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Modelling silviculture alternatives for managing *Pinus pinea* L. forest in North-East Spain

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Abstract

A yield model was developed to simulate silviculture alternatives for *Pinus pinea* L. in north-east Spain (Catalonia). The model uses several functions to estimate the main silvicultural parameters at stand level and a disaggregation system to predict diameter distributions. From a network of 75 temporary plots a system of equations to predict stand variables was simultaneously fitted for two stand density types, namely low and high density stands, using the three-stage least-squares method (3SLS). The diameter distributions were estimated by the Weibull distribution function using the parameter recovery method (PRM) and the method of moments. Based on this yield model, two silviculture alternatives were simulated for each stand density type and site class, resulting in 16 silviculture scenarios. The yield model and silviculture alternatives offer a management tool and a guide for the sustainable forest management of even-aged *Pinus pinea* forests in this region.

Key words: yield models; diameter distribution; silviculture models; stone pine.

Resumen

Modelos de masa para orientar la gestión de *Pinus pinea* L. en el noreste de España

Se ha desarrollado un modelo de masa como base para orientar la gestión de *Pinus pinea* L. en el noreste de España (Cataluña). El modelo integra diferentes funciones que permiten evaluar las principales variables forestales a nivel de rodal, incluyendo un sistema de desagregación para la estimación de las distribuciones diamétricas. A partir de los datos de una red de 75 parcelas temporales y diferenciando dos tipologías de masa en función de la densidad, masas claras y densas, se ajustaron simultáneamente sistemas de ecuaciones utilizando el método de estimación de mínimos cuadrados en tres etapas. Las funciones obtenidas predicen las principales variables de masa para las dos tipologías. Las distribuciones diamétricas se obtuvieron a partir de la función de distribución de Weibull, utilizando el método de recuperación de parámetros (PRM) y el método de los momentos. Finalmente, se simularon dos alternativas selvícolas para cada tipología de masa (claras, densas) y calidad de estación, resultando 16 escenarios selvícolas. El modelo de masa y las alternativas selvícolas obtenidas se presentan como una herramienta útil para el gestor y una guía para la gestión sostenible de las masas de *Pinus pinea* en esta región.

Palabras clave: modelización; distribución de diámetros; modelos selvícolas; pino piñonero.

Introduction

Stone pine (*Pinus pinea* L.) is one of the most useful trees in the Mediterranean basin, offering a variety of products and functions. In north-east Spain (Catalonia) it represents about 41,500 ha of woodland (DGCN, 2001) and is of recognised value, both economic (timber and fruit production) and ecological (dune fixation, soil restoration and biodiversity). *Pinus pinea* forests also contribute to landscape quality in the coastal areas and offer valued recreational and soil conservation uses. These features, together with the economic yield of its two principal productions, wood and pine kernels, have for decades justified the commercial exploitation of this species. Yet despite their economic utility little information is available on *Pinus pinea* forests in this area and no work has been done on structure, production or yield. However, in recent years interest in the management of this tree species has sharply increased

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and forest owners and managers are now voicing a new demand for silvicultural models.

In the last decade several studies on the development, growth and structure of this species have been conducted in Spain, *e.g.,* by García Güemes (1999), Cañadas (2000), Calama and Montero (2004, 2005, 2007), Bravo-Oviedo and Montero (2005) and Montes *et al.* (2006). However, these studies mainly concern other *Pinus pinea* areas in Spain, with the exception of the Calama and Montero (2005) study, in which the authors develop a model to predict diameter increment for stone pine trees throughout Spain. Concerning site index curves, Piqué (2003) developed a model for Catalonia, while the model proposed by Calama *et al.* (2003) is valid for all of Spain.

Pinus pinea stands in Catalonia present special characteristics that are quite different from other forest areas of this species, *e.g.,* very high densities, wide variability of stand structures and the common presence of an understory layer of *Quercus* sp. and other Mediterranean shrubs (Piqué, 2004; DGCN, 2005). Most of the *Pinus pinea* forests are natural or naturalized. Many of them are located on former vineyards ruined by phylloxera between the end of the 19th century and the beginning of the 20th century, or on former cropland abandoned in the wake of industrialization. Practically 100% of forests are privately owned, with multiple, piecemeal ownership and a varied degree of forest management. Forest stands usually present even-aged structures with a rotation of approximately 80 years, depending on site index, and are regenerated by uniform-shelterwood method. The number of thinning along the rotation can vary from 1 to 3 and pruning is not especially generalized. Although in practice selection cutting with diametrical criteria is fairly widespread. Importantly, there is not enough regeneration in most of the forests (Piqué, 2004). Average species growth is around 3 m^3/ha · year (DGCN, 2005) and timber destination depends on tree size and quality. Nowadays main use is industrial packing with an industria-side timber price of around 45 €/m^3 for diameter class > 25 cm (DIBA, 2010). The annual harvesting volume is around 23,000 m^3 for 2004-2008 period (DMA, 2009).

Against this background, an analysis of *Pinus pinea* forest types is required concerning their production and yield, so as to draw up forest management guidelines and make better use of the forests. The implementation of yield models should allow more sustainable management of *Pinus pinea* forests and the production of both timber and pine nuts. Proper management of this species should also help to improve landscape value and achieve better prevention of forest fires.

Empirical growth and yield models are practical tools in forest management and have been widely used for the prediction of future volume and discussion of management options (Vanclay, 1994; Falcao and Borges, 2005). They can be grouped into three types of model: whole-stand models, size-class models and individual tree models (Gadow and Hui, 1999). Individual-tree growth models provide more detailed information than is available from other modelling approaches, and usually perform better than whole-stand models for short-term projections (Burkhart, 2003). For forest management planning, however, standard forest inventories do not usually provide the data required by individual-tree models. At least for even-aged, single-species stands, whole-stand models are an attractive alternative, directly projecting information readily obtained from the inventory data. Whole-stand models represent a good compromise between general applicability and accuracy of estimates (García, 2003).

The simplest whole-stand models are yield models. They are easy to comprehend and use by forest managers, and are functional tools to guide forest management and estimate productions. They are static models, usually presented in tables that estimate the evolution of the main dasometric variables for a pure even-aged stand of a particular area or region and for different site quality classes and silvicultural regimes. There are yield tables for *Pinus pinea* in other regions (Castellani, 1989; García Güemes, 1999; Cañadas, 2000; Calama and Montero, 2005), but there is no information on the widespread *Pinus pinea* forests in Catalonia.

Whole-stand models usually provide rather limited information on the future stand (Vanclay, 1994). As forest management decisions require more detailed information on stand structure and volume distributed by diameter class, whole-stand models can be disaggregated mathematically using a diameter distribution function. Similar approaches have been used by Burk and Burkhart (1984), Knoebel *et al.* (1986), Río and Montero (2001), Diéguez-Aranda *et al.* (2006) and Castedo-Dorado *et al.* (2007) in the development of forest growth models.

The objective of this study was to construct a yield model to provide information on wood production for different ages, site qualities and management options. First, we developed a static yield model for low and high stand densities using a system of interdependent, compatible equations to propose silvicultural options for managing *Pinus pinea* stands. Second, we estimated the diameter distribution of stands in order to describe their structure and obtain information on number of trees per hectare and diameter class. This would be useful in the future to link information at tree level, such as crown development or fruit production.

Material and methods

Data

The data used for this study come from a network of 75 temporary plots located in the principal distribution area of the species in north-east Spain (Fig. 1). Before plot installation careful prospecting was done with the objective of identifying *Pinus pinea* types and their main structural characteristics. Plots were installed covering a wide range of ages, site qualities and stand densities of pure even-aged forests.

The plots were circular and of ranging radius so that they always included 20 trees. Positions of all trees were recorded using angles and distances from the plot centre. Variables measured for each tree were: diameter at breast height, total height and crown diameter and height. In each plot, the five trees nearest to the centre were identified and cores were taken to measure their age, growth and bark thickness. Tree volume was estimated using the equation developed by Martínez-Millán *et al.* (1993) for this species:

$$Vu = 0.056395 \cdot d^{1.94631} \cdot h^{0.92797} \qquad [1]$$

where Vu is tree volume with bark (dm^3), d tree diameter at breast height (cm) and h total tree height (m).

Site index was estimated for each plot using the site index model for stone pine in this region (Piqué, 2003). This model was developed with data from stem analysis, using the Algebraic Difference Approach (ADA) and the Bailey-Clutter function (Bailey and Clutter, 1974), with the following expression

$$H_2 = e^{\left\{5.5618+\left(\ln\left(H_1\right)-5.5618\right)\cdot\left(\frac{t_2}{t_1}\right)^{-0.1846}\right\}} \qquad [2]$$

where H_1 and H_2 are the dominant heights (m) at ages t_1 (years) and t_2 (years). Dominant diameter and dominant height were calculated as the mean value of the 20% thickest trees per plot. This model estimates the site index (H_2 for a reference age of t_2) and the dominant height growth when a height-age pair is available (H_1, t_1). Site index curves for Catalonia represent dominant height development for site indices 21, 17, 13 and 9 m at a reference age of 100 years.

A broad range of stand structures was observed, caused mainly by different silvicultural treatments. After data exploration, plots were therefore assigned to two density groups according to basal area and Reineke's stand density index. These indices were chosen as they are a satisfactory measure of stand density and easy to calculate (Curtis, 1970; Avery and Burkhart, 2002). Also, the Reineke index allows comparison of stand density of forests with different mean diameters and site indices (Daniel *et al.*, 1982). The

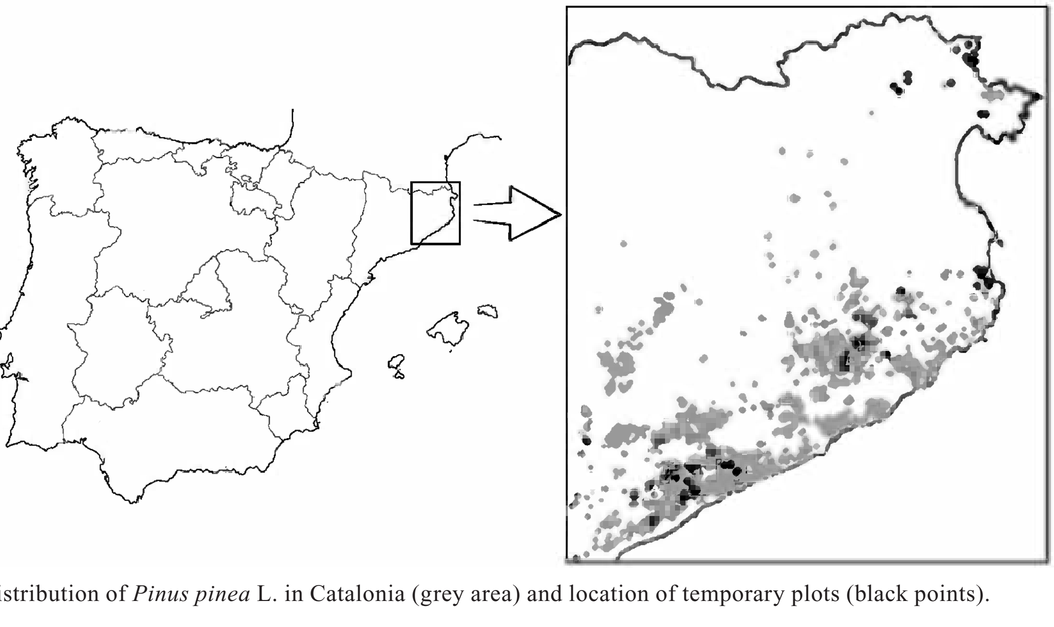

Figure 1. Distribution of *Pinus pinea* L. in Catalonia (grey area) and location of temporary plots (black points).

Table 1. Summary of the main stand variables for low density (LD) and high density (HD) forests

	Low density			High density		
	Average	Standard deviation	Min-Max	Average	Standard deviation	Min-Max
t (years)	57	36	7-125	60	25	16-104
H_0 (m)	10.3	3.9	3.2-16.9	11.1	2.6	3.7-18.4
N (trees/ha)	370	286	120-1,450	762	515	230-2,822
D_g (cm)	27.7	10.1	6.0-46.0	27.2	6.5	9.1-40.4
D_0 (cm)	33.5	11.8	7.6-54.7	32.5	7.1	12.2-50.0
G (m^2/ha)	16.6	5.8	3.0-25.6	36.4	10.4	18.6-69.5
Hm (m)	9.5	3.6	2.7-15.8	10.6	2.5	3.5-16.6
V (m^3/ha)	88.7	46.6	5.4-195.3	200.8	77.5	39.0-449.6
CC (%)	47	12	8-70	70	13	41-91
Reineke	322	94	98-464	727	205	450-1366

t: mean age. H_0: dominant height. N: number of trees per ha. D_g: quadratic mean diameter. D_0: dominant diameter. G: basal area. Hm: mean height. V: total volume. CC: canopy cover. Reineke: Reineke index.

classification criterion was a combination of the two indices, resulting in two types of forest: low density (LD), with Reineke index < 450 and/or basal area < 25 m^2/ha, and high density (HD), with Reineke index > 450 and/or basal area > 25 m^2/ha, representing 40 and 35 temporary plots respectively, and covering a similar broad range of ages and site qualities (Table 1).

Stand level model

Given the type of available data (only one measurement) and the advantages of the whole-stand models, *i.e.,* their practical nature and their use of variables that are easy to measure, in the present study we elected to construct static yield models.

The stand yield models structure proposed by Rojo and Montero (1996) and Madrigal *et al.* (1999) was used for the construction of *Pinus pinea* yield models. The method is based on five static functions that relate different stand variables, in which the dependent variables are dominant height, mean height, number of trees per hectare, quadratic mean diameter and stand volume. This system of equations was fitted for both stand types, namely low and high density stands.

The first function is the site index model (Eq. [2]), which estimates the dominant height development for each site index [$H_0 = f(t, \mathrm{SI})$], common for the two types. The second function (Eq. [3]) predicts the mean height (H_m) from dominant height (H_0) through a linear model:

$$H_m = a_0 + a_1 \cdot H_0 \qquad [3]$$

Several functions widely used in yield tables collected in Rojo and Montero (1996) were tested to estimate the stand density (N, trees/ha), including as independent variables the dominant height in metres (H_0), mean height in metres (H_m) and/or stand age in years (t):

$$\ln(N) = a_0 + a_1 \cdot H_0 \qquad [4]$$

$$\ln(N) = a_0 + a_1 \cdot \ln(H_0) \qquad [5]$$

$$\frac{100}{\sqrt{N}} = a_0 + a_1 \cdot H_0^c \qquad [6]$$

$$\log\left(\frac{\sqrt{N}}{H_0}\right) = a_0 + a_1 \cdot \log\left(H_m^2 \cdot \sqrt{t}\right) \qquad [7]$$

$$\frac{100}{\sqrt{N}} = a_0 + a_1 \cdot H_0 \cdot \sqrt{t} \qquad [8]$$

$$\frac{100}{\sqrt{N}} = a_0 + a_1 \cdot H_0 \cdot t^c \qquad [9]$$

The models tested to estimate the quadratic mean diameter (D_g, in metres) depend on dominant height and stand density. Four models were tested (Rojo and Montero, 1996; García Güemes, 1999):

$$D_g = a_0 + a_1 \cdot \frac{100}{\sqrt{N}} + a_2 \cdot H_0 \qquad [10]$$

$$D_g = a_0 + a_1 \cdot \frac{100}{N^{a_2}} + a_3 \cdot H_0 \qquad [11]$$

$$D_g = a_0 + a_1 \cdot H_o + a_2 \cdot N \qquad [12]$$

$$D_g = a_0 \cdot H_0^{a_1} \cdot N^{a_2} \qquad [13]$$

Finally, the total volume per hectare (V, in m^3/ha) was estimated from H_0, N and D_g. The following functions were compared:

$$\log(V) = a_0 + a_1 \cdot \log(H_0) + a_2 \cdot \log\left(\frac{N}{H_0}\right) + a_3 \cdot \log(D_g) \qquad [14]$$

$$\log(V) = a_0 + a_1 \cdot \log(H_0) + a_2 \cdot \log\left(\frac{100}{\sqrt{N}}\right) + a_3 \cdot \log(D_g) \qquad [15]$$

$$V = a_0 + a_1 \cdot G \cdot H_0 \qquad [16]$$

where G is the basal area in m^2/ha and a_0, a_1, a_2 and a_3 are parameters to be estimated for each function and type of stand density.

In the first step, each function was fitted independently following ordinary linear and non-linear least-squares regression and the best model for each dependent variable was selected according to the evaluation criteria shown in Table 2. The system of equations consisted of mean height, number of trees, mean quadratic diameter and volume equations in a recursive system with a clear sequential relation. When the models are used, some variables do not take their real values but instead take the predicted values estimated from another previous function of the system. The variables on the left are endogenous (H_m, N, D_g, V) and the others are exogenous (H_0, t). The endogenous variables can be on both sides of the equations (right and left), in this case the variables N and D_g, and there can be a cross-equation correlation between error components. Ordinary least-squares regression does not consider this correlation, resulting in biased and inconsistent parameter estimations (Borders and Bailey, 1986; Borders, 1989). Therefore, in a second step the system of equations was fitted simultaneously by a three-stage least-squares method, using N3SLS techniques (Hasenauer *et al.*, 1998; Fang *et al.,* 2001; Huang, 2002).

Diameter distributions

The distribution function used to obtain diameter distributions was the Weibull function, chosen for its flexibility and good results when describing diameter

Table 2. Model performance evaluation criteria

Criterion	Symbol	Formula	Ideal value
Mean residual error	ME	$\sum_{i=1}^{n} \frac{(obs_i - est_i)}{n}$	Zero
Absolute mean residual error	*MAE*	$\sum_{i=1}^{n} \frac{\lvert obs_i - est_i \rvert}{n}$	Zero
Mean square error	*MSE*	$\frac{\sum_{i=1}^{n} (obs_i - est_i)^2}{n-1}$	Zero
Root mean square error	*RMSE*	$\frac{\sqrt{\sum_{i=1}^{n} (obs_i - est_i)^2}}{n-2}$	Zero
Efficiency coefficient	*EF*	$1 - \frac{\sum_{i=1}^{n} (obs_i - est_i)^2}{\sum_{i=1}^{n} (obs_i - obs_{me})^2}$	One
Linear regression	a, b, R^2_{aj}	$obs_i = a + b \cdot est_i + \varepsilon_i$	$a = 0$, $b = 1$, $R^2_{aj} = 1$

obs_i: observed value. est_i : estimated value. obs_{me}: mean observed value. n: mumber of observations.

distributions of even-aged stands (Bailey and Dell, 1973; Cao, 2004), including stone pine stands in central Spain (García Güemes, 1999). The expression of the Weibull distribution function of three parameters applied to diameter distribution with a diameter class of 5 cm is:

$$nCD_i = N \cdot 5 \cdot \frac{a_2}{a_1} \cdot \left[\left(\frac{CD_i - a_0}{a_1} \right)^{(a_2 - 1)} \right] \cdot \mathrm{e}^{-\left(\frac{CD_i - a_0}{a_1} \right)^{a_2}} \qquad [17]$$

where nCD_i is the number of trees per hectare in the diameter class i, CD_i the value of the diametrical class in cm, N the number of total trees per hectare and a_0, a_1, a_2 are the parameters of the Weibull function respectively related to location, scale and shape of the distribution.

Among the different methods that can be used to estimate the parameters of the Weibull function the parameter recovery approach with the method of moments was selected. The parameter recovery method has been found to give better results than the parameter prediction method (Reynolds *et al.*, 1988), and it is especially robust when the parameters are recovered from the moments of the distribution (Vanclay, 1994). The method of moments provides distributions close to the real distributions (Shiver, 1988; Leujene, 1994) and allows compatibility between the basal area obtained from the diameter distribution and from the stand model, a desirable property for yield models (Matney and Sullivan, 1982; Hynk and Moser, 1983).

In this work the algorithm proposed by Burk and Burkhart (1984), which is based on the first moments of the diameter distribution (arithmetic and quadratic mean diameter), was used to estimate parameters a_1 and a_2 of the Weibull function, assuming location parameter a_0 to be known. The authors proposed estimating parameter a_0 as half the minimum diameter observed in the diametrical distribution. The variables minimum diameter ($D_{\min}$) and mean diameter (D_{m}) were thus required to estimate diameter distribution with this method, so linear models were fitted testing different stand variables (t, H_0, H_{m}, N, D_{g}, G) or stand variable combinations as independent variables, as proposed by Matney and Sullivan (1982) and Río and Montero (2001) to obtain $D_{\min}$ and D_{m}. These models were fitted separately for LD and HD stands. The model fitting was carried out using linear regression.

Model performance evaluation

The assessment and selection of models was based on fitting statistics, residual analysis and biological realism and graphical behaviour. The fits were evaluated on six model performance criteria (Table 2).

The model behaviour was evaluated on the basis of practical experience, silviculture and ecology literature for the studied species (García Güemes, 1999; Cañadas, 2000; Montero and Cañellas, 2000; Ruiz de la Torre, 2006; Montero *et al.*, 2008). As independent data were not available, statistical validation was not possible.

Silviculture scenarios

For both low and high density stand types, two silviculture scenarios were simulated, resulting in four silviculture options. In one scenario, which we call «observed silviculture», the density evolution was given by the adjusted functions (Eq. [20] and [20']). In the other one, «oriented or reference silviculture», the evolution of the number of trees per hectare was decided theoretically on the basis of practical experience and literature on *Pinus pinea* forest management, which usually recommends 3-4 thinning every 10-15 years, intense thinning from below at 10-15 years old and, in advanced stages, from below and above of moderate intensity (Cantiani y Scotti, 1988; Castellani, 1989; Montero y Candela, 1998; García Güemes, 1999; Montero *et al.*, 2008). The stand variables for each scenario were predicted at intervals of 10 years using the fitted functions of the stand level model.

Every 10 years a thinning operation was simulated in each silviculture scenario. The thinning intensity at age t_i (number of trees per hectare removed by thinning) was calculated by subtracting the stand density at age t_{i+10} from that at age t_i. The type of thinning was defined by the v_{e}/v coefficient, equal to the ratio of the mean tree volume of the removed crop (v_{e}) and the mean tree volume before the thinning (v). The values for this coefficient were calculated first for heavy thinning from below and later for a combination of thinning from below and above, simulating the thinning from the predicted diameter distribution and the number of trees removed at each age t_i.

The accumulated removed volume (V_{acum}) was calculated as the sum of all the volumes removed in thinnings and the total volume (V_{t}) as the sum of the stand volume and the accumulated removed volume. Mean annual volume increment (MAI) was determined as the ratio of the total volume to age (t). The annual current increment (CAI) of the last 10 years with respect to age (t) was obtained from the relation:

$$\mathrm{CAI}(t)=\frac{\left(Vt\left(t\right)-Vt\left(t-10\right)\right)}{10} \qquad [18]$$

Results

Stand level models

Tables 3 and 4 show, for LD and HD stands, the best models and their fitting statistics for each dependent variable, when fitting each function independently.

When the selected models were fitted simultaneously using N3SLS, the following functions were obtained for LD and HD *Pinus pinea* stands, respectively:

$$H_m=0.920\cdot H_0 \qquad [19]$$

$$H_m=0.949\cdot H_0 \qquad [19']$$

$$N=\left(\frac{100}{3.116+0.034\cdot H_0\cdot\sqrt{t}}\right)^2 \qquad [20]$$

$$N=\left(\frac{100}{1.722+0.025\cdot H_0\cdot\sqrt{t}}\right)^2 \qquad [20']$$

$$D_g=1.957\cdot H_0+1.255\cdot\frac{100}{\sqrt{N}} \qquad [21]$$

$$D_g=1.156\cdot H_0+3.499\cdot\frac{100}{\sqrt{N}} \qquad [21']$$

$$V=10^{\left[1.177\cdot\log\left(H_0\right)-1.960\cdot\log\left(\frac{100}{\sqrt{N}}\right)+1.563\cdot\log\left(Dg\right)\right]} \qquad [22]$$

$$V=10^{\left[1.182\cdot\log\left(H_0\right)-1.813\cdot\log\left(\frac{100}{\sqrt{N}}\right)+1.497\cdot\log\left(Dg\right)\right]} \qquad [22']$$

Tables 5 and 6 show the parameter estimates of the system of equations, along with their fitting statistics.

Table 3. Parameter estimates and fitting statistics of the models for LD forests

Model	SSE	ME	MAE	MSE	RMSE	EF
$H_m=0.921\cdot H_0$	12.663	–0.01	0.43	0.32	0.57	0.97
$N=\left(\frac{100}{3.685+0.028\cdot H_0\cdot\sqrt{t}}\right)^2$	1,457,824	44.90	11.90	37,380.12	195.86	0.54
$D_g=-4.24+1.432\cdot H_0+2.859\cdot\frac{100}{\sqrt{N}}$	271.64	–0.01	1.99	6.96	2.67	0.93
$V=10^{\left[-0.335+0.837\cdot\log\left(H_0\right)-2.032\cdot\log\left(\frac{100}{\sqrt{N}}\right)+2.070\cdot\log\left(Dg\right)\right]}$	468.89	0.19	2.55	12.02	0.01	0.99

Abbreviations as in Table 2. All the parameters are significant at an α level of 5%.

Table 4. Parameter estimates and fitting statistics of the models for HD forests

Model	SSE	ME	MAE	MSE	RMSE	EF
$H_m=0.949\cdot H_0$	8.98	–0.005	0.40	0.26	0.52	0.96
$N=\left(\frac{100}{2.143+0.022\cdot H_0\cdot\sqrt{t}}\right)^2$	5,815,588	96.38	257.49	171,046	419.79	0.36
$D_g=0.335+1.122\cdot H_0+3.516\cdot\frac{100}{\sqrt{N}}$	151.89	–0.006	1.72	4.47	2.14	0.89
$V=10^{\left[-0.347+0.835\cdot\log\left(H_0\right)-2.055\cdot\log\left(\frac{100}{\sqrt{N}}\right)+2.094\cdot\log\left(Dg\right)\right]}$	1,438	0.60	4.97	42.31	6.60	0.99

Abbreviations as in Table 2. All the parameters are significant at an α level of 5%.

Table 5. Parameter estimates and fitting statistics of the models for LD forests after simultaous fitting

Model	a_1	a_2	a_3	SSE	ME	MAE	MSE	RMSE	EF	R^2_{adj}
[19]	0.920 (0.008)			12.66	–0.0003	0.43	0.32	0.57	0.97	—
[20]	3.116 (0.206)	0.034 (0.006)		1,136,117	0.87	108	29,131	172	0.64	—
[21]	1.957 (0.286)	1.255 (0.510)		369	0.021	2.47	9.47	3.11	0.91	—
[22]	1.177 (0.106)	1.960 (0.210)	1.563 (0.105)	1,176	0.25	4.09	30.16	5.56	0.99	—
[23]	5.733 (1.342)	0.0130 (0.001)		701	0.04	—	18.46	—	—	0.71
[24]	0.994 (0.02)			6.31	–0.31	—	0.18	—	—	0.99

Abbreviations as in Table 2. All the parameters are significant at an α level of 5%. In parenthesis approximate standard error.

In general, the statistics are good for both LD and HD stands, although the model efficiency was rather low for the density equations, mainly in the HD type. For the other variables the model efficiency was always higher than 0.89.

Figures 2 and 3 show that the dispersion of residuals is fairly homogenous and so apparent problems of heterocedasticity are not detected for H_m, D_g and V models. However, there is some bias in the N model predictions and a greater dispersion of data than in the other models. In LD stands the largest errors for N predicted values were greater than 500 trees/ha. These densities correspond mainly to the youngest stands (less than 20 years old), usually plantations, which presented high densities but a low basal area and Reineke index. Similar results were found for HD stands, with the largest errors for densities above 1,300 trees/ha, also corresponding to young stands (about 20 years old).

Diameter distributions

The models selected for predicting the minimum and mean diameters (D_{min} and D_m) depend only on quadratic mean diameter, with the exception of the model of D_m in high density stands, where the ratio of dominant height to quadratic mean diameter was also included (Tables 5 and 6):

$$D_{min} = a_1 + a_2 \cdot D_g^2 \quad [23]$$

$$D_{min} = a_1 + a_2 \cdot D_g^2 \quad [23']$$

Table 6. Parameter estimates and fitting statistics of the models for HD forests after simultaneous fitting

Model	a_1	a_2	a_3	SSE	ME	MAE	MSE	RMSE	EF	R^2_{adj}
[19’]	0.949 (0.007)			8.95	–0.005	0.40	0.26	0.52	0.96	—
[20’]	1.722 (0.312)	0.025 (0.005)		5,252,075	0.08	251	154,472	398	0.42	—
[21’]	1.156 (0.336)	3.499 (0.929)		152.11	–0.02	1.72	4.47	2.14	0.89	—
[22’]	1.182 (0.155)	1.813 (0.089)	1.497 (0.087)	5,699	0.65	10.78	167	13.14	0.97	—
[23’]	7.77 (1.362)	0.012 (0.002)		341	0.6	—	10.35	—	—	0.65
[24’]	1.002 (0.003)	1.009 (0.215)		0.90	–0.07	—	0.03	—	—	0.99

Abbreviations as in Table 2. All the parameters are significant at an α level of 5%. In parenthesis approximate standard error.

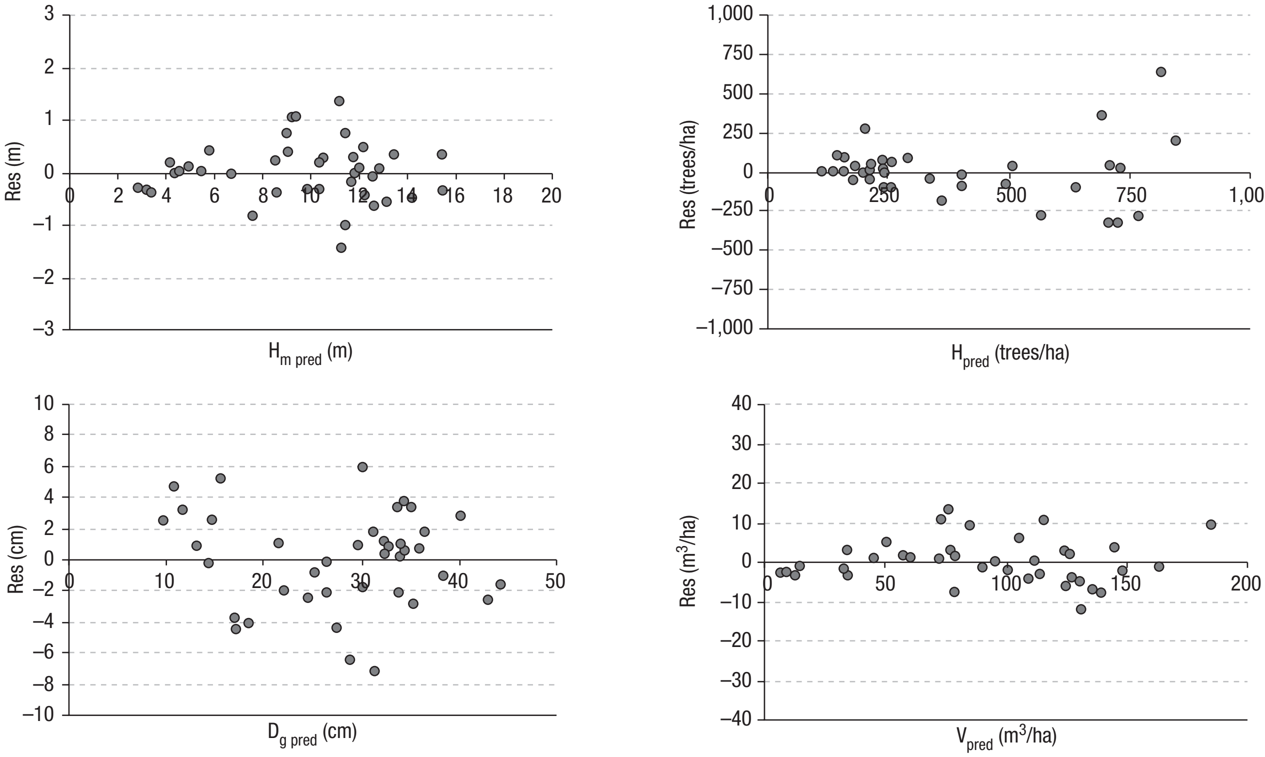

Figure 2. Residuals *versus* predicted values ($H_{m\ pred}$, N_{pred}, $D_{g\ p\text{-}reg}$, V_{pred}) for LD models.

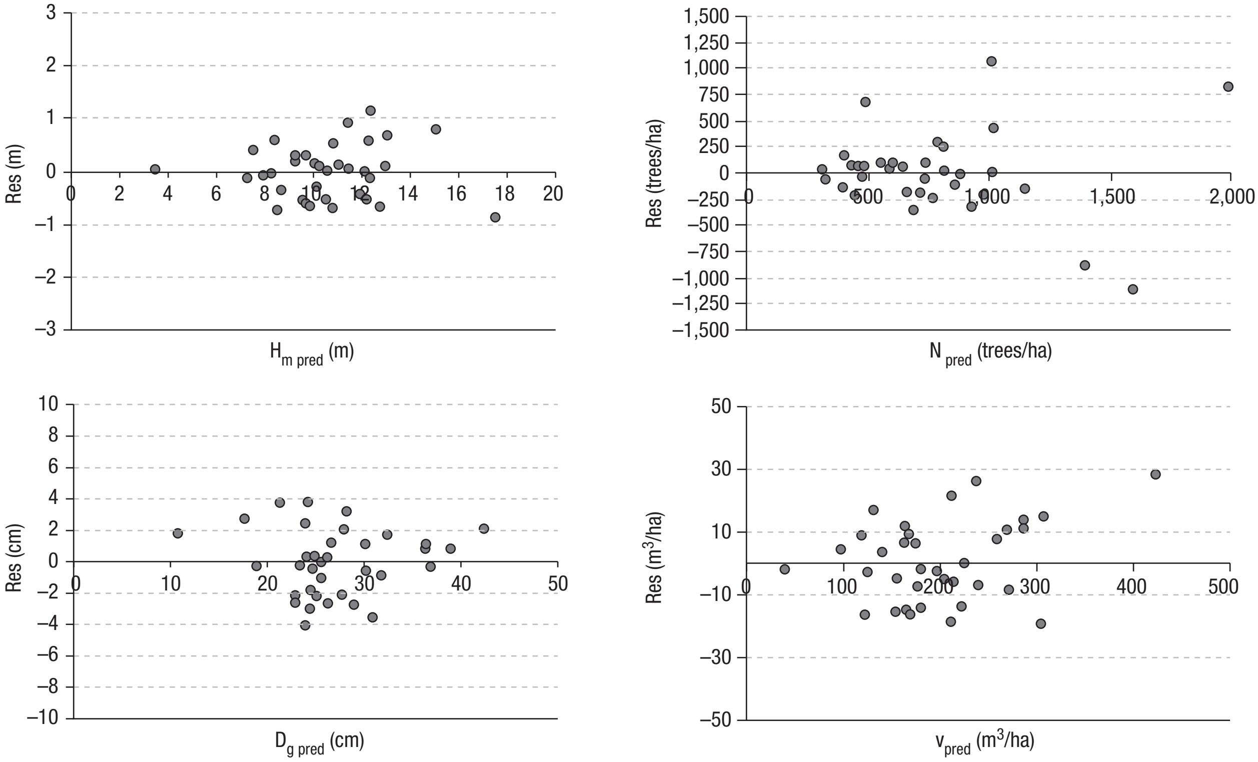

Figure 3. Residuals *versus* predicted values ($H_{m\ pred}$, N_{pred}, $D_{g\ p\text{-}reg}$, V_{pred}) for HD models.

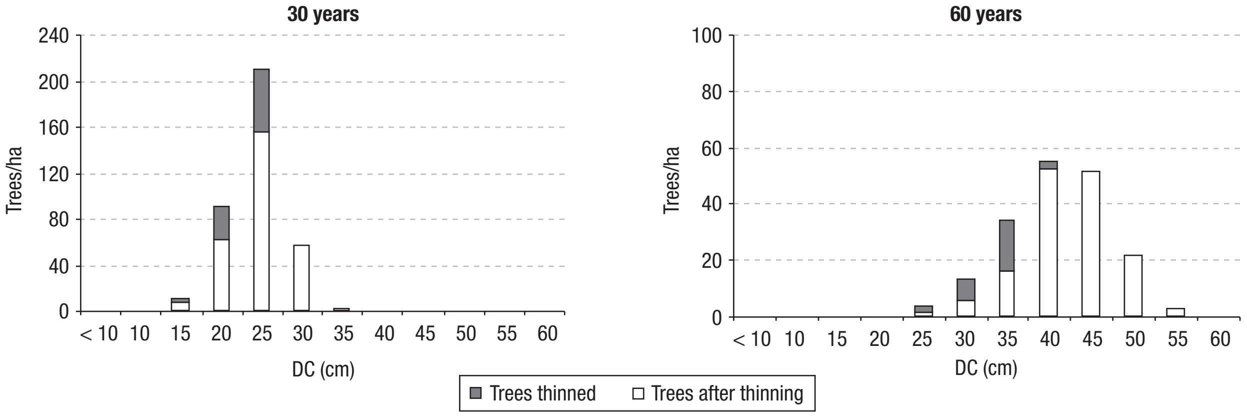

Figure 4. Thinning simulation at ages 30 and 60 years for low density *Pinus pinea* forests with site index 21.

$$D_m = a_1 \cdot D_g \quad [24]$$

$$D_m = a_1 \cdot D_g - a_2 \cdot (H_0/D_g) \quad [24']$$

Models efficiencies were very high for D_m equations (0.99) and for D_{min} they were about 0.7 (Tables 5 and 6).

Silviculture scenarios for LD and HD *Pinus pinea* forests

Yield models for «observed silviculture»

In this case, the evolution of the main stand variables is given by the functions obtained in the stand yield model, which reflect the inventoried stands. The thinning simulation for *Pinus pinea* forests considers heavy thinning from below when the stands are young and moderate thinning (which can also affect dominant trees) at older ages (Fig. 4). The coefficient v_e/v obtained by the analysis of the evolution of diameter distributions oscillates between 0.7 and approximately 0.85 for all quality sites in the LD type, while for the HD forests it ranged between 0.6 and 0.8 (Table 7).

Yield models for «reference silviculture»

In this silviculture scenario the evolution of stand density was decided based on experience and the literature on silviculture and management of *Pinus pinea* forests, taking into account that density depends on stand site index, production objective and type and number of thinnings. Table 8 presents the theoretical densities

Table 7. Value of coefficients v_e/v (v_e: mean tree volume of the removed crop, v: mean tree volume before the thinning) to characterized the thinning type according to age, stand density (LD: low density forests, HD: high density forests) and silvicultural scenarios («observed» and «oriented» silviculture)

Age (years)	Observed silviculture		Oriented silviculture	
	LD forests	HD forests	LD forests	HD forests
<30	0.7	0.6	0.85	0.8
40-50	0.75	0.65	0.9	0.85
60-70	0.8	0.7	0.9	0.85
80-90	0.85	0.75	0.95	0.9
>100	0.85	0.80	0.95	0.9

Table 8. Observed densities (trees/ha) obtained from the yield models («observed silviculture») and theoretical densities (trees/ha) decided for «oriented silviculture» at ages 10 and 100 years, depending on site index and for LD and HD forests

Site index	Observed silviculture				Oriented silviculture			
	LD forests		HD forests		LD forests		HD forests	
	10 years	100 years	10 years	100 years	10 years	100 years	10 years	100 years
21	726	95	2,144	206	400	100	830	200
17	795	126	2,406	280	500	125	830	250
13	864	176	2,679	405	626	175	830	300
9	930	262	2,948	634	830	250	830	350

of reference decided at age 10 years and at age 100 years (approximate rotation age) and the observed densities obtained from the yield models at the same ages («observed silviculture»).

In both LD and HD stands, proposed initial densities are lower than those presented in the «observed silviculture», although the densities proposed at the end of rotation are very similar. The other stand variables were estimated using the corresponding equations of the stand yield model (H_m, D_g and V).

The type of thinning and the procedure to simulate the thinnings were the same as in the «observed silviculture»: intense thinning first from below and later, in advanced stages, from below and above, of moderate intensity. For the LD types the coefficients v_e/v oscillate between 0.85 and 0.95 for all qualities, and in the HD forests these range between 0.8 and 0.9 (Table 7).

Yield tables for *Pinus pinea* L. in Catalonia were constructed using the yield models obtained, models of diameter distributions and the adopted coefficients v_e/v, as a basis for the simulation of the extracted volume and total productions throughout the rotation. Yield tables vary with site index (four qualities), LD and HD stand types and silviculture scenarios, with a total of 16 combinations. Tables 9 to 12 show some examples of «observed and reference silviculture» for LD and HD stands of site index 17 m at a reference age of 100 years. The yield tables incorporate the diameter distributions of the stands before thinning, which provide an accurate picture of stand structure and its time course.

Discussion

Yield model

A stand yield model that also provides diameter distributions was developed for low and high density *Pinus pinea* stands in Catalonia. The structure of the stand yield model is similar to that of yield tables, formed by a system of interdependent equations. Most of the yield tables were drawn up using ordinary linear and non-linear least-squares regression (Madrigal *et al*., 1999; Montero *et al*., 2001), but the use of a three-stage least-squares method (3SLS and N3SLS) is more suitable for fitting a simultaneous system of equations, giving more consistent parameter estimates (Borders and Bailey, 1986). Also, a good fit of each component independently does not necessarily imply a good fit and behaviour of the overall model (Huang, 2002). This method has also been applied in stand yield and growth models that use other structures, but with interdependent equations, such as the models for other pine species in Spain of Palahí *et al*. (2002) or Bravo-Oviedo *et al*. (2004).

The density model proved the most difficult to estimate, with a poor coefficient of determination (Tables 5 and 6), probably due to a small number of plots in young stands, some coming from plantations, where the variability of the number of trees per hectare is higher. However, the identification of two types of *Pinus pinea* stands, low and high density, enable us to reduce the data variability used in each model, giving good predictions of other stand variables and consequently providing a better description of the observed stands.

The models show well-known differences between parameter evolution in LD and HD stands and the influence of site index. HD forests present greater volumes than the LD forests, although their tree diameters are smaller. The best qualities offer greater increases in height, diameter, basal area and volume, mainly in the young stages.

The maximum mean volume growth varied according to site index from 0.9 to 5.1 m^3/ha · year for LD forests and from 2.0 to 10.3 m^3/ha · year for HD forests, values somewhat higher than those obtained by Montero *et al.* (2008). For both stand types the maximum current growth takes place at very young ages, between 20 and 30 years in the best qualities. This growth pattern is typical of this species, as reported elsewhere (Cascio, 1969; Baroni, 1973; La Marca, 1989, Montero *et al.,* 2008).

The disaggregation system of the yield model depends only on the quadratic mean diameter and dominant height, so diameter distributions are easily estimated for each stand stage. The diameter distributions obtained through the Weibull function calculated using the real values of D_{min}, D_m and D_g were very similar to those estimated using the predicted values of these diameters, and also similar to the real diameter distribution (Fig. 5). The parameter recovery approach to disaggregate stand yield and growth models also gives good results for estimating stand structures in other even-aged pine stands (Río and Montero, 2001; Diéguez-Aranda *et al*., 2006; Castedo-Dorado *et al*., 2007). The inclusion of the disaggregation system in the yield model allowed us to estimate the stand structure at each stand stage, as well as to improve the thinning simulation in the silviculture scenarios.

Table 9. Yield tables for *Pinus pinea* L. in Catalonia: case of «observed silviculture» for LD stands of site index 17 m at a reference age of 100 years

t years	H_0 m	Main stands variables before thinning							Volume removed in the thinnings					
		H_m m	N trees/ha	D_g cm	G m²/ha	H %	v m³	V m³/ha	N_c trees/ha	D_{ge} cm	G_c m²/ha	v_e m³	V_e m³/ha	V_{acum} m³/ha
10	4.0	3.7	795	12.3	9.4	92	0.03	21.6	206	9.6	1.5	0.02	3.9	3.9
20	6.6	6.1	589	18.1	15.2	65	0.09	53.3	140	14.2	2.2	0.06	8.9	12.8
30	8.6	7.9	449	22.8	18.3	57	0.18	79.8	96	17.8	2.4	0.12	12.0	24.8
40	10.3	9.5	352	26.8	19.9	54	0.28	99.9	68	21.8	2.6	0.21	14.5	39.3
50	11.7	10.8	284	30.4	20.6	52	0.40	114.7	50	24.7	2.4	0.30	15.1	54.4
60	13.0	11.9	234	33.6	20.8	52	0.54	125.4	38	28.5	2.4	0.43	16.1	70.5
70	14.1	13.0	197	36.6	20.7	52	0.68	133.2	29	30.9	2.2	0.54	15.7	86.3
80	15.2	13.9	168	39.4	20.4	53	0.83	138.8	23	34.6	2.1	0.70	16.1	102.3
90	16.1	14.8	145	42.0	20.0	53	0.99	142.8	18	36.8	2.0	0.84	15.4	117.7
100	17.0	15.6	126	44.4	19.6	54	1.15	145.6	15	39.0	1.8	0.98	14.6	132.4
110	17.8	16.4	111	46.8	19.2	55	1.32	147.5	12	41.0	1.6	1.13	13.9	146.2
120	18.6	17.1	99	49.0	18.7	56	1.50	148.8	10	42.9	1.5	1.28	13.2	159.4
130	19.3	17.8	89	51.2	18.3	57	1.68	149.5	9	44.8	1.4	1.43	12.5	171.9
140	20.0	18.4	80	53.2	17.8	58	1.87	149.8	7	46.5	1.3	1.59	11.8	183.7
150	20.7	19.0	73	55.2	17.4	59	2.06	149.9						

t years	H_0 m	Total volume			Diameter distribution before thinning															
		V_t m³/ha	MAI m³/ha-year	CAI m³/ha-year	< 10	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
10	4.0	21.6	2.2	2.2	9	431	354													
20	6.6	57.2	2.9	3.6		26	229	303	29											
30	8.6	92.6	3.1	3.5		1	37	174	210	26										
40	10.3	124.7	3.1	3.2			8	54	141	128	21									
50	11.7	153.9	3.1	2.9			2	17	63	114	77	11								
60	13.0	179.8	3.0	2.6				6	27	67	86	43	5							
70	14.1	203.7	2.9	2.4				2	11	35	64	60	22	2						
80	15.2	225.0	2.8	2.1				1	5	18	41	55	38	9	1					
90	16.1	245.1	2.7	2.0					2	9	25	42	42	20	3					
100	17.0	263.3	2.6	1.8					1	5	14	29	38	28	9	1				
110	17.8	279.9	2.5	1.7						2	8	19	31	30	16	4				
120	18.6	295.0	2.5	1.5						1	5	13	23	28	21	7	1			
130	19.3	308.9	2.4	1.4						1	3	8	16	24	22	12	3			
140	20.0	321.7	2.3	1.3							2	5	11	19	22	15	5	1		

t: mean age. H_0: dominant height. H_m: mean height. N: number of trees per ha. D_g: quadratic mean diameter. G: basal area. H: Hart index. v: mean tree volume. V: total volume. N_e: number of trees per ha removed. D_{ge}: quadratic mean diameter of removed trees. G_e: basal area removed. v_e: mean tree volume of removed trees. V_e: total volume removed. V_{acum}: sum of all the volumes removed in thinnings. V_t: sum of the stand volume and the accumulated removed volume. MAI: mean annual volume increment. CAI: mean annual current increment last 10 years.

Silviculture scenarios for LD and HD *Pinus pinea* forests in north-east Spain

Two management alternatives were developed for low and high density forests. Low density forests (LD) are characterized by a smaller density of trees along the species rotation, but they have higher diameters with larger crowns and more potential for fruit production. High density forests (HD) have a higher density of trees and not so well-developed crowns as in LD forests, but present good aptitudes for timber production. The total wood production per hectare in this type is greater, although in both types timber and fruit production can be compatible. «Observed silviculture»

Table 10. Yield tables for *Pinus pinea* L. in Catalonia: case of «observed silviculture» for HD stands of site index 17 m at a reference age of 100 years

t	H_0	Main stands variables before thinning							Volume removed in the thinnings					
years	m	H_m m	N trees/ha	D_g cm	G m²/ha	H %	v m³	V m³/ha	N_c trees/ha	D_{ge} cm	G_c m²/ha	v_e m³	V_e m³/ha	V_{acum} m³/ha
10	4.0	3.8	2,406	11.8	26.2	53	0.02	56.8	755	7.8	3.6	0.01	10.7	10.7
20	6.6	6.3	1,650	16.3	34.3	39	0.07	118.5	463	10.7	4.1	0.04	20.0	30.7
30	8.6	8.2	1,187	20.1	37.7	35	0.14	165.3	295	13.1	4.0	0.08	24.6	55.3
40	10.3	9.8	892	23.6	39.0	34	0.22	199.6	197	16.1	4.0	0.15	28.7	83.9
50	11.7	11.1	695	26.8	39.3	34	0.32	224.8	138	18.2	3.6	0.21	29.0	112.9
60	13.0	12.3	557	29.8	38.9	34	0.44	243.6	100	21.1	3.5	0.31	30.6	143.5
70	14.1	13.4	458	32.7	38.4	34	0.56	258.0	75	23.0	3.1	0.39	29.5	173.0
80	15.2	14.4	383	35.4	37.7	35	0.70	269.1	57	25.9	3.0	0.53	30.2	203.2
90	16.1	15.3	325	38.0	37.0	36	0.85	277.8	45	27.7	2.7	0.64	28.8	232.0
100	17.0	16.1	280	40.5	36.2	36	1.02	284.7	36	30.7	2.7	0.81	29.2	261.3
110	17.8	16.9	244	43.0	35.5	37	1.19	290.3	29	32.4	2.4	0.95	27.8	289.1
120	18.6	17.7	215	45.4	34.8	38	1.37	294.8	24	34.1	2.2	1.10	26.4	315.5
130	19.3	18.4	191	47.7	34.1	39	1.56	298.4	20	35.7	2.0	1.25	25.1	340.6
140	20.0	19.0	171	49.9	33.5	40	1.76	301.4	17	37.2	1.8	1.41	23.9	364.6
150	20.7	19.6	154	52.1	32.9	40	1.97	303.9						

t	H_0	Total volume			Diameter distribution before thinning															
		V_t	MAI	CAI																
years	m	m³/ha	m³/ha-year	m³/ha-year	< 10	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
10	4.0	56.8	5.7	5.7	88	1.500	807	11												
20	6.6	129.2	6.5	7.2	3	255	861	497	34											
30	8.6	196.0	6.5	6.7		28	293	592	262	13										
40	10.3	254.9	6.4	5.9		3	76	295	387	126	5									
50	11.7	308.7	6.2	5.4			18	114	269	240	52	1								
60	13.0	356.5	5.9	4.8			4	41	139	223	133	17								
70	14.1	401.5	5.7	4.5			1	14	64	148	165	62	4							
80	15.2	442.1	5.5	4.1				5	28	84	138	103	24	1						
90	16.1	481.0	5.3	3.9				2	13	45	94	109	55	8						
100	17.0	516.8	5.2	3.6				1	6	24	59	90	74	25	2					
110	17.8	551.5	5.0	3.5					3	13	36	66	74	43	10	1				
120	18.6	583.8	4.9	3.2					1	6	21	45	64	53	21	3				
130	19.3	613.9	4.7	3.0						3	12	29	50	54	33	9	1			
140	20.0	642.0	4.6	2.8						2	7	19	36	48	39	17	3			

Abbreviations as in Table 9.

scenarios simulate the volume removed along the species rotation and total production of actual managed forests. The «reference silviculture» scenario has been drawn up as an alternative to the «observed management». Montero *et al.* (2008), present three «observed silviculture» scenarios for *Pinus pinea* in Spain: they correspond to three different levels of management intensity (intensive, medium and moderate silviculture). LD forests observed in Catalonia are similar to the medium silviculture scenario, but HD stands in this region display greater densities than in the moderate silviculture scenario.

The v_e/v coefficients calculated to characterize the thinning type increase with age, since the application of thinning from below narrows the diameter distribution range. In the same way, the «reference silviculture» scenario for both types presents greater coefficients than the «observed silviculture» scenario. In dense stands there is usually a greater tree social differentiation with more presence of dominated trees, which

Table 11. Yield tables for *Pinus pinea* L. in Catalonia: case of «reference silviculture» for LD stands of site index 17 m at a reference age of 100 years

t years	H_0 m	Main stands variables before thinning							Volume removed in the thinnings					
		H_m m	N trees/ha	D_g cm	G m²/ha	H %	v m³	V m³/ha	N_c trees/ha	D_{ge} cm	G_c m²/ha	v_e m³	V_e m³/ha	V_{acum} m³/ha
10	4.0	3.7	500	13.5	7.1	116	0.03	15.8	92	11.9	1.0	0.03	2.5	2.5
20	6.6	6.1	408	19.2	11.8	78	0.10	40.6	71	16.9	1.6	0.08	6.0	8.5
30	8.6	7.9	336	23.7	14.8	66	0.19	64.0	55	20.9	1.9	0.16	8.8	17.4
40	10.3	9.5	281	27.6	16.8	60	0.30	83.9	42	25.2	2.1	0.27	11.4	28.7
50	11.7	10.8	239	31.0	18.1	57	0.42	100.2	33	28.3	2.1	0.38	12.6	41.3
60	13.0	11.9	206	34.1	18.9	56	0.55	113.3	27	31.1	2.0	0.50	13.2	54.5
70	14.1	13.0	179	37.0	19.3	55	0.69	123.8	22	33.7	1.9	0.62	13.4	67.9
80	15.2	13.9	158	39.7	19.5	54	0.84	132.3	18	37.3	1.9	0.80	14.2	82.1
90	16.1	14.8	140	42.1	19.5	54	0.99	139.0	15	39.6	1.8	0.94	14.0	96.1
100	17.0	15.6	125	44.5	19.4	54	1.16	144.4	12	41.8	1.7	1.10	13.7	109.8
110	17.8	16.4	113	46.7	19.3	55	1.32	148.7	11	43.9	1.6	1.26	13.3	123.1
120	18.6	17.1	102	48.8	19.1	55	1.49	152.1	9	45.8	1.5	1.42	12.9	136.0
130	19.3	17.8	93	50.9	18.9	56	1.67	154.8	8	47.7	1.4	1.58	12.5	148.5
140	20.0	18.4	85	52.8	18.6	56	1.85	156.9	7	49.5	1.3	1.75	12.0	160.5
150	20.7	19.0	78	54.7	18.4	57	2.03	158.5						

t years	H_0 m	Total volume			Diameter distribution before thinning															
		V_t m³/ha	MAI m³/ha-year	CAI m³/ha-year	<10	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
10	4.0	15.8	1.6	1.6	2	169	322	7												
20	6.6	43.0	2.2	2.7		12	118	227	51											
30	8.6	72.5	2.4	2.9		1	24	107	155	48	1									
40	10.3	101.3	2.5	2.9			6	37	99	107	31	1								
50	11.7	128.9	2.6	2.8			1	13	47	89	71	17	1							
60	13.0	154.6	2.6	2.6				5	22	54	73	43	8							
70	14.1	178.3	2.5	2.4				2	10	30	55	55	24	3						
80	15.2	200.2	2.5	2.2				1	5	17	37	50	36	11	1					
90	16.1	221.1	2.5	2.1					2	9	23	39	40	21	4					
100	17.0	240.5	2.4	1.9					1	5	14	29	37	28	10	1				
110	17.8	258.5	2.3	1.8						3	9	20	31	30	16	4				
120	18.6	275.2	2.3	1.7						1	5	13	24	28	21	8	1			
130	19.3	290.8	2.2	1.6						1	3	9	18	25	23	12	3			
140	20.0	305.4	2.2	1.5							2	6	13	20	22	15	5	1		

Abbreviations as in Table 9.

involves lower values of this coefficient. The values obtained for dense stands at mature ages (70-80 years) are similar to those proposed by Río (1999) for *Pinus sylvestris* at the same ages. Also, for the LD type, the coefficients agree with those reported by Baroni (1973) or Castellani (1989) for *Pinus pinea.*

Whereas the «observed silviculture» scenarios characterize the typical *Pinus pinea* stands in this region, with fairly elevated densities in both LD and HD stands at young ages, the «reference silviculture» proposes lower densities from young ages with the aim of accelerating the diameter growth of trees, providing better tree dimensions at rotation age. In this sense, we propose some general silvicultural guidelines for managing *Pinus pinea*, based on the yield tables:

— Regeneration by uniform-shelterwood or clearcutting in patches or strips at ages 70 to 100, depending on site index (site index 21 and 13, respectively).

— Perform early and heavy thinning from below, not later than year 15.

Table 12. Yield tables for *Pinus pinea* L. in Catalonia: case of «reference silviculture» for HD stands of site index 17 m at a reference age of 100 years

t years	H_0 m	Main stands variables before thinning							Volume removed in the thinnings					
		H_m m	N trees/ha	D_g cm	G m²/ha	H %	v m³	V m³/ha	N_c trees/ha	D_{ge} cm	G_c m²/ha	v_e m³	V_e m³/ha	V_{acum} m³/ha
10	4.0	3.8	830	16.8	18.4	90	0.04	36.82	129	12.9	1.7	0.04	4.6	4.6
20	6.6	6.3	701	20.9	24.0	59	0.11	79.16	105	16.0	2.1	0.09	9.5	14.1
30	8.6	8.2	596	24.3	27.6	49	0.20	117.39	84	18.5	2.3	0.16	13.2	27.3
40	10.3	9.8	512	27.4	30.1	45	0.29	150.40	67	21.6	2.5	0.25	16.8	44.1
50	11.7	11.1	445	30.1	31.7	42	0.40	178.53	55	23.7	2.4	0.34	18.6	62.8
60	13.0	12.3	390	32.7	32.8	40	0.52	202.47	45	25.6	2.3	0.44	19.8	82.6
70	14.1	13.4	345	35.2	33.5	39	0.65	222.87	37	27.4	2.2	0.55	20.4	103.0
80	15.2	14.4	308	37.5	33.9	39	0.78	240.35	31	30.3	2.3	0.70	22.0	125.0
90	16.1	15.3	277	39.7	34.2	39	0.92	255.38	27	31.9	2.1	0.83	22.0	147.0
100	17.0	16.1	250	41.8	34.3	39	1.07	268.38	23	33.5	2.0	0.97	21.9	169.0
110	17.8	16.9	227	43.8	34.3	39	1.23	279.68	20	35.0	1.9	1.11	21.7	190.6
120	18.6	17.7	208	45.8	34.2	39	1.39	289.54	17	36.5	1.8	1.25	21.3	212.0
130	19.3	18.4	191	47.7	34.1	39	1.56	298.18	15	37.9	1.7	1.41	20.9	232.9
140	20.0	19.0	176	49.5	33.9	39	1.74	305.79	13	39.3	1.6	1.57	20.5	253.4
150	20.7	19.6	163	51.4	33.7	39	1.92	312.51						

t years	H_0 m	Total volume			Diameter distribution before thinning															
		V_t m³/ha	MAI m³/ha-year	CAI m³/ha-year	< 10	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
10	4.0	36.8	3.7	3.7		51	466	311	3											
20	6.6	83.8	4.2	4.7		6	114	374	200	6										
30	8.6	131.5	4.4	4.8		1	31	168	285	106	4									
40	10.3	177.7	4.4	4.6			10	69	190	194	48	1								
50	11.7	222.7	4.5	4.5			3	28	104	178	114	17								
60	13.0	265.2	4.4	4.3			1	12	54	125	138	55	5							
70	14.1	305.4	4.4	4.0				5	28	79	121	88	22	1						
80	15.2	343.4	4.3	3.8				2	15	48	92	98	46	7						
90	16.1	380.4	4.2	3.7				1	8	29	65	89	64	19	2					
100	17.0	415.4	4.2	3.5					4	17	44	73	71	34	6					
110	17.8	448.6	4.1	3.3					2	10	29	56	68	46	14	1				
120	18.6	480.2	4.0	3.2					1	6	19	41	59	52	24	5				
130	19.3	510.2	3.9	3.0						3	12	29	49	53	33	10	1			
140	20.0	538.7	3.8	2.9						2	8	21	38	48	38	16	3			

Abbreviations as in Table 9.

— Moderate thinnings, even of dominant trees, every 10-15 years, depending on site index, up to year 40-60 (3-4 thinnings in total along the rotation).

— Pruning only in best sites for increasing timber quality or in case of high fire risk (1-2 prunings, coinciding with first thinnings).

— Cleaning mainly in case of high fire risk, coinciding with first two thinnings. Cleaning can be selective and it is also recommended at time of stand regeneration or pine nut harvesting.

Hence with this management approach, although the total timber production is lower, we obtain trees of greater size and higher value, for both timber and fruit production. Many authors have confirmed the positive relationship between the size of the trees and their timber value and fruit production (Montero and Candela, 1998; García Güemes, 1999; Cañadas, 2000; Calama and Montero, 2007). In addition, when other functions of the forest are considered, such as landscape, recreation, protection or prevention of forest fires, the

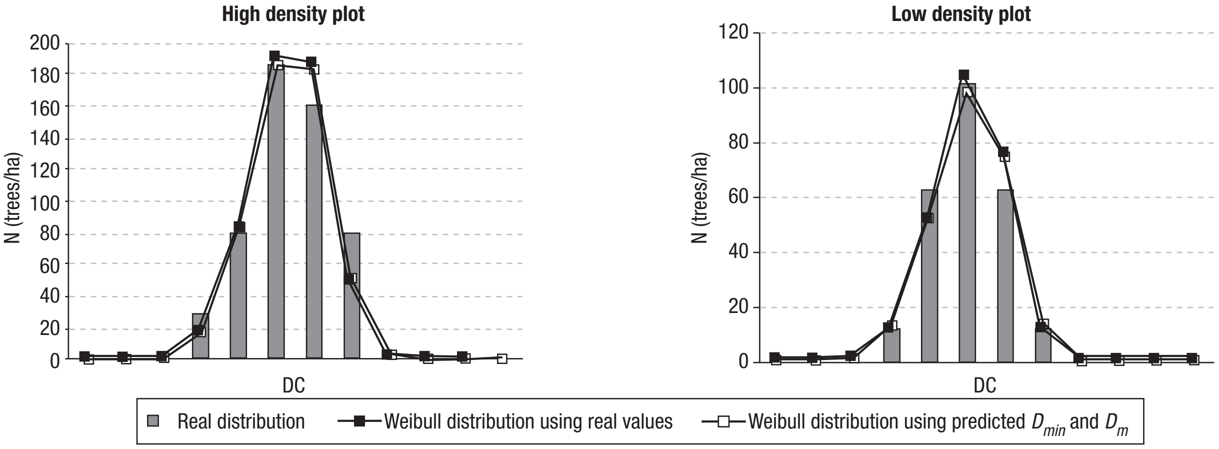

Figure 5. Comparison between real diameter distributions of two temporary plots and diameter distributions predicted by the Weibull function using the real values of D_{min}, D_m and D_g and those obtained from predicted D_{min} and D_m.

«reference silviculture» also offers an improvement to stone pine forest through the constitution of well-developed, stable trees with large crowns and stems.

The models obtained for *Pinus pinea* in Catalonia are a first approach to the knowledge of the growth and productive value of these forests and a basis to guide their management. It would be of interest to include in the future the fruit production in the yield tables and to remeasure the plots with the aim to explore the possibility of designing a dynamic growth model allowing a closer simulation of different silvicultural treatments.

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