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ORIGINAL PAPER

A new method for the identification of old-growth trees in National Forest Inventories: application to *Pinus halepensis* Mill. stands in Spain

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Abstract
• ***Context*** Old-growth trees play a very important role in the maintenance of biodiversity in forests. However, no clear definition is yet available to help identify them since tree age is usually not recorded in National Forest Inventories.
• ***Aims*** To develop and test a new method to identify old-growth trees using a species-specific threshold for tree diameter in National Forest Inventories.
• ***Methods*** Different nonlinear mixed models for diameter–age were generated using data from the Spanish Forest Inventory in order to identify the most appropriate one for Aleppo pine in its South-western distribution area. The asymptote of the optimal model indicates the threshold diameter for defining an old-growth tree. Additionally, five site index curves were examined to analyze the influence of site quality on these models.
• ***Results*** The Hossfled III mixed model was found to be the most appropriate to fit diameter–age curves for Aleppo pine trees. The overall diameter at breast height threshold for old-growth trees was 40.6 cm, although over a range of sites with increasing site quality, the threshold figure was 36.0, 38.0, 40.4, 43.1, and 46.3 cm, respectively.
• ***Conclusions*** This method allows the identification of old-growth trees and therefore of biodiversity hotspots, thus providing decision makers with a useful tool for management purposes.

Keywords Tree age · Forest biodiversity · Diameter–age relationship · NFI

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1 Introduction

The importance of old trees in the assessment of biodiversity is well recognized (Barbati et al. 2012) and such trees are considered high-interest ecological niches (Smith, 2012; Franzreb 2011) as they provide important habitats for species of birds, insects, lichens, fungi and bryophytes (Brändli et al. 2007). The term “ancient tree” or “old tree” may be understood as an age classification to describe the stage of maturity following the loss of apical dominance. During this stage, the crown begins to reduce in size (crown retrenchment) and the current growth-ring area, that is, the annual increment of woody tissue, eventually reduces in comparison to earlier developmental stages of tree growth (White 1998 in Fay 2007).

National Forest Inventories (NFIs) provide the main source of information at national level on forest area, land-use change and carbon stock estimations. Traditionally, the main focus of NFIs was wood production, but today, the national and international interest in forest biodiversity has lead to changes in the type of data recorded. Seven core biodiversity variables were selected in the frame of COST Action E-43 (*Harmonization of the National Forest Inventories in Europe*: *Techniques for Common Reporting*), including tree age (Chirici et al. 2011), which has frequently been proposed as a biodiversity indicator (UNEP 2001; EEA 2003). For this reason, recent trends as regards conservation plans and forest management include the creation of islands of old-growth forest (McRoberts et al. 2011).

The few methods proposed for the identification of old trees which do not require tree age to be known, can be classified into subjective and objective methods. Subjective methods are mainly based on tree morphology; for example, Raimbault (1995) divides the lifespan of the tree from seed to death into ten stages based on the morphology of the tree. On the other hand, when objective methods are applied, generally there is a single threshold for all species or group of species: (1) diameter greater than 50 cm at a height of 1.30 m above ground (Braumandl and Holt 2000); (2) Fay (2007) defines size girth categories; an "ancient tree" being one with a girth greater than 2.5 m for smaller tree species, greater than 4.0 m for oaks and Scots pine and 4.5 m for other species. No attempt has been made to harmonize these criteria since this always depends on data availability and no allowance has been made for the fact that trees grow at different rates, depending on the species as well as on stand and site characteristics.

In the framework of COST E-43 (Chirici et al. 2011), the "proportion of old plots" indicator was found to be the best one for characterizing old-growth forest because it can be assessed in all stands. This indicator is determined through the variable "forest age" defined by the age of the dominant tree species. Old plots are defined as those with an age exceeding half the natural life span of the dominant tree species in the plot. The natural life span of a tree species is defined as the average number of years from germination to natural death of the 100 oldest (largest) trees per hectare in the upper canopy layer growing in natural or virgin forest (undisturbed by human activity) in the terminal phase of development (Chirici et al. 2011). Hence, to estimate this indicator, dominant tree age (defined as the mean age of the 100 trees per hectare with the largest diameters) must be determined.

Although age is obviously the ideal variable for evaluating both old trees and old stands, this information is not available in most countries (Forest Europe 2011). Furthermore, in those cases where this information is recorded, it is usually stand level data and generally only for even-aged stands (McRoberts et al. 2011) as a common definition of forest age in the case of uneven-aged stands has not yet been developed. Hence, given that there are few reliable references for natural life spans and bearing in mind the need to use variables which are available in NFIs, alternative methods must be assessed in order to establish a harmonized definition.

In this regard, Chirici et al. (2011) propose the use of diameter at breast height (dbh) as the most suitable variable for estimating tree age. dbh is the ecological field variable for which the most complete and detailed information is available (McRoberts et al. 2011).

Whereas the growth rate varies among species and dominant tree age is its most appropriate indicator for characterizing old-growth (Chirici et al. 2011), cumulative growth curves were considered as the best option to identify old-growth trees. The cumulative growth curve of the diameter represents the accumulated diameter growth as age increases. These curves are sigmoid shaped. During maturity and senescence the diameter growth rate decreases. This is reflected in the cumulative curve by an asymptotic behavior.

The hypotheses of this paper are that the asymptote can be used as a diameter indicator to identify old-growth trees (threshold diameter) and that the site index modifies its value. In accordance with these hypotheses, the main objective of this study is to establish a method for identifying old-growth trees and in turn, old stands, using information available in the majority of NFIs (thus enabling a harmonized definition). In order to achieve this main objective, the following specific objectives must be addressed: (1) to find the best dbh-dominant age nonlinear mixed model representing the cumulative diameter growth curve and the value of its asymptote which will be used as the threshold diameter; (2) to test and analyze the effect of including site class indices in the models and to discuss the role played by other variables such as stand density and (3) to compare threshold diameters with those obtained using other methods.

An analysis of Aleppo pine (*Pinus halepensis* Mill.) in its South-Eastern Spanish distribution area (region of Murcia) is presented in this study to illustrate the application of this method. Aleppo pine is one of the most representative Mediterranean pine species of the Iberian Peninsula and tends to be the dominant species in forest stands where it is present. The forested area of this region comprises around 189,000 ha, nearly 87 % of which is covered by Aleppo pine in either pure stands or mixed with broadleaf Mediterranean species such as *Quercus ilex* L. subsp. *ballota* or other pine species such as *Pinus nigra* Arn (ICONA 1992). In its natural distribution area, the Aleppo pine can reach ages in excess of 300 years. For example, in Algeria, Touchan et al. (2010) documented individuals with an age of 312 years (using an increment borer). The reference literature for Spain puts the natural lifespan at between 200–250 years (Blanco et al. 1997) although the international dendrochronology series points to 250–300 years, which will therefore be the lifespan considered. The oldest examples documented in the Iberian Peninsula are, in fact, about 190 years old (Ribas Matamoros 2006).

2 Material and methods

2.1 Data

The data employed in this study to test our method are taken from NFI-4 plots (Fourth Spanish National Forest Inventory, 2008 to 2017) in the region of Murcia, where Aleppo pine is the dominant species.

In the Spanish NFI, permanent plots are established systematically at the intersections of a 1-km×1-km grid. Permanent field plots consist of four concentric circular areas with radii of 5, 10, 15 and 25 m. In each plot, tree age and diameter growth increment of the measured dominant tree are determined by means of core extraction at a height of 0.5 m above ground level. There are a number of reasons why cores are extracted at this height: firstly, the plots are permanent so any possible difficulty with future measurement should be avoided; secondly, the closer to the ground the increment cores are taken, the more accurate the age estimation will be, since rings may be lost due to sampling height, and finally, a minimum distance from the ground is necessary in order to twist the increment borer.

Two data sets from the NFI-4 were used:

(a) NFI-4 data for plots in the province of Murcia where Aleppo pine is the dominant tree species and where age is measured. In this case, diameter, height, core and location are recorded. Four hundred sixty-five cores were analyzed for the purposes of this study, although only 393 were finally selected. The others were rejected either because the dominant trees in the plot were not the target species or in some cases because the core did not reach the pith. Cores were air-dried, fixed on wooden mounts, sanded, and ring width measured using a measuring device. The sample trees had a diameter under bark (at 0.5 m above ground level) of between 6.7 and 47.1 cm and ages ranged from 19 to 158 years.

(b) NFI-4 data for plots in the province of Murcia where Aleppo pine is present: 1,142 plots. Using this data set, the Aleppo pine diameter distribution function was calculated.

2.2 Nonlinear mixed diameter–age models for Aleppo pine in Murcia

The accumulated diametric growth of dominant trees was modeled using diameter under bark at a height of 0.5 m above ground level. Growth models with horizontal asymptote were selected for testing. Although a number of models were tested, only those listed in Table 1 were selected. The inclusion or rejection of candidate models was based on the goodness-of-fit of the model parameters and on whether the results were logical.

As the dependent variable is the radial increment per year of each tree, data are serially correlated. For this reason, to fit the relationship between growth and age for Aleppo pine in the studied area, we used a nonlinear mixed growth model. Between-tree variations are introduced by incorporating a random effect for each individual tree.

The package employed was *nlme* (Pinheiro et al. 2011) in the statistical software R ver. 2.13.2. (R Development Core Team 2011). The significance level considered is always 0.05 and the nonlinear mixed models are fitted through maximum likelihood. To compare the fitted growth models and determine the most suitable, the significance of the parameters of the models are taken into account along with Akaike's information criterion (AIC, BIC and −logLik values) and the analysis of the model residuals. The nonlinear mixed model which produces the best fit is selected and the horizontal asymptote of this curve (estimated with the fixed effects parameter values) represents the threshold diameter under bark (ub) at 0.5 m above ground level at which a tree is classified as old-growth.

A site index model was used to check whether significant variations exist in the threshold diameter depending on the site quality. The site index model developed in the study area by Ruiz-Peinado et al. (2010) was considered for this purpose:

$$H = H_0 \times \frac{t^{1.25}(t_0 \times R_o + e^{8.1})}{t_0^{1.25}(t^{1.25} \times R_o + e^{8.1})} \quad (1)$$

$$R_0 = H_0 - 16.53 + \left[(H_0 - 16.53)^2 + 2H_0 \frac{e^{8.1}}{t_0^{1.25}}\right]^{0.5} \quad (2)$$

where H is the estimated height, Ho is the dominant height at the reference year (t_0), which is 60 years (Ruiz-Peinado et al. 2010); t is the age (number of years) where height is H; R_0 is defined by Eq. (2).

The selected 393 dominant trees from which increment cores were taken were sampled in the NFI plots. Each one of these NFI plots was classified “a posteriori” into one of the five classes according to the site quality, defined by the relationship between dominant height (calculated using NFI plot data) and stand age, Eq. (2): 44 trees correspond to site index curve Q4 (i.e., stands with dominant height 4 m at the reference age); 102 trees correspond to site index curve Q6; 106 trees correspond to site index curve Q8; 76 trees correspond to site index curve Q10; and 65 trees correspond to site index curve Q12. A “harmonized” fit of the selected model was carried out, generalizing its parameters as a function of its quality. The horizontal asymptotes of these five

Table 1 Selected growth models with the data set

Growth model (Di)	Formula	Asymptote formula
Hossfeld I (Peschel, 1938)	$y = \frac{t^2}{(a+bt+ct^2)} \quad \forall a > 0; 0\forall c > 0$	$\lim_{t\to\infty} y = \frac{1}{c}$
Hossfeld modified (Kiviste et al. 2002)	$y = \frac{t^2}{(a+bt)^2} \quad \forall a > 0$	$\lim_{t\to\infty} y = \frac{1}{b^2}$
Hossfeld III (Hossfeld, 1822)	$y = \frac{t}{a+bLn(t)+ct}$ $\forall a > 0; \forall b0$	$\lim_{t\to\infty} y = \frac{1}{c}$
Gemesi (Kiviste, 1988)	$y = e^{\frac{t}{(a+bt)}-1} \quad \forall a > 0; \forall b > 0$	$\lim_{t\to\infty} y = e^{\frac{1}{b}} - 1$
Richards–Chapman (Mitscherlich, 1919)	$y = a\left(1 - e^{-bt}\right)^c$ $\forall a > 0; \forall b > 0; \forall c > 0$	$\lim_{t\to\infty} y = a$
Weibull II (Weibull, 1951)	$y = a\left(1 - e^{-bt^c}\right)$ $\forall a > 0; \forall b > 0; \forall c > 1$	$\lim_{t\to\infty} y = a$
Mitscherlich III (Mitscherlich, 1919)	$y = e^{a-bLn(1-e^{-ct})} \quad \forall b > 0$	$\lim_{t\to\infty} y = e^a$

curves of the generalized nonlinear mixed model represent the threshold diameters ub at 0.5 m above ground level at which a tree is classified as old-growth depending on the site quality.

Once the asymptote of the non-generalized model (representing the threshold diameter under bark at 0.5 m above ground level) has been estimated, the relationship between diameter under bark at 0.5 m above ground level and diameter at breast height is established using the data from the 393 *P. halepensis* trees in the Murcia region. This allows us to estimate the dbh threshold diameter (most commonly used variable) that can be used to identify old trees.

Finally, a Weibull diametric distribution function for all the Aleppo pines in the Murcia region (1,142 plots) was fitted (Bailey and Dell 1973). The objective of the distribution function fit for Aleppo pine was to determine the percentage of old-growth trees in Murcia (taking the asymptote of the fitted nonlinear mixed model as the threshold diameter) and to assess whether this result was reasonable. A high percentage of old-growth trees would clearly indicate an error in the proposed method, due mainly to the relatively new reforestations undertaken in the Murcia region.

This approach allows old-growth stands of each species to be determined by identifying all the trees in the NFI plots which exceed the estimated dbh threshold considered (or thresholds if site quality is considered). It is also important to take into account the number of old-growth trees present in the plots. Unfortunately, in the 1,142 Spanish NFI plots in which Aleppo pine is present, the age data for this species is not always available, so it is not possible to establish site quality. For this reason, the distribution of old-growth Aleppo pine trees has been determined without considering the site quality.

3 Results

3.1 A nonlinear mixed diameter–age model for Aleppo pine

For each fitted model, the number of parameters and whether these are fixed or random are shown in Table 2 along with a comparison of the goodness- of- fit according to the results of Akaike's information criterion. The Hossfeld III mixed growth model (Fig. 1 and Table 3) was chosen as it provided the best fit of all the models tested, producing the lowest values of Akaike's information criterion. The simplicity of the Hossfeld III model was also taken into account and the fact that the residuals do not show any trend (Fig. 2a). The value of the horizontal asymptote of the Hossfeld III curve is 37.0 cm (Table 6), which represents the threshold diameter ub at 0.5 m above ground level at which a tree is classified as old-growth. The analysis of residuals reveals a root mean square error of 83.683 and a mean of the residuals of −0.008.

3.2 Site quality curves developed using the Hossfeld III mixed nonlinear diameter–age model for Aleppo pine

Hossfeld III mixed age–diameter models were defined for each of the five site qualities. The mixed model was parameterized according to all the possible combinations of site quality and tested. The best fit is obtained when the only generalized parameter is *c* (Qc), which is the parameter affecting the asymptote (producing the lowest values of Akaike's information criterion and significant parameter values, Table 4), and the model displays a good distribution of residuals by not showing any trend (Fig. 2b), the root mean square error being 81.879 and the mean of the residuals −0.008 (Table 5). The horizontal asymptotes of the five Hossfeld III site index curves (Table 6) are as

Table 2 Results of Akaike's information criterion (AIC), Bayesian information criterion (BIC) and logarithm of the maximized restricted likelihood (logLik) of the eight selected growth models

Growth model	Number of fixed parameters	Number of random parameters	Degrees of freedom	AIC	BIC	logLik
Hossfeld I MM	3	3	10	62,716	62,798	−31,348
Hossfeld mod MM	2	2	6	70,090	70,139	−35,039
Hossfeld III MM	3	3	10	48,777	48,859	−24,378
Gemesi MM	2	2	6	64,547	64,596	−32,267
Richards–Chapman MM.3	3	1(c)	7	63,503	63,561	−31,774
Weibull II MM	3	3	10	62,774	62,856	−31,377
Mitscherlich III MM.1	3	1(a)	7	63,384	63,442	−31,685

ANOVA comparison. *MM* mixed model; *mod* modified; *MM.i* mixed model, only one random parameter. If i=1 the random parameter is a and if i=3 the random parameter is c

follows: 32.0 cm for the lowest quality site index (Q4); 34.2 cm for Q6; 36.8 for Q8; 39.7 cm for Q10 and 43.2 cm for the best quality site index (Q12). These horizontal asymptotes represent the threshold diameter under bark at 0.5 m above ground level at which a tree is classified as old-growth in each of the five site index qualities defined.

3.3 Relationship between diameter under bark at 0.5 m above ground level and dbh

Different models were considered to find a relationship between the diameter under bark at 0.5 m above ground level and the dbh, but as the fits were quite similar, a simple linear regression was selected, not only because the fit was good but also for its simplicity; Eq. (3).

$$\begin{aligned} \mathrm{dbh} &= 0.9217\mathrm{d}_{0.5} + 6.5196 \\ R^2 &= 0.5774 \end{aligned} \quad (3)$$

where $d_{0.5}$ is the diameter under bark at 0.5 m over ground (in centimeter).

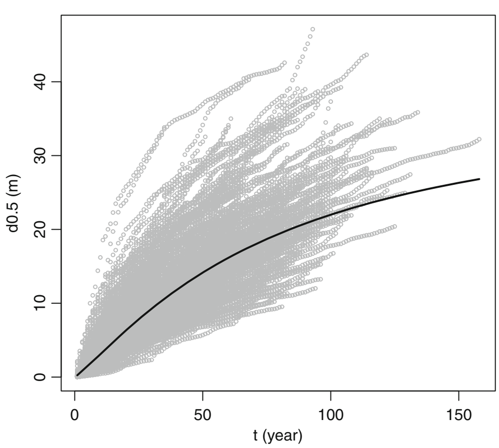

Fig. 1 Hossfeld III mixed growth model for *Pinus halepensis* in Murcia region. Relationship between diameter under bark at 0.5 m over ground (in centimeter) and age (in year)

The estimated dbh after calculating the asymptote of the Hossfeld III mixed model without considering the site quality is 40.6 cm, while the values are 36.0, 38.1, 40.4, 43.1, and 46.3 cm respectively from the worst (Q4) to the best quality index (Q12).

3.4 Diametric distribution function

A Weibull distribution function (Eq. (4)) was fitted to the diametric distribution of *P. halepensis* in the region of Murcia (Fig. 3). When the estimated threshold dbh (calculated using the Hossfeld III mixed model), 40.61 cm, is included in the Weibull function, it indicates that only 3.67 % of the Aleppo pines in Murcia have a dbh above this threshold.

$$F(x) = 1 - e^{-\left(\frac{x-69.5}{169.02}\right)^{1.73}} \quad (4)$$

In other words, according to this method, 3.67 % of these pines are old-growth.

4 Discussion

Due to the importance of old trees and areas of old-growth forest in terms of biodiversity conservation, identifying

Table 3 Results of the Hossfeld III mixed model. Where a, b and c are the parameters of the Hossfeld III mixed model; the values, standard error and t value of the fixed effects are shown as well as the standard deviation of the random effects

Parameters	Fixed effects			Random effects
	Value	Std. error	t value	Std. dev
a	4.095	0.223	18.350	4.361
b	−0.489	0.069	−7.063	1.343
c	0.027	0.002	16.821	0.031

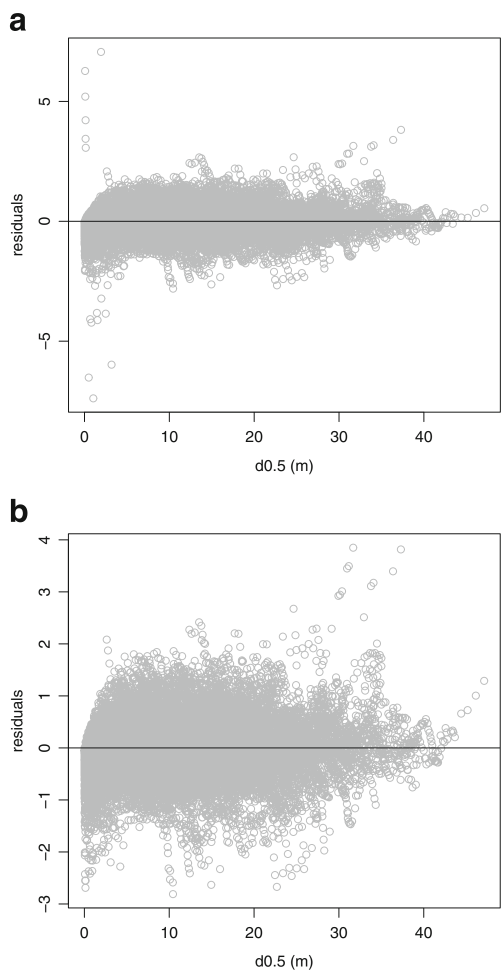

Fig. 2 Residuals plots (residuals vs diameter at 0.5 m above ground data) for the Hossfeld III mixed model (**a**) and for the Hossfeld III generalized (parameter *c*) mixed model (**b**)

these areas has become an important objective. However, no suitable methods have been developed to date, either at national or international level, which are capable of fulfilling this objective. In this respect, it is important to find a common or harmonized data set which can be used to define such areas and which can be used by policy makers on a broad geographical scale. National Forest Inventories provide a valuable source of information to address this objective.

Table 5 Results of Hossfeld III mixed model parameterized with site index quality in the parameter *c* (Qc). Where a_0, b_0, c_0, and c_1 are the parameters of the model; the values, standard error, and *t* value of the fixed effects are shown as well as the standard deviation of the random effects

Hossfeld III MM Qc $\{t/(a_0+b_0\times\log(t)+(c_0+c_1\times Q)\times t)\}$

Parameter	Fixed effects			Random effects
	Value	Std. error	*t* value	Std. dev
a_0	4.108	0.224	18.340	4.380
b_0	−0.494	0.069	−7.106	1.348
c_0	0.035	0.003	11.779	0.031
c_1	−0.001	0.000	−3.179	0.504

In Spain, the method used to identify old trees in the last NFI cycle was based on species related literature (longevity, characteristics, and management information), on the diameter data recorded in the previous NFI and the diameter distribution function (Alberdi et al. 2012). Using this information, diameter thresholds were established for each species. It was found that age thresholds varied considerably from one species to another, suggesting that the use of a single value for all the species (Braumandl and Holt 2000; Fay 2007) provides too coarse an estimation. However, neither the natural lifespan nor growth of the species was taken into account, nor whether the thresholds calculated were influenced by the management practices employed. Hence, a new and more reliable method was needed. In the Fourth Spanish NFI, dominant age measurements were taken in the plots using an increment borer, thus providing data which could be used to develop a new approach.

A dbh-dominant age mixed growth model was developed for Aleppo pine to find the asymptote of the curve which would determine the species threshold for classification as an old-growth tree. Therefore, it was necessary to determine the relationship between dbh and diameter ub at 0.5 m above ground level ($d_{0.5}$). Although the value of the coefficients of determination (R^2) between the stump dbh and diameter are generally very high, it should be noted that the value is lower in this case (0.5774) as $d_{0.5}$ is an estimation

Table 4 Results of Akaike's information criterion (AIC), Bayesian information criterion (BIC) and logarithm of the maximized restricted likelihood (logLik) of Hossfeld III parameterized with site index quality (Q) mixed models. ANOVA comparison

Growth model	Degrees of freedom	AIC	BIC	logLik
Hossfeld III MM	10	48,777	48,859	−24,378
Hossfeld III MM.Qa	11	48,823	48,913	−24,400
Hossfeld III MM.Qb	11	48,831	48,921	−24,404
Hossfeld III MM.Qc	11	47,619	47,709	−23,798

MM mixed model *MM.Qx* mixed model parameterized in *x*

Table 6 Results of the Hossfeld III mixed model and the Hossfeld III mixed model parameterized with site index quality in parameter *c* (Qc)

Hossfeld III.MM		
	dbh (cm)	Asymptote, $d_{0.5\ m}$ (cm)
	40.6	37.0
Hossfeld III MM Qc $\{t/(a_0+b_0\times\log(t)+(c_0+c_1\times Q)\times t)\}$		
Quality	Dbh (cm)	Asymptote, $d_{0.5\ m}$ (cm)
Q4	36.0	32.0
Q6	38.1	34.2
Q8	40.4	36.8
Q10	43.1	39.7
Q12	46.3	43.2

dbh represents the threshold dbh (in centimeter) to identify an old-growth tree and its corresponding asymptote value (diameter in centimeter at 0.5 m). Q4, Q6, Q8, Q10 and Q12 represent the five site index curves of the Hossfeld III mixed model parameterized with site index quality

under bark, measured in the laboratory from increment cores, while dbh is measured over bark in the field. The growth model developed gave an estimated dbh threshold for Aleppo pine of 40.6 cm. This would appear to be a reasonable value for management and conservation purposes since only 3.67 % of the monitored trees in the NFI-4 exceed this threshold. Although many authors have studied the relationship between diameter growth and stand factors (Gillis et al. 2003; Kneeshaw and Gauthier 2003), no significant results were obtained in the present study as regards the relationship between diameter growth and stand density (in square meter per hectare); (results not shown). Site index curves were evaluated since site index reflects the influence of site quality variables on tree growth. The large scales and very different plot situations included in the NFIs may underlie the lack of conclusive findings, although very different results are obtained at smaller scales. The use of established and proven site index equations for Aleppo pine (Ruiz-Peinado et al. 2010) provided the best option for including site quality in the model, with five site index qualities being identified. As regards the dbh threshold values for the different site qualities, the highest and lowest were separated by a total difference of 10 cm. Using this approach, a more detailed classification of old-growth trees and stands can be carried out since the definition of site index includes physiographic, climatic and soil characteristics, the combined influence of which leads to different growth patterns in this species.

The main aim of this study was to define a new method, based on NFI data, for estimating the number of old-growth trees, thus allowing stakeholders to evaluate the effect of forest management on the diversity of forest systems. A potential application of this approach in the short term is to identify old-growth stands of each species, providing vital information for the conservation of our forest biodiversity.

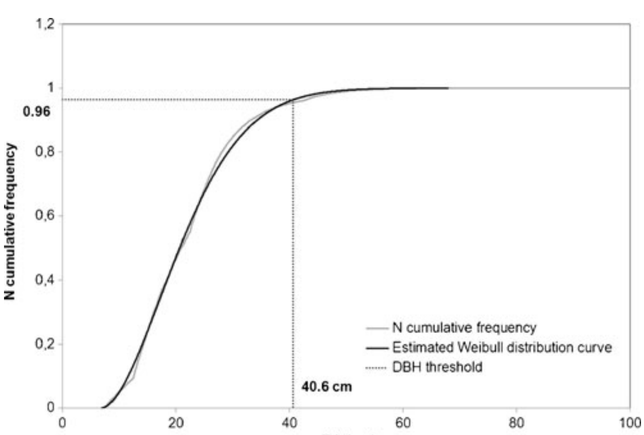

Fig. 3 Weibull distribution function (*in black*) fitted to the diametric distribution of *Pinus halepensis* (*in gray*) in Murcia region. 96.3 % of the trees are smaller than the calculated dbh threshold (40.6 cm) for identifying old-growth trees. The threshold has been estimated using the Hossfeld III mixed growth model

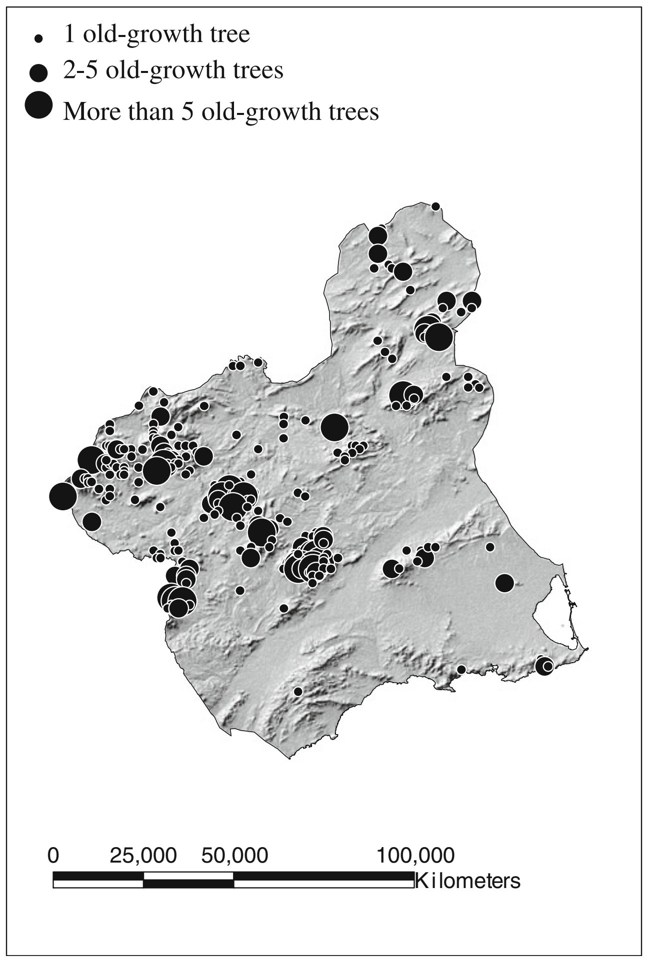

Fig. 4 Aleppo pine old-growth trees in Murcia region according to the results obtained using the proposed model. The larger dots indicate a higher proportion of old-growth trees in the stand

In Fig. 4, which shows the distribution of old-growth Aleppo pines, it can be observed that they tend to be found in the mountainous areas of the study region which have suffered least disturbance and therefore are best preserved. This finding supports the suggestion that old-growth stands occupy sites where the impact of human activity is negligible. For example, there are a relatively high proportion of old-growth trees in the *Sierra Espuña*, which is one of the most important protected areas within the region where Aleppo pine is the dominant species.

When this method is compared to others previously developed for NFI data, the results obtained are quite different. In the approach proposed by Chirici et al. 2011, dominant ages above 120 years should be sought where the aim is to identify even-aged old-growth stands and where the objective is to identify old trees, the search should be for ages greater than half the life span, which is about 137 years in the case of Aleppo pine based on the international dendrochronology series. The diameters which correspond to 120 and to 137 years (according to the fixed effects of the Hossfeld III mixed model) are estimated at 28.6 and 29.9 cm dbh, respectively (when the model is not parameterized with site quality). This approach (the estimation of these values using the defined Hossfeld III growth model) can be used because the data comprises the ages of the dominant trees, which is consistent with the definitions proposed in COST Action E-43. If the abovementioned figure of 29.9 cm is entered in the diameter distribution, the percentage of old-growth trees in the region of Murcia would be 18.23 %, which is a large proportion of the Aleppo pine in this region, especially for management purposes.

In conclusion, threshold diameters (dbh) for determining old-growth trees can be established using this new method for NFI data. This method is more realistic and more detailed than any other approach proposed to date and can be applied to different species with NFI data.

By applying this approach to Aleppo pine in Murcia, old-growth trees were identified as those exceeding a diameter of 40.61 cm. This figure is consistent with the existing literature. If more detail is required and site quality is taken into consideration, diameter thresholds vary from 36.0 to 46.3 cm in the case of Aleppo pine.

This approach in conjunction with NFI data permits the identification of forest stands with a high percentage of old-growth trees. This capacity to identify forest biodiversity hotspots is vital to large-scale forest management.

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