analyses to be carried out on stand structure, production and economics in relation to species, layers and silvicultural methods.

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