



## Adapting a model for even-aged *Pinus pinea* L. stands to complex multi-aged structures

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### ABSTRACT

Stone pine (*Pinus pinea* L.) stands have been usually managed as even-aged stands. Main objectives in management combine two main commercial productions, timber and pine nuts with other social aspects: soil protection, recreational use and biodiversity conservation. Multifunctional management, together with the occurrence of successive events affecting regeneration have oriented managers to propose a management schedule based on the establishment and preservation of a low-stocking multi-aged complex structure on favourable locations. Despite the recent effort on modelling growth and yield on even-aged stands of stone pine, no studies focusing on modelling dynamics for uneven-aged stands have yet been developed up to present.

In this study, a proposal is presented for adapting and calibrating an existing tree-level model, originally developed for even-aged stands of stone pine (model PINEA2), to multi-aged complex stands. Data from four multi-aged trials and 61 plots from the National Forest Inventory were used to adapt the whole set of functions included in the original model. In our study, four different methods have been proposed to adapt the original equations: (1) *direct validation and re-parameterization*; (2) *size class modelling*; (3) *refit of functions after removing typical even-aged covariates*; and (4) *multilevel calibration*. Adaptation is based on assuming that a multi-aged stand of stone pine can be seen as the sum of independent, smaller, even-aged groups. The low densities of the stands, the early liberation of the most vigorous trees in all size classes and the major importance of root-level competition for water in Mediterranean forests are the main factors explaining these particular dynamics. Results show the suitability of the proposed method, attaining unbiased estimates with a degree of accuracy similar to that achieved in applying the original model to even-aged stands. The adapted model (PINEA\_IRR) constitutes a flexible tool for the management and maintenance of stone pine stands, covering a wide range of within stand structural complexity, including forests in transition.

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### 1. Introduction

The uneven-aged forest stand can be defined as a heterogeneous spatial arrangement of trees varying in age and size over a given area, leading to some degree of vertical structuring (Moser, 1972; Schütz, 2002). Recent social awareness of issues such as the increasing structural and biological diversity of forests and interest in non-market benefits from woodlands has led to a demand for the perpetuation of existing uneven-aged stands as well as the transformation of even-aged stands into more complex multi-aged structures. Contrary to commonly held perceptions, most natural forests consisting of shade-intolerant species as well as fire-dependent systems tend toward homogeneity (see e.g. Schütz, 2002), so the perpetuation of and transformation to multi-

aged structures requires the recurrent application of intensive silvicultural interventions. To achieve this, foresters require management schedules appropriate for uneven-aged stands as well as specific tools for checking the long-term sustainability of the proposed silvicultural systems. Where uncertainty arises in the decision making process associated with sustainable forest management, growth and yield models which describe stand dynamics over time under different management and environmental scenarios are currently recognized as one of the most powerful tools available. The importance of modelling is evidenced by the hundreds of forest models published annually in forest literature.

In spite of this importance, most of the attention has generally focused on the development of models for pure even-aged stands, whereas modelling growth and yield in complex uneven-aged stands has not been as extensive (Peng, 2000). Modelling these complex structures is affected by the following features of uneven-aged stands:

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- Multi-aged complex structures include a wide range of conditions and possible situations which are difficult to characterize. There is a lack of suitable information covering all the possible complex states of a stand (Øyen and Nilsen, 2004; Groot et al., 2004), which hampers the task of stand level modelling.
- Several stand level covariates widely used in modelling even-aged stands are of no use in multi-aged conditions (Sterba and Monserud, 1997; Peng, 2000; Eerikäinen et al., 2007), such as age, dominant height and dominant diameter, site index, number of stems per hectare or Reineke's stand density index.
- In an even-aged stand, the differences in growth pattern detected between trees within a given site can be mainly attributed, apart from genetics and microsite, to initial size and competition. However, in an uneven-aged stand, as tree age varies within each size class, individual age or at least, a specific distribution of ages for a given size, must be also considered (Thorpe et al., 2007).
- Because of the high vertical and horizontal differentiation of uneven-aged stands, which could influence tree growth, spatial tree growth models including distance dependent competition indices and directional distribution of competitors are considered to account for variation better than non-spatial models (Pretzsch, 1995; Pukkala and Miina, 1998; Vettenranta, 1999; Bauhus et al., 2002).
- Uneven-aged forest management is based on continuous or periodical forest renewal (Schütz, 2002), so modelling this type of stands requires the inclusion of either specific models or heuristical values for recruitment (Eerikäinen et al., 2007).

Furthermore, modelling multi-aged stands by considering the stand as the basic unit is only possible in those forests which display a state of equilibrium, either using a static function, such as Liocourt's inverse j-shaped function (Meyer, 1952), or by using matrices which describe the transition between different stable states (Kölstrom, 1993). For complex stands that do not display a state of equilibrium and/or for forests in transition, the basic modelling unit should be the average tree per class size (Ralston et al., 2003; Liang et al., 2005) or the individual tree (Sterba, 2004). Tree-level modelling can provide accurate stand growth predictions for the full range of conditions between pure even-aged and mixed uneven-aged stands, and allows the effects of competition as well as the heterogeneous spatial distribution of the trees and sizes to be considered (Monserud and Sterba, 1996; Porté and Bäterlink, 2002; Eerikäinen et al., 2007).

Due to the heterogeneity of complex stands, the construction of a tree-level model requires intensive sampling to be carried out in a large number of experimental uneven-aged plots located in different conditions of stand structure and site quality. This requirement means that the construction of such a model is very costly. As an alternative, most common approaches have involved either the construction of a single model for even-aged and multi-aged stands (Monserud and Sterba, 1996) or the adaptation of an existing model for even-aged stands to take into account multi-aged conditions. Typical adaptation approaches are based on re-parameterization of the original functions to data from uneven-aged stands (Payandeh and Papadopol, 1994), application of correction factors over previously existing functions (Sterba and Monserud, 1997), modification or inclusion of useful variables for multi-aged conditions (Sterba et al., 2002) and adjustment of the even-aged function to the different size/age categories (Mason et al., 1999).

The objective of this study is to present a methodology for adapting an existing tree-level model (PINEA2) developed for even-aged stands of stone pine, for use in multi-aged complex stands. Stone pine (*Pinus pinea* L.) is a typical Mediterranean species, occupying more than 400,000 ha in Spain, both inland and in coastal regions. Economic benefits from these stands include edible pine nuts, timber, firewood and grazing, whilst current

management objectives also include social aspects such as recreational use, biodiversity conservation and CO<sub>2</sub> fixation. Stone pine stands have traditionally been managed as even-aged structures although competition for water and soil resources, advanced recruitment in forest gaps, failure of natural regeneration, the impact of goat grazing and the preservation of older, large cone producing trees, has sometimes resulted in multi-aged complex structures. At the present time, more than 15,000 ha of stone pine located in Central Spain are maintained and managed as uneven-aged stands due to their importance in soil protection, landscaping, recreation and fruit production. The silvicultural system for uneven-aged stands which is applied consists of maintaining low stocking (as proposed by Kerr and O'Hara, 2000 for shade-intolerant species) by applying periodic selective cuttings with a felling cycle of 25 years and maintaining basal area between 5 and 20 m<sup>2</sup>/ha. The aim of selective cuttings is to: (1) remove mature non-fruiting or non-vigorous trees; (2) preserve older standing trees with large cone production; (3) concentrate growth on the best fruit producers from the younger strata, removing those defective trees which hamper the better ones; (4) help recruitment establishment in the gaps; and (5) attain the diameter distribution structure for complex stands proposed by Calama et al. (2005).

Despite the availability of local records describing the history and management of multi-aged stone pine stands (Finat et al., 2000; Montero et al., 2003; Río et al., 2003; Calama et al., 2005), to date, no attempt has been made to model their growth and yield. In the present work, different approaches are used in the adaptation according to the availability of data and the formulation of PINEA2 functions. Together with the previously mentioned approaches for adaptation, plot-level calibration through empirical best linear unbiased prediction (EBLUP) of random plot parameters is proposed as an alternative to traditional calibration methods.

## 2. Data

### 2.1. Multi-aged trial plots (MA trial)

Four permanent trial plots (VA-1, VA-2, AV-1, and AV-2) were installed between 2000 and 2002 in managed, uneven-aged stands of stone pine in Central Spain. Plots are either circular or rectangular, with areas ranging from 2800 to 4800 m<sup>2</sup> in order to include all the possible heterogeneity in tree size detected within the stand. Within each plot, the x,y coordinates for every stone pine with height greater than 20 cm were recorded. Position and diameter of all the stumps remaining from the last cutting were also measured. In the selected stands there was evidence of no silvicultural intervention (thinning or pruning) during the preceding 10 years. For trees with a breast height diameter (dbh) greater than 5 cm, the following measurements were taken: dbh, stump diameter, total height (*h*), height to crown base (hbc), crown diameter (cw), bark thickness, total age (measured at stump height) and radial increment for the last 5 years (estimated from two increment cores taken at breast height). In a sample of 10 trees per plot breast height age was measured, in order to estimate the number of years necessary to reach breast height and calculate breast height age (T<sub>n</sub>). In smaller plants, only total height and crown diameter were measured. All these data were used to determine dbh increment for the past 5 years and to reconstruct ("backdate") the past state of the stands (Hökka and Groot, 1999; Sterba et al., 2002; Øyen and Nilsen, 2004). Three to four different 25-year age classes and 10 cm diameter classes were identifiable in the plots (Fig. 1); hence, they were considered representative of multi-aged stone pine stands. The main stand variable statistics for each plot are presented in Table 1.

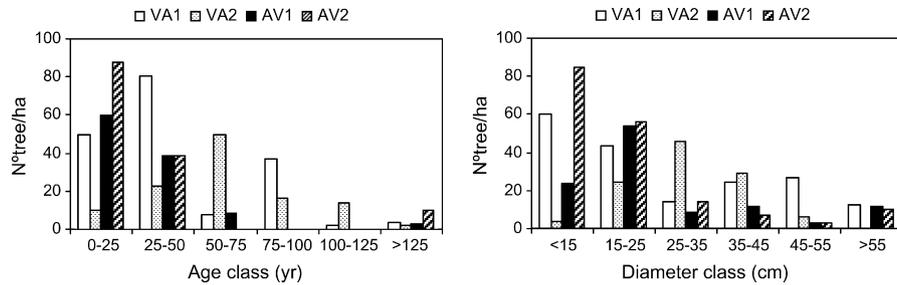


Fig. 1. Observed frequencies per 25 age years (left) and 10 cm diameter (right) classes for the four plots in MA trial.

## 2.2. National Forest Inventory (NFI) plots

The NFI is a systematic sample of permanent plots distributed on a 1 km square grid, with a remeasurement interval of 10 years. Sixty-one plots from the NFI network located in pure (>90% of trees with dbh > 5 cm are *P. pinea*) stone pine forests in Central Spain were deemed representative of complex structures. Since tree age is not recorded in the NFI, the plots selected were those which contained trees in more than three 10 cm diameter distribution classes in the 2nd inventory (1994). The 'low stocking' requirement was met by selecting plots with a basal area <25 m<sup>2</sup>/ha and stand density <400 stems/ha. Finally, only those plots which were remeasured in the 3rd NFI (2004) were considered.

NFI plots are circular in shape and composed of four sub-plots with radii of 5, 10, 15 and 25 m in which trees are selected according to their breast height diameter (7.5, 12.5, 22.5 and 42.5 cm, respectively). Breast height diameter and total height are measured for all the selected trees, whilst crown diameter and section diameter at a height of 4 m are only measured on a sample of 3–4 trees per plot. Diameter increment at tree level is estimated as the difference of measured diameters between the 2nd and 3rd inventory. Coordinates of the trees with respect to plot centre are not measured in NFI plots. Summary statistics for NFI plots are also included in Table 1.

## 2.3. Cone data

There are currently no data available for cone crops in multi-aged stands, although a large amount of information exists regarding tree-level cone production in even-aged stands. This data set includes a 10-year (1996–2005) series of annual production from more than 1000 trees growing in 200 plots covering the whole study region. The latter data were previously used to develop a single-tree model for cone production in even-aged stands (Calama et al., 2008). In the present work, these data have been used to adapt the previous cone model to conditions in uneven-aged stands.

## 3. Methods

### 3.1. Background: model PINEA2

PINEA2 is a tree-level integrated model developed for the multifunctional management of even-aged stands of stone pine (see Calama et al., 2007 for more detail). The PINEA2 model simulates the development and yield of even-aged stands of stone pine under different management schedules by predicting the growth of each tree in 5-year stages throughout the productive cycle. Management decision schedules are characterized by the length of the productive cycle and the periodicity and intensity of thinning. PINEA2 is a modular system composed of three basic modules: site quality, state and transition. The basic input variables for the model are: stand age, dominant height, stand density and single-tree diameter list. Functions included in the different modules are:

- **Site quality module:**
  - Algebraic difference equation for site index prediction.
- **State module:**
  - Generalized height diameter equation.
  - Crown dimension functions.
  - Stem taper equation.
  - Ecological based model for annual cone production.
  - Biomass fractions equations.
- **Transition module:**
  - 5-Year diameter increment function.

### 3.2. Alternatives for adaptation

The basic assumption for adapting PINEA2 is to consider a multi-aged stand of stone pine as a mixture of small even-aged groups of trees (including single-tree groups). Under this assumption, the dynamics of a tree in a given group are influenced by exogenous factors (as competition or site quality) in the same way as if it were growing in an even-aged stand. Adaptation is then

Table 1  
Summary statistics for MA trials and NFI plots

Plot	stems/ha	qmd (cm)	hg (m)	BA (m <sup>2</sup> /ha)	Vol (m <sup>3</sup> /ha)	Coverture (m <sup>2</sup> /ha)	Last cutting
VA-1	175	33.4	12.7	15.3	83.9	4492	1987
VA-2	110	32.8	9.5	9.3	40.0	2623	1992
AV-1	123	34.9	14.8	11.8	72.4	3720	1990
AV-2	177	26.5	13.1	9.7	51.8	2960	1990
NFI 61 plots							
Mean	190	32.3	8.99	14.1	71.5	–	–
Maximum	382	47.4	14.36	24.4	151.6	–	–
Minimum	63	17.2	4.64	4.0	19.2	–	–

qmd: quadratic mean diameter; hg: Lorey's mean height; BA: basal area; Vol: total volume.

based on testing whether it is reasonable to consider the dynamics of complex multi-aged stands of stone pine as a special case of even-aged stand dynamics as described by PINEA2. Together with this main assumption, we decided to avoid the inclusion of stand level covariates typical of even-aged stands, such as site index, stand age or mean and dominant height (hereafter defined as *typical even-aged covariates*). The plot-level variables evaluated were: basal area, quadratic mean diameter and stand density as well as the typical even-aged covariates computed per size classes. Tree-level covariates evaluated were:

- *Size attributes*: dbh, height, crown width, height to crown base.
- *Tree maturity*: tree age, measured at stump height.
- *Distance independent competition indices*: crown ratio, BAL, size ratios.
- *Distance dependent competition indices*: influence area overlap indices, area potentially available indices and distance weighted size ratios. These indices were computed using different criteria for the selection of competitors. Edge effect was corrected using Martin et al. (1977) method. Since no coordinates were available in NFI plots, these indices were only computed for MA trials.

In view of previous conditions, the different functions in PINEA2 were independently adapted by using one of the following approaches:

- (1) *Direct application and heuristic re-parameterization of original functions*. Those functions in PINEA2 which did not include *typical even-aged covariates* in their formulation were validated by directly applying them to the data from the multi-aged stands. If small deviations were identified among predicted and observed values, the parameters could be numerically modified in order to attain unbiased estimates, as proposed by Payandeh and Papadopol (1994) to calibrate the ONTWIGS model.
- (2) *Class-size level modelling*. A second approach consists of substituting the *typical even-aged* stand covariates in a given function for its corresponding covariate computed per diameter class, and then applying it to multi-aged stands. This approach is directly derived from considering a multi-aged stand as the union of different, small even-aged groups. This has been termed the 'summation' method, and has been widely used to adapt stand density index for use in uneven-aged stands (Woodall et al., 2003a).
- (3) *Refit functions after removing typical even-aged covariates*. The original even-aged data base can be used to refit the functions of a model by replacing the *typical even-aged covariates* with stand or tree-level *typical multi-aged covariates* (as proposed by Sterba et al., 2002). This is the only possible approach for adapting those functions in which no observations of the response variable are available for multi-aged stands, as is the case of annual cone production.

A function adapted using approaches (1)–(3) is validated if unbiased and accurate estimates are obtained on applying it to data from both the MA trial and the complex NFI plots. Bias is evaluated considering mean error ( $E$ ), the level of significance associated with the mean error ( $p$ -value), as well as the level of significance ( $p$ -novel) associated with the novel validation test proposed by Kleijnen (1999). Accuracy is described by using modelling efficiency (EF) and root mean square error (RMSE) for the predictions.

- (4) *Multilevel calibration and covariate selection*. Although several functions in PINEA2 are formulated as multilevel mixed models, including plot and tree random parameters, due to inherent correlation among traits, multilevel calibration is only proposed for the single-tree diameter increment function. The original diameter increment function (Calama and Montero,

2005) is formulated as a multilevel linear mixed model including random plot ( $u$  and  $v$ ), tree ( $w$ ) and 5-year period ( $k$ ) parameters, together with fixed covariates such as site index, dominant height, number of stems per ha, tree diameter and the ratio between tree diameter and mean squared diameter. Many of the latter are of little use in a multi-aged context. This function was derived from the following basic function, only including tree dbh as predictor covariate:

$$\log(\text{id} + 1) = 1.6142 + u + (-0.1856 + v) \log(\text{dbh}) + w + k + e \quad (1)$$

where  $[u, v]$  follows a bivariate normal distribution with mean zero and variance terms  $\sigma_u^2 = 0.0779$ ,  $\sigma_v^2 = 0.0110$  and  $\sigma_{uv}^2 = 0.0670$ ,  $w$  and  $k$  follow a univariate normal distribution with mean zero and variance  $\sigma_w^2 = 0.0109$  and  $\sigma_k^2 = 0.0067$ , respectively, and  $e$  is a residual term with mean zero and heteroscedastic variance  $\sigma_e^2 = 0.1039 - (0.00699 \log(\text{dbh}))$ .

Multilevel calibration is based on predicting the EBLUPs for the random components included in a multilevel model by using a sample of available observations. EBLUP prediction is carried out following the methodology proposed by Henderson (1963), Harville (1976) or Vonesh and Chinchilli (1997). In the present work, we used all the available increment data from the MA trials and complex NFI plots, in order to predict EBLUPs for each tree ( $w$ ), plot ( $u, v$ ) and period ( $k$ ) random component included in Eq. (1). Predicted EBLUPs indicate the deviation with respect to the average pattern of growth in even-aged stands due to unobservable factors acting at each level.

The predicted EBLUPs are then used for identifying those possible covariates at tree- or plot-level which explain the specific pattern for uneven-aged stands. Variables were first selected based on the Pearson correlation coefficient with predicted EBLUPs. Subsequently, the inclusion of pre-selected plot and tree-level variables in the model was evaluated in terms of RMSE reduction and bias. Due to the sampling characteristics of NFI plots, only the 199 trees with measured increment data in the MA trial were used to identify possible explanatory covariates at tree level.

Multilevel mixed formulation also allows the model to be calibrated for new locations by predicting plot-level components using an additional subsample of observations, as stated by Lappi and Bailey (1988), Fang and Bailey (2001) or Calama and Montero (2005). We used data from the MA trials (4 plots with 199 trees) and NFI (488 trees from the 35 plots which included at least 10 trees) to determine the optimal number of additional observations necessary for accurate plot-level calibration. This was done by evaluating different calibration sample sizes (including 1–5 tally trees per plot), carrying out 100 random simulations with the inclusion of different trees in each simulation. Calibration is considered adequate if the RMSE is smaller than that attained using the fixed effects approach (i.e. when random plot components attain the expected value of 0) in at least 90% of the simulations, if RMSE is under 1 cm in at least 90% of simulations, and if mean error is slight or non-significant ( $p > 0.01$ ) in at least 50% of the simulations.

#### 4. Results: model PINEA\_IRR

PINEA\_IRR is an adaptation of PINEA2 for complex structures. PINEA\_IRR retains the 5-year stage sequential character and the modular structure of PINEA2 (Fig. 2), including site, state and transition modules although the different functions and equations are adapted for use in multi-aged conditions.

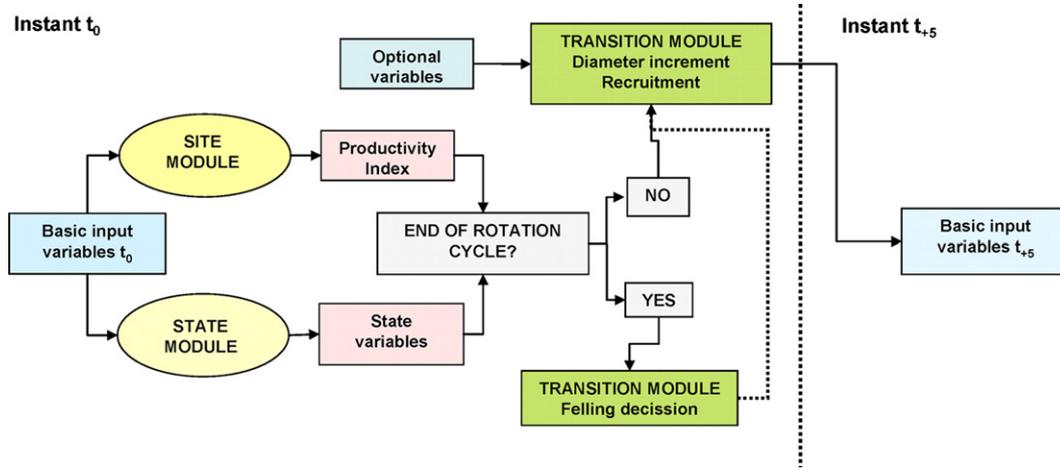


Fig. 2. Flow diagram for PINEA\_IRR model.

4.1. Site module

4.1.1. Productivity index

Site index is computed in PINEA2 using an algebraic difference equation (Calama et al., 2003), which includes the dominant height of the stand at a given stand age as a predictor covariate. In the present work we develop a new productivity index by using approach (2). In order to achieve this objective, the dominant height for each diameter class was estimated in each MA trial plot (NFI data was disregarded as tree age was not available), using the average heights and ages of the two thickest trees per 10 cm diameter class. These values were then used to compute a productivity index  $PI_i$  for diameter class  $i$ , by directly applying the same equation used in PINEA2, considering a reference age of 100 years:

$$PI_i = \exp \left[ 4.1437 + (\ln(H_i) - 4.1437) \left( \frac{100}{T_i} \right)^{-0.3935} \right] \quad (2)$$

where  $H_i$  and  $T_i$  indicate the dominant height and age for diameter class  $i$ . The accuracy of the approach was evaluated by analysing the constancy of estimated class productivity indices (in terms of coefficient of variation) across diameter classes (Table 2). Large deviations are associated with the lowest diameter class (dbh < 15 cm), a result that is in accordance with the lack of precision detected when applying the dominant height growth model to young even-aged stands (Calama et al., 2003). If this class is not considered, the coefficient of variation for  $PI_i$  decreases from ranges of 11.64–15.00% to 6.60–14.00%. If the average plot productivity index is compared with the site index previously estimated in even-aged stands located close to the multi-aged plots, the values are also quite similar.

Table 2  
Estimated productivity index ( $PI_i$ ) per diameter class and average productivity index (PI) per plot computed using or not using < 15 cm diameter class (data from MA trials)

Plot	$PI_i$ per diameter class (cm)					Considering <15 cm class		Without considering <15 cm class		SI (m)
	<15	15–25	25–35	35–45	>45	PI	CV (%)	PI	CV (%)	
VA-1	14.72	15.10	18.52	16.98	13.37	15.74	12.84	15.99	14.00	16
VA-2	14.51	13.51	12.76	9.69	12.021	12.50	14.56	12.00	13.78	12
AV-1	14.80	15.47	20.31	20.36	19.35	18.06	15.00	18.87	12.27	18
AV-2	13.78	18.83	16.31	18.13	16.84	16.78	11.64	17.53	6.60	18

CV: coefficient of variation; SI: estimated site index in a nearby even-aged plot.

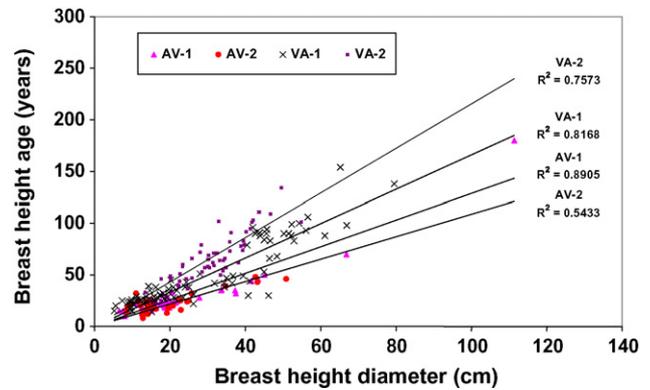


Fig. 3. Breast height age–breast height diameter relation for the four multi-aged trials.

4.1.2. Breast height diameter–breast height age relationship

In a multi-aged context, the estimation of individual ages is necessary to characterize the age structure of the stand. In even-aged stands, the relationship between size and age depends on site quality and stand density, but in low density multi-aged stands, where closure is kept at constant low values throughout the cycle, we can hypothesize the existence of a close, site-dependent relationship between tree size and tree age. Fig. 3 suggests that this hypothesis is supported by the data from multi-aged trials. Assuming a non-intercept model (given that by definition dbh equals 0 at breast height age  $T_n = 0$ ) a near linear relationship between dbh and  $T_n$  can be identified for each plot. A slight significant negative correlation was also detected between the slope parameter for each plot and the previously defined

productivity index PI ( $r = -0.9259$ ,  $p$ -value 0.037). Thus, the following model was proposed to relate dbh to Tn:

$$Tn = [3.8990 - 0.1461 PI]dbh \quad (3)$$

Since this equation was developed using data from only four trials, it should be used with caution when predicting age in other stands, especially if stocking conditions in the new stand vary substantially from those in the MA trial.

#### 4.2. State module

##### 4.2.1. Height–diameter generalized function

The height–diameter relationship is modelled in PINEA2 using a generalized height–diameter function forced to pass through the point of dominant stand diameter–dominant stand height. The height–diameter relationship is age-dependent, so the adaptation of this function to multi-aged conditions using approach 2 was evaluated. The height–diameter function was modified by substituting dominant stand diameter and height for the maximum diameter and maximum height attained in each 10 cm diameter class.

$$h = 1.3 + \left[ 3.0816 \left( \frac{1}{dbh} - \frac{1}{D_i} \right) + \left( \frac{1}{H_i - 1.3} \right)^{1/2} \right]^{-2} \quad (4)$$

where in this case  $D_i$  and  $H_i$  represent the maximum diameter and height defined for the diameter class  $i$ . Table 3 shows the results of the proposed adaptation for the 225 trees in the MA trials and the 781 trees in NFI plots with dbh and  $h$  measurements. The adaptation of the function leads to unbiased estimates in three of the four analysed MA trials (except in AV-2, with  $p$ -value for mean error 0.0027,  $p$ -value for novel test 0.0001), with RMSE values close to 1 m and EF values about 0.90. Jointly considering the whole set of NFI plots, the adaptation leads to slightly biased ( $p$ -value for mean error 0.0338,  $p$ -value for novel test 0.0930) estimates, with RMSE value of 1.11 m and EF of 0.83. Testing the NFI results at plot level (results not shown), of the 61 analysed plots, significant ( $p$ -value < 0.01) bias is detected in only three plots, slight bias ( $p$ -value < 0.05) is identified in seven plots and non-significant bias ( $p$ -value > 0.05) is observed for the remaining 51 plots. In applying novel test at plot level, significant ( $p$ -value for novel test < 0.01) bias is detected in eight plots, slight bias ( $p$ -value for novel test < 0.05) is identified in four plots, whilst 49 plots show non-significant bias ( $p$ -value for novel test > 0.05).

##### 4.2.2. Crown equations

Crown width (cw, in m) and height to crown base (hbc, in m) are predicted in PINEA2 using the following functions developed by Cañadas et al. (2001):

$$hbc = h \exp(-12.54(dbh/h) - 11.07(1/Tn) - 295.04(dbh/h)(1/Tn)) \quad (5a)$$

$$cw = 0.813 - 0.202 hbc + 0.169 dbh \quad (5b)$$

Since the variables included are of practical use in uneven-aged stands and can be measured or estimated, we first tried approach 1,

**Table 3**

Summary statistics for the class-size adaptation of the height–diameter model (data from MA trials and NFI plots)

Plot	N	RMSE (m)	E (m)	p-Value	EF	p- <i>Novel</i>
VA-1	84	1.22	0.199	0.1344	0.895	0.0013
VA-2	53	0.57	0.078	0.3198	0.897	0.1719
AV-1	38	1.27	-0.007	0.9723	0.924	0.4712
AV-2	50	1.20	0.573	0.0027	0.935	0.0001
NFI (61 plots)	781	1.11	-0.084	0.0338	0.830	0.0930

**Table 4**

Summary statistics for the adaptation of the crown dimensions model (data from MA trials)

Plot	N	RMSE (m)	E (m)	p-Value	EF	p- <i>Novel</i>
<b>Crown width</b>						
VA-1	84	0.88	0.573	<0.0001	0.907	<0.0001
VA-2	53	0.56	0.178	0.0175	0.841	0.0443
AV-1	38	1.28	0.035	0.8651	0.901	0.0737
AV-2	50	0.61	-0.050	0.5619	0.943	0.0001
<b>Height to crown base</b>						
VA-1	84	0.88	-0.434	<0.0001	0.842	<0.0001
VA-2	53	0.67	0.227	0.0117	0.552	0.0269
AV-1	35	0.91	-0.033	0.8299	0.751	0.0009
AV-2	35	0.46	0.057	0.4705	0.978	0.6915

directly applying the equations to the data from the MA trial. Table 4 shows how the direct application of the models leads to biased ( $p$ -value and  $p$ -novel < 0.0001) crown dimension estimates for plot VA-1 and slightly biased estimates ( $p$ -value and  $p$ -novel < 0.05) in VA-2. With respect to plots AV-1 and AV-2, unbiased estimates are obtained except when applying novel test to either crown width estimates in AV-2 or height to crown base estimates in AV-1. Absolute RMSE values for the four plots ranges between 0.56 and 1.28 m for crown width (EF 0.84–0.91) and 0.46–0.92 m for height to crown base (EF 0.55–0.98).

##### 4.2.3. Stem taper curve

As section diameters were not measured for the trees in the MA trials, 205 trees from NFI plots with additional section diameter measured at a height of 4 m were used to adapt the stem taper equation by Calama and Montero (2006). The adaptation was carried out following approach (1), by adding a heuristical value  $\alpha$  to an existing parameter from the original equation in order to attain unbiased, accurate estimates. The proposed model is expressed as

$$d_s = dbh \left( \frac{h - h_s}{h - 13} \right) + 1.1924 \left( \frac{h^{1.5} - h_s^{1.5}}{h^{1.5+\alpha}} (h_s - 13) \right) - 2.4463 \left( \frac{(h - h_s)^4 (h_s - 13)}{h^4} \right) \quad (6)$$

where dbh and  $d_s$  represent breast height diameter and section diameter (mm in this equation),  $h$  and  $h_s$  are total height and section height (dm in this equation) and  $\alpha$  equals -0.2 if the dbh of the tree is under 25 cm. Table 5 shows the results per diameter class for the proposed adaptation. The predictions for sections at 4 m are unbiased (except for diameter class 35–45 cm,  $p$ -novel < 0.0001), with RMSE ranging between 19 and 47 mm (depending on diameter class). Modelling efficiency per diameter class is close to or above 0.90 for all the classes except for the 25–35 cm class (EF 0.43). The low EF value for this class is not due to inaccuracy of the adaptation but to the fact that predicted values in this class are close to the average value for the data set. EF for

**Table 5**

Summary statistics for the adaptation of the stem taper curve equation (data from 205 trees in NFI plots)

Diameter class (cm)	N	RMSE (mm)	E (mm)	p-Value	EF	p- <i>Novel</i>
<15	17	19.68	-1.132	0.8120	0.985	0.6999
15–25	64	25.22	-0.024	0.9938	0.938	0.0425
25–35	58	27.37	0.957	0.7907	0.421	0.0977
35–45	55	38.72	6.159	0.2373	0.896	<0.0001
>45	11	49.42	17.475	0.2353	0.960	0.3645
Total	205	30.87	2.757	0.2005	0.923	0.0046

global prediction (jointly considering all the diameter classes) reaches 0.92.

4.2.4. Average cone production model

The model for cone production in even-aged stands uses the following variables as predictors: cross-sectional area at breast height, number of stems/ha, social status of the tree (ratio dbh/qmd) and either site index or a categorical indicator of an ecological stratification of the territory (Calama et al., 2008). In the present work, approach (3) for adaptation was employed, using data from even-aged stands to refit a model for single-tree cone production. Stems per hectare, ratio dbh/qmd and site index were not considered. Assuming that crown dimensions provide good indicators of stand density and social status of the tree in a multi-aged stand, crown attributes were evaluated for inclusion in the model. The final expression for the cone model suitable for multi-aged stands is given by

$$wc = \exp^{(0.2053+3.2322g+0.1221 cw+UN)} - 1 \tag{7}$$

where *wc* is the average weight (kg) of healthy cones for a given tree, *g* represents cross-sectional area at breast height (m<sup>2</sup>), *cw* is crown width (m) and *UN* is a categorical variable representing natural stratification of the territory based on soil and climate attributes (Calama et al., 2008). The fitted model including the new covariates gives slightly biased estimates (*E* = 0.201 kg; *p*-value 0.0496), reaching an EF value of 0.41.

4.2.5. Biomass fraction equations

The biomass fraction allometric equations proposed by Montero et al. (2005) were directly applied to PINEA2 and PINEA\_IRR since they only use single-tree dbh as an explanatory variable and were constructed using data indistinctly from even and uneven-aged stands. The proposed equations allow biomass fractions (kg of dry matter) to be estimated for stem, large (>7 cm), medium (2–7 cm) and small (<2 cm) branches, root and needles.

4.3. Transition module

4.3.1. Diameter increment function

The diameter increment function forms the core of the PINEA2 model since it permits single-tree growth to be described and therefore, by aggregation, to describe the growth of the stand as a result of different exogenous and endogenous factors. Fig. 4 shows the pattern of the relationship between 5-year diameter increment and breast height diameter for the 788 trees from the NFI and MA multi-aged stands, compared with the increment pattern attained

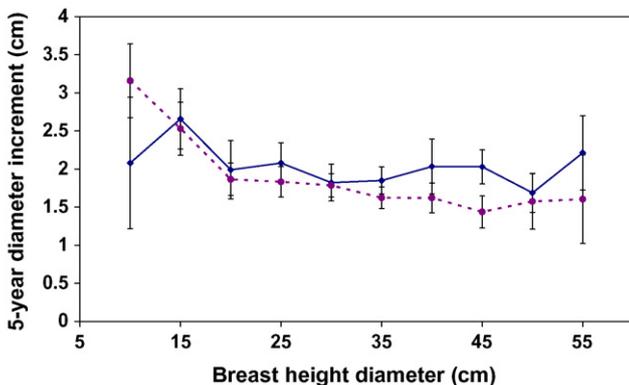


Fig. 4. Pattern of diameter increment for even-aged (dashed lines) and uneven-aged (solid lines) as a function of breast height diameter. Bars represent standard errors for the mean value.

Table 6

Summary statistics for the adaptation of the diameter increment model as a function of the number of trees used for plot-level calibration (NFI: 61 plots with 488 trees)

Number of tally trees	Tree-level covariates	p90 RMSE (cm)	p50 E (cm)	p50 p-value
0 (fixed)*	No	0.9213	-0.2351	<0.0001
1	No	0.8443	-0.1180	0.0011
2	No	0.8019	-0.1053	0.0032
3	No	0.7693	-0.1050	0.0015
4	No	0.7474	-0.0936	0.0041
5	No	0.7306	-0.0950	0.0040

p90 RMSE, p50 *E* and p50 *p*-value are, respectively, the 90th percentile for RMSE, and the median for *E* and *p*-value computed after 100 random realizations. \*In fixed effects model all realizations lead to the same value of RMSE, *E* and *p*-value.

by 539 trees from the data base of even-aged stands of stone pine. As can be seen, not very large differences were detected, with larger individual increments in the even-aged stands at younger stages whilst the greater increments corresponded to older trees in the multi-aged structures. The adaptation of the diameter increment function was carried out using approach (4), by first predicting EBLUPs for the plot (*u*, *v*), tree (*w*) and period (*k*) random components for the 61 NFI plots and the 4 multi-aged trials.

Significant negative correlation was detected between basal area and parameters *u* (*r* = -0.6410, *p*-value < 0.0001) and *v* (*r* = -0.5991, *p*-value < 0.0001), so the following model was then transformed and re-parameterized to include this variable:

$$\log(id + 1) = 1.8573 - 0.01752 BA + u' + (-0.0907 - 0.0052 BA + v') \log(dbh) + w + k + e \tag{8}$$

where *u'* and *v'* are now random plot components following a bivariate normal with mean zero and variance terms  $\sigma_u^2 = 0.0143$ ,  $\sigma_v^2 = 0.0015$  and  $\sigma_{uv} = 0.0031$ , whilst *w*, *k* and *e* are as previously stated.

4.3.1.1. Plot-level calibration. Multilevel mixed formulation of model (8) allows plot-level calibration for new locations if diameter increment cores are taken from a small sample of trees. The results for the NFI (Table 6) indicate that if no trees are sampled (fixed effects model) the RMSE is 0.921 cm, whilst calibration using diameter increments from 2 trees per plot in order to predict random parameters *u'* and *v'* leads to a RMSE close to 0.80 cm in 90% of the realizations, and a median error of -0.105 cm (median *p*-value 0.0032). In the MA trial (Table 7) the RMSE reaches 1.013 for the fixed effects model, whilst calibration using 4 trees leads to an RMSE under 0.985 cm in 90% of the realizations, with a median error -0.104 cm (median *p*-value

Table 7

Summary statistics for the adaptation of the diameter increment model as a function of the number of trees used for plot-level calibration and tree-level covariates inclusion (MA trials: 4 plots with 199 trees)

Number of tally trees	Tree-level covariates	p90 RMSE (cm)	p50 E (cm)	p50 p-value
0 (fixed)*	No	1.0138	-0.1743	0.0151
1	No	1.0518	-0.0635	0.1858
2	No	1.0057	-0.0689	0.1241
3	No	0.9870	-0.1068	0.0481
4	No	0.9855	-0.1047	0.0518
5	No	0.9699	-0.0748	0.1319
0 (fixed)*	Yes	0.9914	-0.1529	0.0288
4	Yes	0.9430	-0.0935	0.0933

p90 RMSE, p50 *E* and p50 *p*-value are, respectively, the 90th percentile for RMSE, and the median for *E* and *p*-value computed after 100 random realizations. \*In fixed effects model all realizations lead to the same value of RMSE, *E* and *p*-value.

0.0520). However, in the MA trial, a calibration using 2 trees only reduces the RMSE to 1.006 cm.

**4.3.1.2. Inclusion of tree-level covariates.** The crown ratio ( $r = 0.1908$ ,  $p$ -value 0.0069) and area overlap index defined by a radius of influence 25 times the dbh (hereafter  $ao_{25}$ ,  $r = -0.3516$ ,  $p$ -value  $< 0.0001$ ) were those attributes more closely related to tree-level EBLUPs, whilst to a lesser extent, tree age showed slight significant negative correlation ( $r = -0.1569$ ,  $p$ -value 0.0269). However, indices of area potentially available ( $p$ -value 0.2389) and distance independent competition indices such as BAL ( $p$ -value 0.8153) or the dbh/qmd ratio ( $p$ -value 0.3039), did not explain the increment at tree level. The previously mentioned relationships indicate that for the same stand and tree size, the younger trees with a large crown ratio, growing under lower levels of competition are those which attain larger increments. The best linear model for tree-level EBLUP  $w'$  is constructed as

$$w' = -0.04151 + 0.09340 CR - 0.00336 ao_{25} \quad (R^2 = 0.27) \quad (9)$$

For practical use, the previously estimated value for  $w'$  can be directly added to model (8), reducing the RMSE down to 0.99 cm, with a mean error ( $-0.152$  cm,  $p$ -value 0.0288), thus resulting in an effect similar to that of plot calibration using increment cores from 2 trees (Table 7). Finally, through the inclusion of tree-level covariates along with plot-level calibration (using 4 trees), the RMSE is reduced to 0.94 cm, with a non-significant median error ( $-0.093$  cm,  $p$ -value 0.093).

#### 4.3.2. Recruitment and mortality

PINEA2 does not currently have a specific function for recruitment. Therefore, in order to simulate the development of uneven-aged stands, it is assumed (on the basis of previous studies by Finat et al. (2000) and Calama et al. (2005)), that to reach a stable state in a multi-aged schedule, it is necessary to incorporate 145 trees/ha to metric class (class including trees with dbh  $> 5$  cm) during the 25-year rotation cycle. We assume that recruitment occurs over time in a uniform way (6 trees of dbh 5 cm per ha and year) and that this recruitment is randomly distributed throughout the space, although in reality, the recruitment process usually occurs as occasional events and there is a high probability of recruitment occurrence under crown canopies (Barbeito et al., 2008). No function has been included in the model with respect to mortality since trees with a high likelihood of dying are assumed to be removed every 25 years.

## 5. Discussion and conclusions

In this study, a proposal is presented for adapting and calibrating an existing tree-level model, originally developed for even-aged stands of stone pine (PINEA2), to multi-aged complex structures. Due to the scarcity of uneven-aged stand data in comparison with the even-aged data base used to construct PINEA2, we consider it more appropriate to adapt the latter to multi-aged stands rather than to fit a new specific model. Together with a reduction in measurement costs, the adaptation allows posterior use of the same model for even-aged, transition and uneven-aged conditions, facilitating comparisons between management schedules and compatible estimates of growth and yield in forests showing different levels of structural complexity.

The alternative advanced in this work proposes the modification of the whole set of original functions in PINEA2 (included in transition, state and site modules), whilst maintaining the functional structure of the complete model. This differs from most of the previous research on this subject where only the

growth and/or mortality functions were calibrated (McTague and Stansfield, 1994; Sterba et al., 2002), whilst the rest of functions in the models were applied indistinctly to even and uneven stands. In this respect, we hypothesized and evaluated whether stand structure can affect not only the dynamic processes of the stand (such as growth), but also the static relationships prevailing at 'within stand' level. The original functions in PINEA2 describe growth and dynamics at tree level as a result of the interaction between the subject tree and its neighbouring environment, which facilitates the adaptation of the model to different levels of surrounding complexity (Monserud and Sterba, 1996; Peng, 2000). In our study, four different methods have been proposed to adapt the original equations. Three of the methods: (1) *direct validation and re-parameterization*, (2) *size class modelling* and (3) *refit of functions after removing typical even-aged covariates* have been previously used to adapt models to complex structures. With respect to the fourth method (4) *multilevel calibration*, although closely related to the approach presented by Stage and Wykoff (1993), and directly proposed as an alternative for calibration by Hökka and Groot (1999), as far as we know, it has never been used for the purpose described in the present study.

Direct validation was applied to adapt both the submodule for crown dimensions and the stem taper curve. Heuristic re-parameterization of the stem curve indicates that in uneven-aged stands, trees from the lower diameter classes are more cylindrical than trees of the same diameter growing in an even-aged stand. Since for a given diameter, a young tree growing in uneven-aged condition is expected to suffer greater levels of competition than a tree growing in an even-aged stand, the result obtained confirms the pattern of tapering detected for the main part of the species (Larson, 1963), where trees growing under higher levels of competition are more cylindrical than the rest.

Class-size modelling has been used to adapt age-dependent relationships such as site index and height-diameter models. Estimation of site productivity in uneven-aged stands has been at the centre of much attention since the seminal work of Duerr and Gevorkiantz (1938). The direct application of a site index equation makes no sense in multi-aged stands, so site productivity in multi-aged stands is taken into account by either including ecological (climate, soil, topography, etc.) factors (Monserud and Sterba, 1996; Sterba et al., 2002), ecological type classification (Hanewinkel and Pretzsch, 2000; Eerikäinen et al., 2007), applying site index values estimated in nearby even-aged stands, or in an indirect way, by considering past growth (Liang et al., 2005; Thorpe et al., 2007) or the initial conditions of the stand as an indicator of site potential. Other approaches have focused on defining site indices based on the height-diameter relationship (Vanclay and Henry, 1988) or tree growth adjusted for stand density (Vanclay, 1989). The present study suggests an intuitive way to estimate site productivity based on applying typical site index equations to trees from the different size classes. Our estimates are quite consistent among classes and are largely correlated with site index estimates measured in nearby even-aged stands, pointing to the suitability of using, in a plot of similar size to those used in this study, the height and age of the two thickest trees calculated for each 10 cm diameter class over 15 cm, to estimate an adequate index of potential site productivity for multi-aged stands.

Our proposal assumes that the growth pattern of dominant trees is constant among size classes, in other words, that with the exception of the younger classes, dominant trees in each class will grow under a level of competition similar to that of an even-aged stand. Although this assumption is perhaps not realistic in densely stocked multi-aged stands typical of shade tolerant species, we consider it acceptable in Mediterranean stands, and especially in stone pine forests, where competition is governed by root-level

water supply and stands are usually so open that the initial suppression of recruitment is of little importance. The short periodicity of interventions also favours the opening of gaps and early liberation of vigorous trees regardless of size. Nevertheless, the inclusion of this productivity index in the adapted functions is not proposed since the results obtained come from only a small sample of plots.

Successful class-size modelling of the height–diameter relationship is supported by the widely accepted assumption (Lappi, 1997) that this relationship is age dependent, indicating that static relationships among tree dimensions are similar in even-aged or multi-aged stands. In general, the suitability of class-size modelling is justified if a strong relationship exists between tree age and size at a given site, despite multi-aged conditions (as demonstrated in Fig. 3). This result also confirms our initial hypothesis that low-density uneven-aged stands of stone pine can be considered as a cluster of different, small, even-aged units.

The proposed model for average cone production retains cross-sectional area of the tree and ecological classification of territory, but now also includes crown width as an explanatory covariate, attaining results quite similar to those of the original function for even-aged stands. The inclusion of crown width is justified by the fact that crown dimensions in multi-aged complex structures can be considered a good indicator of the level of surrounding competition and structure (Bauhus et al., 2002; Woodall et al., 2003b). This model assumes that a tree of similar size growing in either an even-aged or an uneven-aged stand made up of small even-aged groups will attain, on average, the same cone production. Due to the previously mentioned factors of low stocking, competition for water and early liberation of vigorous trees, this assumption can be accepted, at least in the case of trees beyond the younger classes. Nevertheless, new studies, focusing on cone production in multi-aged stands, should confirm the validity of this adaptation.

The diameter increment function forms the core of tree-level models. As shown in Fig. 4, large differences in tree growth patterns are not apparent between even-aged and multi-aged stands, although in the latter, smaller trees display lower increments whilst the opposite is true of larger trees. This result agrees with previous findings in multi-aged complex structures (Schütz, 1997) and is explained principally by the fact that in a multi-aged stand, a small tree is surrounded by bigger trees from older classes, whilst in an even-aged stands the surrounding trees are of a similar size. Nevertheless, multilevel formulation of the original function and plot-level calibration help to confirm the fact that, as regards growth at tree level, analysed low-density stone pine multi-aged stands can be considered a special case of general, even-aged stands.

Basal area is the main factor explaining between plot variability in tree growth, indicating that trees in heavily stocked stands attain smaller increments than the rest. Defined PI was only available for the four MA plots; therefore it was not possible to evaluate the accuracy of PI in explaining tree growth. Nevertheless, site productivity is indirectly considered in the model by including the predicted EBLUPs at plot level, parameters  $u$  and  $v$ . These parameters characterize a bivariate index reflecting the “hidden” effect of site productivity or structure on growth. Different sampling alternatives for predicting plot-level EBLUPs were evaluated. It was found that by taking past increment cores from a subsample of 2–4 trees in a plot of up to 0.48 ha, more accurate and unbiased estimates could be obtained. In this respect, plot-level calibration using a small sample of trees provides a new alternative for defining site quality in multi-aged stands. This is an improvement on using raw past increment as a site indicator in multi-aged stands as proposed by Liang et al. (2005) or Thorpe et al. (2007). However, future efforts should focus on validating this approach by relating the bivariate

index to the new productivity index as well as to ecological factors for a wider range of complex states.

We found that variables (other than tree diameter), which largely explain tree-level variability in diameter increment are, on the one hand, an indicator of tree vigour (crown ratio) and on the other, an influence area overlap index of competition (ao25). Our results agree with those previously obtained by Río et al. (2003), and confirm the greater efficiency of spatial competition indices to predict tree growth in uneven-aged stands (Golser and Hasenauer, 1997; Pukkala and Miina, 1998; Hanewinkel and Pretzsch, 2000; Woodall et al., 2003b) in comparison to distance independent indices. Of the distance dependent indices, influence area overlap indices display better correlations than distance weighted size ratios or area potentially available indices, which could indicate that the spatial distribution of trees is more related to competition than to neighbour size. Considering that the area of competition (defined by a radius of influence of 25 times the dbh) is much larger than the crown projection area, the results confirm again that in the analysed low density multi-aged stands of stone pine, competition exists as a partially symmetric process occurring at root level.

It is recommended that the PINEA\_IRR model be used in pure stands of stone pine which have trees in at least 3 different 10 cm diameter classes. The PINEA\_IRR should only be applied in low-stocking conditions (stands with BA < 25 m<sup>2</sup>/ha and density < 400 stems/ha) in order to cover the whole range of situations identified in the data set used. The practical application of PINEA\_IRR requires the measurement of breast height diameter in all the trees within the stand, together with total height and age for a sample of 1–2 dominant trees from each 10 cm diameter class as basic input variables. The diameter increment function can be improved if either a sample of diameter increment cores and/or tree coordinates are available. From these measurements it is possible to predict the growth and dynamics of any complex stand over the course of a complete productive cycle, allowing comparisons of different management schedules, including those governed by the PINEA2 model. Management decision schedules are characterized by the length of the productive cycle and the periodicity and intensity of selective cuttings. In relation to this, the PINEA\_IRR has been successfully used to compare growth and yield (in terms of cone, timber, and CO<sub>2</sub> fixation) between even-aged and ideal uneven-aged stands (Río et al., 2008), showing that uneven-aged management of the stands favours cone production, whereas it is less favourable for timber yield and CO<sub>2</sub> fixing capacity.

Because of its tree-level formulation, modular structure and suitability for local calibration, the PINEA\_IRR model constitutes an interesting and flexible tool for the management and maintenance of stone pine stands, covering a wide range of within stand structural complexity, including forests in transition. Although the model is of obvious interest, future research should be directed towards improving it by, for example, evaluating the suitability of a productivity index and incorporating a cone model developed using data from multi-aged stands. Together with this, special attention should be given to developing and incorporating statistical models for predicting the rate and spatial distribution of recruitment. Finally, future effort should focus on carrying a global validation of the model by testing the whole set of equations over a set of data collected from permanent plots installed in multi-aged complex stands.

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