Stand-level yield model for Scots pine (*Pinus sylvestris* L.) in north-east Spain

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SUMMARY

Simultaneous stand-level growth and yield models for *Pinus sylvestris* in north-east Spain were developed based on 21 permanent sample plots established in 1964 by the Instituto Nacional de Investigaciones Agrarias (INIA). The plots ranged in site index from 13 to 26 m (dominant height at 100 years), and were measured an average of 5 times. The estimation data consisted of 79 growth periods of stands ranging in age from 36 to 132 years. Non-linear three-stage least squares method was used to simultaneously fit prediction and projection equations for stand basal area, volume and stand density. An existing model for dominant height growth fitted with the same estimation data was used to project dominant height. The models were evaluated both quantitatively and qualitatively. Correlation among error components of the prediction equations for basal area and volume as well as the projection equations for number of trees per hectare and volume were strong and significant. The mean biases for basal area, volume and number of trees per hectare predictions were positive. The presented system of models can serve for forest-level management planning as a simple yield prediction system that requires only stand level input data.

Key words: non-linear multistage regression, simulation, simultaneous equations

INTRODUCTION

Pinus sylvestris L. plays an important role in Spanish forestry because of its economic, ecological and social relevance. *P. sylvestris* forms large forests in most of the mountainous areas of Spain, occupying an area of 1,280,000 ha (Montero *et al*., 2001). Efficient forest management planning of Scots pine in Spain needs reliable information on forest stand development under different treatment alternatives for evaluating the numerous forest management alternatives. Yield prediction models can be categorised by the complexity of the mathematical approach involved. Clutter *et al.* (1983) divided yield prediction models into: (a) models in tabular form; and (b) equations and systems of equations. In Spain, yield predictions have been traditionally taken from yield tables-tabular records showing the expected volume of wood per hectare by combinations of measurable characteristics of the forest stand (age, site quality, stand density). Yield tables are static models that usually apply to fully stocked or normal stands. Examples of yield tables for Scots pine in Spain are in García Abejón (1981), García Abejón and Gómez Loranca (1984), Garcia Abejón and Tella Ferreiro (1986) and Rojo and Montero (1996). However, during the last decade several forest growth modelling studies expressing stand growth and yield as systems of interrelating equations that can predict future stand development with any desired combination of inputs have been undertaken in Spain [*e.g.*, by Espinel *et al.* (1997) for *Pinus radiata* in País Vasco, by Río (1998) for *Pinus sylvestris* L. in Sistema Central and Ibérico, by Álvarez González *et al.* (1999) for *Pinus pinaster* Ait. and by Palahí *et al.* (2002b) for *Pinus sylvetris* in north-east Spain].

Forest stand modelling approaches may be thought to lie on a continuum with respect to structural complexity and output detail (Daniels and Burkhart, 1988). This continuum may be broken into three broad categories: (1) whole-stand models (2) size-class distribution models, and (3) individual-tree models.

A number of researchers have used multiple regression to construct aggregate stand growth and yield expression (*e.g.*, Bennet *et al*., 1959; Schumacher and Coile, 1960; Clutter, 1963; Burkhart *et al*., 1972; Sullivan and Clutter, 1972; Murphy, 1983; Burkhart and Sprinz, 1984; Borders and Bailey, 1986; Pienaar and Harrison, 1989; Amaro *et al*., 1997; Río, 1998). These models provide growth and yield estimates for the whole stand as a function of stand level attributes such as age, density and site index, as well as interactions among these variables. Stand density, in turn, might be taken to be a function of an initial measure of stand density, age and site quality. Site quality, expressed by site index, depends on the development of dominant height in relation to age (Clutter *et al*., 1983). It is apparent that forest growth and yield models are an interdependent system of underlying growth processes. In such a system each equation describes a different relationship among a set of variables in the system, but all relationships are assumed to hold simultaneously (Borders and Bailey, 1986). Clutter (1963) introduced the notion of compatibility in growth and yield equations by recognising that the algebraic form of the yield model can be derived by mathematical integration of the growth model. Sullivan and Clutter (1972) extended Clutter's models by simultaneously estimating yield and cumulative growth as a function of initial stand age, initial basal area, site index, and future age. Burkhart and Sprinz (1984) presented a method for simultaneously estimating the parameters in the Sullivan-Clutter equation system. Furnival and Wilson (1971) suggested that techniques commonly used to fit interdependent multiequation models in econometrics might be applicable for growth and yield modelling situations. Murphy and Sternitzke

(1979) and Murphy and Beltz (1981) applied a technique known as restricted three-stage least squares to fit simultaneous growth and yield models. The successful application of these techniques (*e.g.*, by Borders and Bailey, 1986; Pienaar and Harrison, 1989; Río, 1998; Mabvurira and Miina, 2001), provided foresters with simulation tools developed using theoretically sound statistical procedures. In Spain, Río (1998) applied the above mentioned techniques to fit simultaneous growth and yield models for Scots pine in Sistema Central and Sistema Ibérico.

The objective of this study was to develop a system of interdependent and compatible equations to predict stand growth and yield of Scots pine stands in north-east Spain using three-stage least squares techniques as the estimation procedure.

MATERIAL AND METHODS

Data

The data were measured in 21 permanent sample plots (Table 1) established in 1964 by the Instituto Nacional de Investigaciones Agrarias (INIA) to represent most Scots pine sites in north-east Spain. The plots were located in the 3 provinces of Huesca, Lérida and Tarragona. The plots were naturally regenerated and thinned between the first and second measurement. The sites ranged in site index (at an index age of 100 years) from 13 to 26 m according to the site index model developed by Palahí *et al.* (2002a). The mean plot area was 0.1 ha. The plots were measured at 5-year intervals, except for the last measurement where the interval varied from 10 to 16 years. The last measurement was conducted

Table 1

Summary of the characteristics of the 21 permanent plots as computed from the 79 observations used in the study. The stand characteristics are given for the beginning of the growth period

Variable	Average (min, max)	Standard deviation
Stand age (yr)	67.4 (36, 132)	23.2
Site index (m)	19.9 (13.7, 25.8)	3.30
Basal area ($m^2\ ha^{-1}$)	41.7 (22.6, 60.9)	8.7
Number of trees ha^{-1}	1,199.7 (424, 2896)	684.0
Dominant height (m)	15.6 (8.7, 23.3)	3.3
Volume ($m^3\ ha^{-1}$)	312.2 (97.3, 602.6)	109.0
Number of measurements per plot	4.7 (2, 6)	1.0

during the year 2000 and there was an average of 5 measurements per plot. At each measurement, tree diameter at 1.3 meters height (dbh) from all trees thicker than 5 cm, and tree heights of a sample of at least 20 trees per plot from different diameter classes were recorded. A height-diameter regression equation for each plot at a time was fitted using the sample tree data. The regression equation was then used to estimate the height of trees other than sample trees. The total tree volumes were computed using the formula developed by Pita Carpenter (1967):

$$v = -28.34 + 2.16 \times h + 16.59 \times d^2 + 2.794 \times d^2 \times h \qquad [1]$$

where v is tree volume in dm^3, h is tree height in m and d is dbh in dm.

Stand aggregates (dominant height, basal area, number of trees and volume per hectare) were computed for each plot and measurement. Site index was determined from the dominant height and age of each plot, using the site index model developed by Palahí *et al.* (2002a).

Most plots were thinned after the first measurement. Many of the removed trees were dying or already dead when the thinning was carried out. Because it was not known whether a removed tree was living or dead the first measurement interval was not used in the estimation process.

System of equations

Several basal area and volume prediction and projection models (Amaro *et al.*, 1997, Mabvurira and Miina, 2001) as well as survival functions (Pienaar and Shiver, 1986) were fitted to the data using ordinary least squares. The best models as determined by percent of variation explained, residual analysis and biological realism were selected. The use of sequential measurements with the objective of predicting over discrete time intervals is commonly done by using difference forms of the integral functions (*e.g.,* Tomé, 1988; Borders, 1989; Huang 1994; Amaro *et al.,* 1997; Mabvurira and Miina, 2001). These are derived from the integral form using the functional equivalence at two different times. This algebra frees one of the function parameters in that its value becomes independent of the ratio of the function´s value at the two times (Amaro *et al.,* 1997). Compatible basal area and volume projection equations using the methodology described above were derived from the selected prediction equations [3] and [5]. The simultaneous system of compatible prediction and projection equations consisted of stand basal area and volume prediction models and a model for number of trees per hectare (henceforth referred to as survival function) (Equations 2-6):

$$N_2 = N_1 \times e^{[\beta_0 \times (T_2 - T_1)]} + \varepsilon_1 \qquad [2]$$

$$G_1 = \alpha_0 \times e^{\frac{\alpha_1}{T_1}} \times H_1^{\alpha_2} \times N_1^{\alpha_3} + \varepsilon_2 \qquad [3]$$

$$G_2 = G_1 \times e^{\left(a_1 \times \left(\frac{1}{T_2} - \frac{1}{T_2}\right)\right)} \times \left(\frac{H_2}{H_1}\right)^{\alpha_2} \times \left(\frac{N^2}{N^1}\right)^{\alpha_3} + \varepsilon_3 \qquad [4]$$

$$V_1 = \lambda_0 \times G_1^{\lambda_1} \times H_1^{\lambda_2} \times N_1^{\lambda_3} + \varepsilon_4 \qquad [5]$$

$$V_2 = V_1 \times \left(\frac{G_2}{G_1} \right)^{\lambda_1} \times \left(\frac{H_2}{H_1} \right)^{\lambda_2} \times \left(\frac{N_2}{N_1} \right)^{\lambda_3} + \varepsilon_5 \qquad [6]$$

where N_1, N_2 and V_1, V_2 and G_1, G_2 and H_1, H_2 are, number of trees per hectare, volume (m³/ha), basal area (m²/ha) and dominant height (m) at stand ages (years) T_1 and T_2 respectively, and β_i, α_i, λ_i, are unknown parameters to be estimated from the data and e_i are unknown stochastic error terms.

Since the use of the system of the equations requires the estimation of the future dominant height (H_2) with a dominant height growth model, estimated H_2 was used instead of measured H_2 when the system was fitted. The dominant height growth model (Equation 7) developed by Palahí *et al.* (2002a), using the same permanent sample plots data as in this study, was used for this purpose:

$$H_2 = \frac{T_2^2}{18.6269 + T_2 \times \left[\frac{T_1}{H_1} - 0.03119 \times T_1 - \frac{18.6269}{T_1} + 0.03119 \times T_2 \right]} \qquad [7]$$

Equations 2-6 form a recursive system of equations exhibiting sequential relationships. Variables on the left-hand side are endogenous (N_2, G_1, G_2, V_1, V_2) and all other variables are exogenous (N_1, H_1, H_2, T_1, T_2). Endogenous variables can occur on both the left-hand side (LHS) and right-hand side (RHS) of an equation. For this type of equation system, ordinary least squares (OLS) can be used to obtain parameter estimates if there is no cross-equation correlation between error components of the various equations in the system, but the resultant prediction and projection models would not be compatible. When cross-equation correlation between error components exist, the RHS endogenous variables might be correlated with error components of LHS endogenous variables (Borders, 1989). In OLS, variables on the RHS are assumed to be uncorrelated with the error terms, and are usually assumed to be non random. Because of this, parameter estimates by OLS can be shown to be biased and inconsistent, commonly called least squares bias. Due to the limitations of OLS for fitting interdependent systems of equations, for fitting the system of equations [2] to [6] the non-linear 3-stage least square method (N3SLS) was used. In the first step, ordinary least squares are used to estimate the parameters of each of the equations which do not have any dependent variables on the right hand side of the equation. The predicted values are then used in equations where they appear on the right-hand side in order to estimate parameters in these equations by ordinary least squares. Residuals from the fitted equations are used to estimate the contemporaneous covariance matrix between equations in the second step. This covariance matrix is used in a generalised least squares estimation procedure in the third step in which parameter constraints across equations are also imposed. The MODEL procedure in SAS software (SAS, 1999) was used to implement this fitting technique. This method (N3SLS) maintains compatibility between all prediction and projection equations and account for all interdependencies in the system of equations. Details of multistage regression theory are found in works by Dutta (1975), Judge *et al.* (1980), Pindyck and Rubinfeld (1981) and Fomby *et al.* (1984).

Models evaluation

The models were evaluated both qualitatively and quantitatively according to the methods recommended by Soares *et al.* (1995), von Gadow and Hui (1998) and applied by Amaro *et al.* (1997), Tomé and Soares (1999) and Mabvurira and Miina (2001). As a consequence of the small size of the available data set, it was decided to use all data for fitting the model, therefore it was not possible to evaluate the prediction ability of the models on the basis of prediction residuals. Quantitative evaluation was then based on ordinary residuals. Comparison of observed and simulated growth series for the available plots was also performed.

Qualitative evaluation involved the examination of model predictions to ensure their consistency and adherence to current biological theories on forest growth.

Fitting statistics

Quantitative evaluation involved the characterisation of model error (bias and precision) and the computation of the model efficiency (R^2). In addition, residuals were examined to detect any obvious patterns and systematic discrepancies. Model bias and precision were evaluated by computing the mean residuals (MRES), the absolute mean residuals (AMRES), and the root mean square error (RMSE) (Equations 8, 10 and 12). These were also expressed in relative terms as percentages of predicted mean values (Equations 9, 11 and 13). The bias and precision of the projection models of the system were also examined using different projection intervals.

$$\text{MRES} = \frac{\sum (y_i - \hat{y}_i)}{n} \tag{8}$$

$$\text{MRES\%} = 100 \times \frac{\sum (y_i - \hat{y}_i) / n}{\sum \hat{y}_i / n} \tag{9}$$

$$\text{RMSE} = \frac{\sqrt{\sum (y_i - \hat{y}_i)^2}}{n - 1} \tag{10}$$

$$\text{RMSE\%} = 100 \times \frac{\sqrt{\sum (y_i - \hat{y}_i)^2 / (n - 1)}}{\sum \hat{y}_i / n} \tag{11}$$

$$\text{AMRES} = \frac{\sum |y_i - \hat{y}_i|}{n} \tag{12}$$

$$\text{AMRES\%} = 100 \times \frac{\sum |y_i - \hat{y}_i| / n}{\sum \hat{y}_i / n} \tag{13}$$

where n is the number of observations, and y_i and $\hat{y}_i$ are observed and predicted values, respectively.

In addition, the error component in the projection equations G_2 and V_2 was divided into the prediction error component and the projection error component. The projection error component was calculated using the actual values of G_1, and V_1 as predictors so that only the projection equations of the system are used. The prediction error component was calculated as the difference between the total error component, calculated using the predicted G_1, and V_1 in the projection equations G_2 and V_2, and the projection error component.

Simulations

In addition, the models were further evaluated by graphical comparisons between measured and simulated stand development. The simulations were based on the set of models developed in this study and on the dominant height model developed by Palahí *et al.* (2002a). The simulation of one time step consisted of the following steps:

1. For each plot, compute the initial basal area (Eq. 3) based on the initial number of trees per hectare, dominant height and current age.
2. Calculate initial stand volume from Eq. 5.
3. For each plot, increment stand age by the time step and project the number of trees per hectare at the projection age by using Eq. 2.
4. Project dominant height at the projection age by using Eq. 7.
5. Project basal area and stand volume at the projection age by using Eqs. 4 and 6.

The stand volume development of four plots representing different site indices and stand densities at different stand ages was simulated over the whole life period of the plot. In addition all growth intervals of all plots were simulated and the simulated 5-year change in stand characteristics was compared to the measured change. The change of the last period, which was longer than 5 years, was converted into 5-year change by multiplying by 5/interval (interval is the time period between the last two measurements in years).

RESULTS

Table 2 shows the parameter estimates of the system of Equations 2-6, as well as their associated standard errors. All parameter estimates were logical and significant at 0.01 level. Because of the simultaneous estimation of parameters, prediction and projection models for both volume and basal area are compatible.

Correlation among some error components for basal area and volume as well as for number of trees per hectare and volume were significant (Table 3). A negative cross-equation correlation between the residuals for the basal area and volume at the same age means that if the basal area (Eq. 3) is over predicted, it is likely that stand volume is under predicted (Eq. 5). On the other hand, the cross equation correlation between the residuals of the stand volume prediction equation (Eq. 5) and the stand volume projection equation (Eq. 6) is positive which means that if the stand volume is over predicted in the beginning of the growth period, then it is likely to be over predicted also in the end of the five-year growth period.

Table 2

Parameter estimates and their standard errors for Equations 2-6

Parameter	Estimate	Standard error
β_0	−0.0043	0.0004
α_0	0.0876	0.0412
α_1	−16.8549	2.6139
α_2	1.3635	0.0851
α_3	0.3865	0.0374
γ_0	1.8882	0.2163
γ_1	1.1788	0.0320
γ_2	0.5423	0.0430
γ_3	−0.1160	0.0133

Table 3

Cross-equation correlation matrix of residuals of the simultaneous equation system (Equations 2-6)

	N_2	G_1	V_1	G_2	V_2
N_2	1.0000	0.0023	−0.1504	−0.0079	−0.3862 **
G_1		1.0000	−0.5598 **	−0.2131 **	0.2415 **
V_1			1.0000	0.1244	0.0052
G_2				1.0000	−0.1290
V_2					1.0000

** Significant ($\alpha = 0.005$).

There were no serious patterns on the distribution of residuals in the volume, basal area, and stand density models (Fig. 1). Mean residuals were positive for all equations of basal area, volume and number of stems per ha (Table 4), showing that some positive bias exists in the set of models. Relative and absolute mean residuals, which are measures of precision, were largest for stand volume equations (V_1 and V_2) at around 10 %. The model efficiency (R^2) was rather low for the basal area equations (G_1 and G_2). Furthermore, the error component of the projection sub-models for basal area and volume was analysed by dividing it into prediction error component and the projection error component. Since the predicted variables of the prediction sub-models (Equations 3 and 5) are used as predictors in the projection sub-models (Equations 4 and 6), the error component of the projection sub-models includes the error induced by the prediction sub-models. In the projection equations for basal area and volume (Eqs. 4 and 6) around 74 % and 70 % of the total residual mean square error and mean absolute error, respectively, was due to the use of the prediction sub-models.

Figure 2 shows the measured and predicted changes of different stand variables for all plots in all the measurements. There is some bias in the model predictions as it was already mentioned above, but no special trend can be appreciated between the predicted and the measured change in the stand variables analysed.
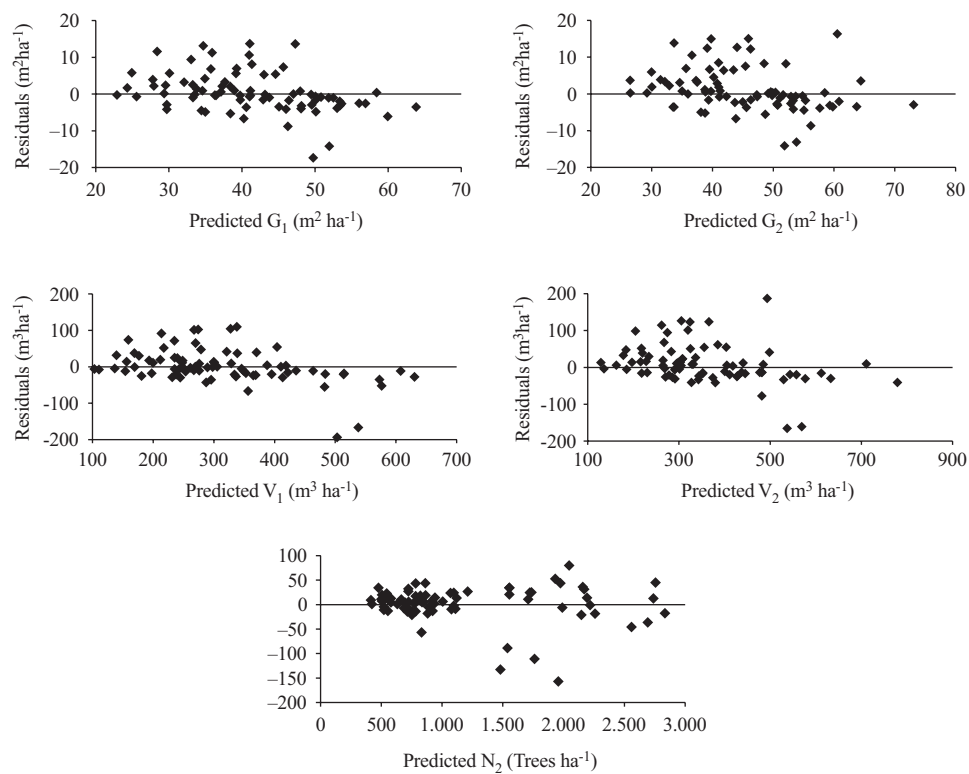
Fig 1.–Residuals versus predicted values for the sub-models of stand basal area, volume and number of trees per ha.

Table 4

Characterisation of error for Equations 2-6. See Equations 8-13 for the explanation of symbols

	R^2	MRES	MRES%	AMRES	AMRES%	RMSE	RMSE%
N_2 (ha^{-1})	0.99	1.8027	0.1546	23.6411	2.0278	36.6285	3.1419
G_1 (m^2 ha^{-1})	0.60	0.4604	1.1154	3.9350	9.5330	5.5520	13.4505
G_2 (m^2 ha^{-1})	0.62	1.1871	2.6260	4.3038	9.5201	6.0512	13.3854
V_1 (m^3 ha^{-1})	0.81	1.3252	0.4263	31.0741	9.9956	47.5102	15.2826
V_2 (m^3 ha^{-1})	0.81	8.8312	2.4767	36.7857	10.3165	54.7404	15.3519

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N-change (ha⁻¹)

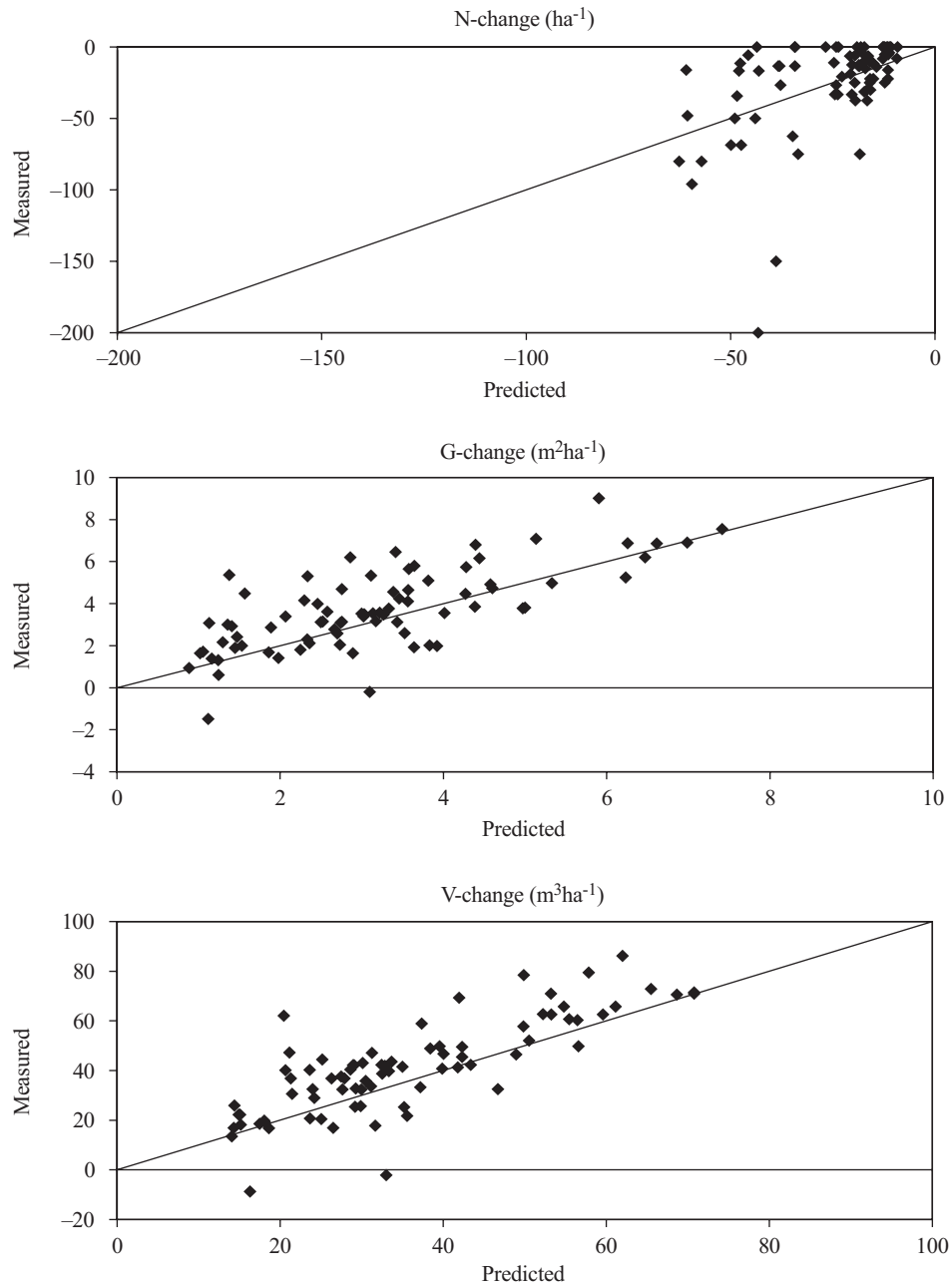
G-change (m²ha⁻¹)

V-change (m³ha⁻¹)

Fig 2.–Measured and predicted 5-year changes of all plots for all measurement intervals. V is stand volume; G is basal area; N is number of trees per ha.

Figure 3 shows the bias (mean residual) and precision (mean absolute residual) by each of the projection models of the system using different projections intervals. On one hand, the predictive ability of all projection sub-models decreases as the projection length increases. On the other hand, the projection sub-models for basal area and volume under-estimate G_2 and V_2, respectively, for a projection length less than or equal to 15 years, while they give overestimates for projection lengths longer than 15 years. The N_2 sub-model gives overestimates for a projection length longer than 5 years.
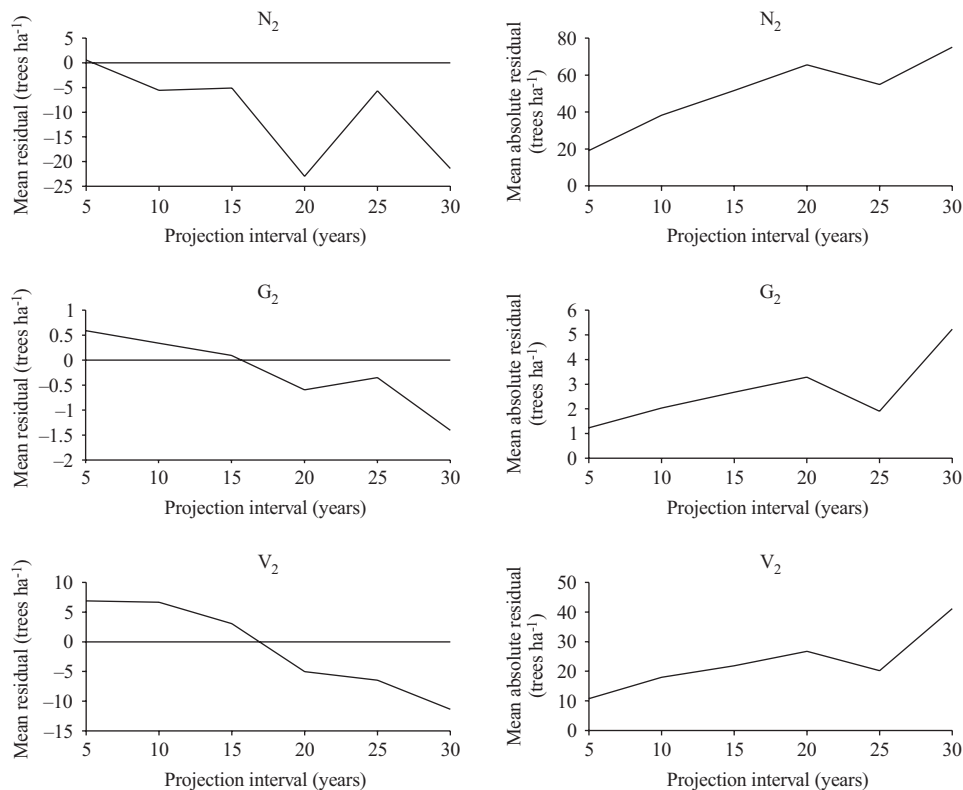
Fig 3.–Dependence of model bias (Mean residual) and precision (Mean absolute residual) on the projection length for the projection sub-models of number of trees per hectare (N_2), basal area (G_2) and volume (V_2).

To demonstrate the practical application of the system of equations, simulations of stand volume and basal area were produced and compared with real stand development for three different site indices (Fig. 4). The projections of stand development are inva-riant, regardless of the number of intermediate projection intervals used. The starting points for the past and projected stand volume and basal area simulations are the initial number of trees per hectare and dominant heights at the stand age of the first plot measurement.

The three selected plots cover the range of variation in site index and stand age among the plots used to develop the system of models. Figure 4 shows that the model set developed in this study enables a reasonably accurate long-term simulation of stand development for the three selected plots.
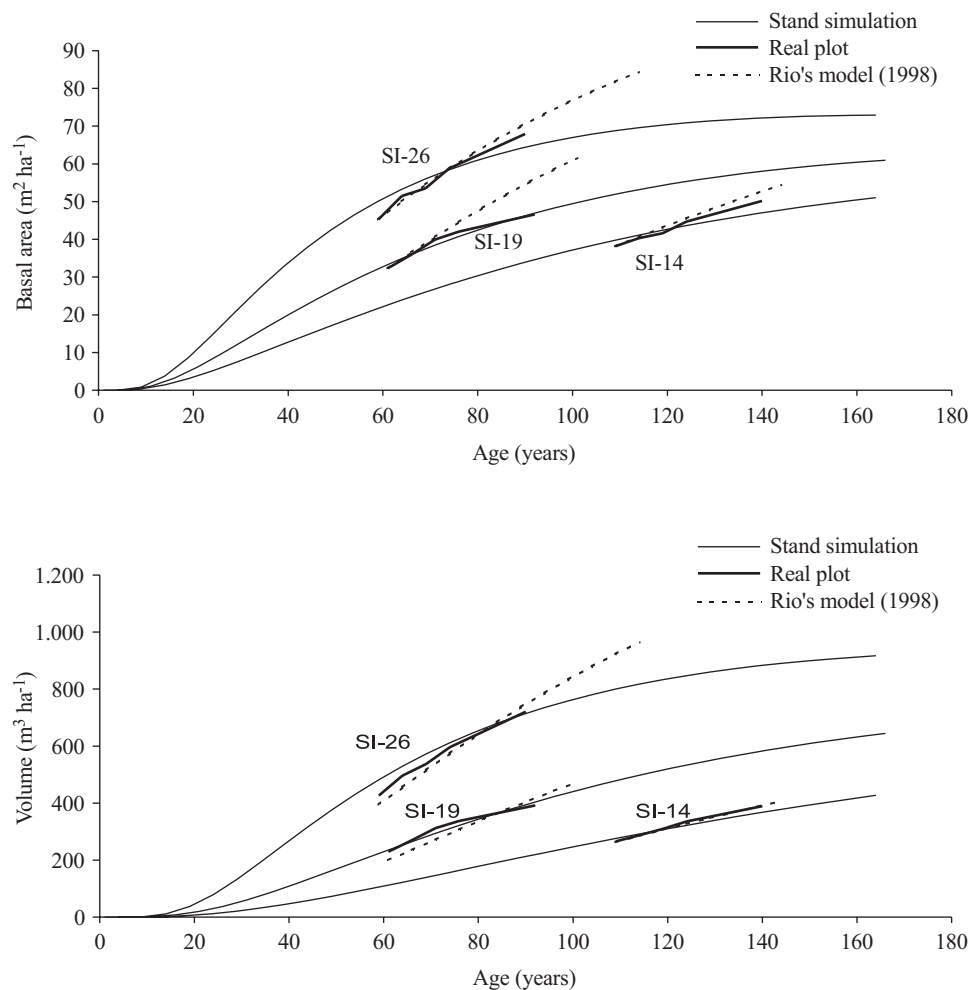

Fig. 4.–Simulations of stand basal area and volume over time for site indices 14, 19 and 26 m compared to the real stand development and the simulated stand basal area and volume development by using Río's models (1998) over the measured period. The initial stand densities for site indices 26, 19, 14 m are 566, 733 and 962 trees per hectare at stand ages of 59, 61 and 109 years, respectively.

DISCUSSION

We were aware of the restrictions of our data, with a small number of permanent plots and having only three plots with measurements over the age of one hundred years. The lack of permanent sample plots measured at young ages was also an important restriction. The initial assumptions concerning the model error term, namely non-independence of explanatory variables and the possibility of serial correlation, are violated to some degree due to the structure of the data; all permanent sample plots were measured several times. But, for instance, Río *et al.* (2001) did not detect any serial autocorrelation in a similar data set for Scots pine in Spain, in which several diameter-density relationships were modelled.

This study presents stand-level growth and yield models for Scots pine in north-east Spain. The models for stand density, stand basal area and volume were fitted simultaneously using non-linear three-stage least square method (N3SLS), while the dominant height model developed by Palahí *et al.* (2002a) was used independently to predict dominant height development. It would have been possible to include a dominant height projection model into the simultaneous system of equations, *i.e.* estimating it simultaneously with the other equations as applied by Borders and Bailey (1986) and Pienaar and Harrison (1989). However, because dominant height drives the system of the growth and yield models and it is also used to estimate the site index of a given stand as well as in other growth models for the species [for instance, an available individual tree model developed by Palahí *et al.* (2002b)], it had to be assured that a robust and reliable projection model for dominant height, not connected to a particular growth model, is available.

The functional form of the basal area equation appeared to be the most difficult to estimate. One explanation for the poor coefficient of determination of the selected basal area prediction model might be found in the data structure used for fitting the models. The stand characteristics were very variable among plots, not being possible to see any relationship between basal area and age and basal area and number of trees per hectare. A solution would have been to exclude the basal area prediction equation from the simultaneous system of equations and use only the projection for basal area since basal area is usually measured in forestry practice. The problem with this option would have been the impossibility to predict basal area after thinnings in a compatible way, by knowing only the remaining number of trees per hectare in the stand. However, although growth simulations for thinned stands are possible using the system of models presented in this study, they might not be as reliable as for unthinned stands due to the lack of data from thinned stands. As suggested by Piennar and Harrison (1989), an additional predictor variable that accounts for thinning effects would need to be introduced in the current system of equations to obtain more accurate growth simulations for thinned stands.

The performance of Río's models (1998) for Scots pine in Sistema Central and Ibérico was compared to the models presented in this study (Fig. 4). The recursive system of equations developed by Río (1998) to model stand growth and yield did not include a basal area prediction equation, but only a projection equation. Therefore, observed basal area of the first plot measurement was needed to initialise the simulation of stand basal area and volume development with Río's model, while predicted basal using Equation 3 was used to initialise the simulated stand development with the models presented in this study. Figure 4 shows that Río's basal area model clearly overpredicts basal area for the plot with site index 19 m, and does not logically describe, specially for the best sites, the

asymptotic trend that characterises stand basal area growth. The stand volume development predicted by Río's model is quite accurate for the plot measurement period. However, for the best site Río's model (1998) shows a non-asymptotic trend of stand volume development that might not be realistic. One explanation for the non-asymptotic trend in stand basal area and volume development using Río's model might be due to the characteristics of the modelling data set for fitting the models, which included permanent sample plots ranging in stand age from 20 to 75 years. The overprediction of basal area growth for the plot with site index 19 m, is not reflected in an overprediction of stand volume development as it would be expected. The reason could be that Río (1998) used the dominant height growth model developed by Rojo and Montero (1996) for estimating the site index, which is later used as a predictor in the stand volume model. Palahí *et al.* (2002a) showed how the dominant height model of Rojo and Montero (1996) underpredicts dominant height growth development in the modelling data of this study, which concerns north-east Spain, for the best sites and at young to medium ages.

Parameter estimates of the system of equations are consistent with current knowledge of forest growth relationships and ensure compatibility between prediction and projection functions for both volume and basal area (Table 2). Furthermore, the strong cross-equation correlation among some error components in the system of equations (Table 3) provides further justification for the use of N3SLS method in fitting simultaneous systems of equations.

Simulations of volume and basal area growth for different stand densities and site indices as presented in Figure 4 follow accurately the actual growth pattern of real plots and seem to behave logically out of the range of ages of the estimation data. The system of models presented in this study can serve as a simple-to-use yield prediction system for forest-level management planning since the system requires only stand level inventory input, namely, stand age, number of trees per hectare and dominant height or site index.

RESUMEN

Elaboración de un modelo de crecimiento y producción para rodales de masas regulares de *Pinus sylvestris* L. en el noreste pensinsular

Se presenta un sistema interdependiente y compatible de modelos de crecimiento y mortalidad obtenido mediante el método de estimación no lineal de mínimos cuadrados en tres-etapas, obtenido a partir de 21 parcelas permanentes de *Pinus sylvestris* establecidas en 1964 por el Instituto Nacional de Investigaciones Agrarias en el noreste peninsular. Las parcelas permanentes con una calidad de sitio, definida como la altura dominante a los 100 años de edad, de entre 13 a 26 m fueron inventariadas una media de 5 veces. El método no lineal de mínimos cuadrados en tres etapas fue utilizado para fijar simultáneamente ecuaciones de predicción y proyección del área basal, volumen del rodal y número de pies por hectárea. Un modelo de crecimiento dinámico para la altura dominante, ya existente y fijado con los mismos datos que los del presente estudio, fue utilizado para proyectar la altura dominante. Los modelos fueron evaluados cuantitativa y cualitativamente. La correlación entre

los componentes del error de las ecuaciones de predición del área basal y volumen del rodal, así como entre las ecuaciones de proyección del número de pies por hectárea y volumen del rodal fueron significativas. La media del sesgo para todos los modelos fue positiva. El estudio describe las ventajas de este tipo de sistemas de modelos compatibles e interdependientes. Se discute su posible uso práctico en la planificación y gestión forestal del pino silvestre dada su simplicidad y a que el tipo de datos de entrada para realizar simulaciones es sólo información a nivel de rodal (número de pies por hectárea y altura dominante o índice de sitio a una edad determinada).

Palabras clave: Modelos de producción y crecimiento, regresión no lineal en múltiples etapas, simulación.

REFERENCES

ÁLVAREZ GONZÁLEZ J.G., RODRÍGUEZ SOALLEIRO R., VEGA ALONSO G., 1999. Elaboración de un modelo de crecimiento dinámico para rodales regulares de *Pinus pinaster* Ait en Galicia. Invest. Agr.: Recur. For. Vol. 8 (2): 319-334.

AMARO A., REED D., THEMIDO I., TOMÉ M., 1997. Stand growth modelling for first rotation *Eucalyptus globus* Labill in Portugal. In: Amaro A., and Tomé T. (Eds.), Empirical and process based models for forest tree and stand growth simulation. Edições Salamandra. pp. 99-110.

BENNETT F.A., McGEE C.E., CLUTTER J.L., 1959. Yield of old-field slash pine plantations. USDA For. Serv. Stn. Pap. 107, 19 pp.

BORDERS B.E., 1989. Systems of equations in forest stand modelling. For. Sci. 35: 548-556.

BORDERS B.E., BAILEY R.L., 1986. A compatible system of growth and yield equations for slash pine fitted with restricted three-stage least squares. For. Sci. 32: 185-201.

BURKHART H.E., SPRINZ P.T., 1984. Compatible cubic volume and basal area projections for thinned old-field Loblolly pine plantations. For. Sci. 30: 86-93.

BURKHART H.E., PARKER R.C., ODERWALD R.G., 1972. Yields for natural stands of Loblolly pine. Div. For. Wildl. Resour. Va. Polytech. Inst. State Univ. Publ. FWS-2-72, 63 pp.

CLUTTER J.L., 1963. Compatible growth and yield models for Loblolly pine. For. Sci. 9: 354-371.

CLUTTER J.L., FORSTON J.C., PIENAAR L.V., BRISTER G.H., BAILEY R.L., 1983. Timber management - a quantitative approach. Wiley, New York.

DANIELS R.F., BURKHART H., 1988. An Integrated System of Forest Stand Models. For. Ecol. Manage. 23: 159-177.

DUTTA M., 1975. Econometric methods South-Western Publ Co, Cincinnati, Ohio. 382 p.

ESPINEL S., CANTERO A., SÁENZ D., 1997. Un modelo de simulación para rodales de *Pinus radiata* D. Don en el País Vasco. IRATI 97. I Congreso Forestal Hispano Luso. Mesa 3, 201-206.

FOMBY T.B., HILL R.C., JOHNSON S.R., 1984. Advance econometric methods. Springer-Verlag, New York. 624 p.

FURNIVAL G.M., WILSON R.W., 1971. Systems of equations for predicting forest growth and yield. Statist. Ecol. 3: 43-55.

GARCÍA ABEJÓN J.L., 1981. Tablas de producción de densidad variable para *Pinus sylvestris* en el Sistema Ibérico. Comunicaciones I.N.I.A Serie: Recursos Naturales. N.º 10, 47 p.

GARCÍA ABEJÓN J.L., GÓMEZ LORANCA J.A., 1984. Tablas de producción de densidad variable para *Pinus sylvestris* en el sistema Central. Comunicaciones I.N.I.A Serie: Recursos Naturales. N.º 29, 36 p.

GARCÍA ABEJÓN J.L., TELLA FERREIRO G., 1986. Tablas de producción de densidad variable para *Pinus sylvestris* L. en el Sistema Pirenaico. Comunicaciones I.N.I.A. serie: Recursos Naturales, N-43, 28 p.

HUANG S., 1994. Ecologically based reference-age invariant polymorphic height growth and site index curves for White spruce in Alberta. Tech. Paper. Alberta Env. Prot. Land & Forest Serv. For. Manag. Div.

JUDGE G., GRIFFITHS W.E., HILL R. C., LEE T., 1980. The theory and practice of econometrics. John Wiley and sons, New York. 793 p.

MABVURIRA D., MIINA J., 2001. Simultaneous growth and yield models for *Eucalyptus grandis* (Hill) Maiden plantations in Zimbabwe. S. Afr. For. J. 191: 1-8.

MONTERO G., CAÑELLAS I., ORTEGA C., DEL RÍO M., 2001. Results from a thinning experiment in a Scots pine (*Pinus sylvestris* L.) natural regeneration stand in the Sistema Ibérico Mountain Range (Spain). For. Ecol. Manage. 145: 151-161.

MURPHY P.A., 1983. A nonlinear timber yield equation system for Loblolly pine. For. Sci. 29: 582-591.

MURPHY P.A., BELTZ R.C., 1981. Growth and yield of Shortleaf pine in the west Gulf region. USDA Forest Serv. Res. Pap. SO-169, 15 p. South Forest Exp. Stn, New Orleans, LA.

MURPHY P.A., STERNITZKE S., 1979. Growth and yield estimation for Lobolly pine in the West Gulf. USDA Forest Serv. Res. Pap. SO-154, 8 p. South Forest Exp. Stn, New Orleans, LA.

PALAHÍ M., TOMÉ M., PUKKALA T., TRASOBARES A., MONTERO, G., 2002a. Site index model for Scots pine (*Pinus sylvestris* L.) in north-east Spain. Submitted to Forest Ecology and Management.

PALAHÍ M., PUKKALA T., MIINA J., MONTERO G., 2002b. Individual-tree growth and mortality models for Scots pine (*Pinus sylvestris* L.) in north-east Spain, Submitted to Ann. Sci. For.

PIENAAR L.V., HARRISON W.M., 1989. Simultaneous growth and yield prediction equations for *Pinus elliottii* plantations in Zululand. S. Afr. For. J. 149: 48-53.

PIENAAR L.V., SHIVER B.D., 1986. Basal area prediction and projection equations for pine plantations. For. Sci. 32: 626-633.

PINDYCK R.S., RUBINFELD D.L., 1981. Econometric models and economic forecast. McGraw-Hill, New York. 630 p.

PITA CARPENTER A., 1967. Tablas de cubicación por diámetros normales y alturas totales, Instituto Forestal de Investigaciones y Experiencias, Ministerio de Agricultura, Marid.

RÍO M. del., 1998. Régimen de claras y modelo de producción para *Pinus sylvestris* L. en los sitemas Central e Ibérico. Tesis Doctoral, ETSIM-UPM, 219 pp, unpublished.

RÍO M. del., MONTERO G., BRAVO F., 2001. Analysis of diameter-density relationships and self-thinning in non-thinned even-aged Scots pine stands, For. Ecol. Manage. 142: 79-87.

ROJO A., MONTERO G., 1996. El pino silvestre en la Sierra de Guadarrama. Centro de publicaciones del Ministerio de Agricultura, Pesca y Alimentación, 293 p.

SAS Institute Inc., 1999. SAS/ETS User's guide, version 8, Cary, NC: SAS Institute Inc., 1596 pp.

SOÁRES P., TOMÉ M., SKOVSGAARD J.P., VANCLAY J.K., 1995. Evaluating a growth model for forest management using continuous forest inventory data. For. Ecol. Manage. 71: 251-265.

SCHUMACHER F.X., COILE T.S., 1960. Growth and Yield of Natural Stands of the Southern Pines. T.S. Coile, Inc., Durham, NC, 115 pp.

SULLIVAN A.D., CLUTTER J.L., 1972. A simultaneous growth and yield model for Loblolly pine. For. Sci. 18: 76-86.

TOMÉ M., 1988. Modelação do crescimento da Árvore Individual em povoamentos de *Eucalyptus globulus* Labill. (1.ª rotação). Região Centro de Portugal. Tese Dout. Eng. Silv. UTL. ISA.

TOMÉ M., SOÁRES P., 1999. A comparative evaluation of three growth models for eucalypt plantation management in coastal Portugal. In: Amaro, A., and Tomé, T. (Eds.), Empirical and process based models for forest tree and stand growth simulation.. Edições Salamandra, pp. 517-533.

VON GADOW K., HUI G., 1998. Modelling forest development. Faculty of Forest and Woodland Ecology, University of Gottingen, 213 pp.