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RESEARCH ARTICLE

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A new approach to defining rotation ages on the basis of productive and technological aspects. Application to natural *Pinus sylvestris* L. stands in Central Spain

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Abstract

Aim of study: To propose a new approach to defining rotation ages on the basis of productive and technological aspects and to present an example of application of the methodology to natural *Pinus sylvestris* stands in relation to silvicultural treatment (light or heavy thinning) and site index.

Area of study: Central Spain.

Material and methods: We assumed that the price per m^3 of logwood suitable for veneer is four times higher than logwood not apt for veneer. Considering the yield distribution for different technological and commercial classes, a model of diameter distributions and yield tables, the variation in an average price index for different age classes, site indexes and silvicultural treatments was calculated. The age at which the price index rises by less than 3%, the proportion of trees with d.b.h. higher than 40 cm, and other aspects such as the possible presence of fungal decay in old-growth stands were also taken into account to establish three criteria for defining rotation ages.

Main results: The proposed methodology generates a wide range of rotation ages between 100 and 140 years for lightly thinned stands, and between 90 and 140 years for heavily thinned stands, depending on the site index.

Research highlights: The proposed approach is based on technological and productive criteria, with the limitations imposed by sanitary risks. The methodology can be applied to generate rotation ages in relation to different site indexes and silvicultural treatments, provided that the timber market prices and the yield distribution for different technological and commercial classes are known, and that a model of diameter distributions and yield tables are available.

Additional keywords: Scots pine; price index; veneer timber; yield tables; diameter distributions

Abbreviations used: d.b.h. (diameter at breast height).

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Introduction

Scots pine (*Pinus sylvestris* L.) stands occupy an area of nearly 1,280,000 ha in the Iberian Peninsula, of which about 90,000 ha of mostly natural stands lie in the *Sistema Central* in Spain (Montero *et al*., 2008). The economic importance of *P. sylvestris* forests in the Sistema Central is indicated by the approximately 100,000 m^3 of sawn timber (with a high proportion of good quality timber) which potentially could be cut annually and used to supply several sawmills, which are also an important source of employment in the area. However, the environmental, landscaping and social benefits of these forests, which are known to play an essential role in the biological balance and the social development of the area, are increasingly being recognised (Montero *et al.*, 2001), as it evidenced by the recent declaration of a part of the Sierra de Guadarrama like National Park.

The silvicultural management of natural stands of *P. sylvestris* is well established in Spain and specifically in the study area (Montero *et al.*, 2001; 2008). This provides a solid basis for evaluating treatment possibilities. The management method is mainly based on periodic compartments with silvicultural shelterwood systems (in regular or semiregular stands) or with two final cuts (in regular stands), in both cases with natural regeneration; the rotation age usually varies between 100 and 120 years (Montero *et al.*, 2008).

Defining the rotation age for a particular tree species in an area is very important and gives rise to great controversy both in forest research (forestry economics) and forest management. Numerous methods have been developed on the basis of mathematical, economic and financial criteria (Clutter *et al.,* 1983; Davis *et al*., 2001). These methods have been described and explained with reference to Scots pine in the *Sistema Central* (Montero *et al*., 2001).

Few other studies have focused on determining the optimal rotation age of the species in the *Sistema Central* (Montero *et al*., 1992; Diaz-Balteiro & Romero, 1995; Rojo-Alboreca & Montero, 1996; Del Río & Montero, 2001).

It is universally known that as the age of a forest stand increases, the size of the trees and technological quality of the timber also increase, and the unit price thus increases simultaneously to the growth in volume, which is called "growth in quality" (Mackay, 1944). Montero *et al*. (1992) took this into account in analyzing a large sample of 18,192 trees (measured in stands with intermediate site index) with a diameter at breast height (d.b.h.) higher than 30 cm (all trees were cut for exploitation during a five year period in a forest in the area) to determine the proportion of timber suitable for veneer in different diameter classes (d.b.h. classes). These authors also calculated a unit price index for d.b.h. classes on the basis of timber market conditions at the time for Scots pine in the *Sistema Central*. The findings were applied to a sample of 29 plots inventoried in stands with intermediate site index and in which no or few silvicultural treatments had been carried out (as was usual in the area). The plots were grouped into four age classes: 80-100, 100-120, 120-140 and 140-160 years. The change in the average price index was determined for stands in the four age classes. This information allowed the technological rotation of *P. sylvestris* to be limited to around 140 years and the ecological and silvicultural conditions of the stands to be considered. However, it was estimated that the rotation age in the area could be reduced to 120 years by applying a light thinning regime or even to 100 years by applying a heavy thinning regime (Montero *et al*., 1992).

Growth and yield models (such as yield tables) or diameter distribution models were not used in the aforementioned study (Montero *et al.*, 1992).

Diaz-Balteiro & Romero (1995) concluded a low overall profitability of Scots pine in strictly financial terms and under the assumptions made, including restocking of agricultural land. However, the findings are irrelevant in relation to the present study, which mostly involves natural stands.

Yield tables were developed in a later study including light and heavy thinning regimes (corresponding to the treatments C and E defined by Assmann, 1970) for Scots pine in the *Sistema Central*, on the basis of data from the inventory of 104 field plots and cutting and measuring 39 sample trees (Rojo-Alboreca & Montero, 1996). The maximum income rotation ages established in these tables for the five site index classes ranged between 82 and 76 years for the light thinning regime (C) and between 78 and 74 years for the heavy thinning regime (E). Large differences in relation to technological rotation ages proposed by Montero *et al*. (1992) are mainly due to the fact that the silvicultural treatments considered in the yield tables (Rojo-Alboreca & Montero, 1996) are much more intensive (even for the light thinning regime) than those applied to the field plots included in the previous study. However, considering the multiple use of these forests and the real needs of the timber market in the area, it was concluded that rotation ages of 100 and 120 years for heavy and light thinning regimes respectively are more appropriate than the previously considered maximum income rotation ages (Rojo-Alboreca & Montero, 1996). Silvicultural schemes for each thinning regime were therefore proposed after taking into consideration the rotation ages established.

Yield tables were previously constructed for Scots pine in the Central Range (García-Abejón & Gómez-Loranca, 1984), although the proposed thinning regime was based on a simulation from the values of the Hart-Becking index and not on actual thinning data, as in the case of those developed by Rojo-Alboreca & Montero (1996).

More recently, Del Río & Montero (2001) developed a growth and yield model for thinned and non-thinned stands of *P. sylvestris* in the Central and Iberian Ranges, which they implemented in the computer simulator SILVES. They used data from 105 plots grouped in 10 thinning trials established in natural and artificial regeneration stands, covering different site indices and ages ranged from 20 to 75 years. We decided not to use this model because it is not applicable to the age range to be simulated in the present study, which begins at age 80 as will be indicated below.

Although the rotation age of *P. sylvestris* has also been studied in other areas of Spain, such as the province of Girona (NE Spain) (Palahí & Pukkala, 2003; González *et al.*, 2005) and the autonomous region of Galicia (NW Spain) (Rojo-Alboreca *et al.*, 2005), none of these studies are applicable to the natural stands of the species in the *Sistema Central*.

The objective of this study was to propose a new approach to defining rotation ages on the basis of productive and technological aspects and to present an example of application of the methodology to natural Scots pine stands in Central Spain in relation to silvicultural treatment (light or heavy thinning) and site index. For this purpose, we assumed that the price per m^3 of logwood suitable for veneer is four times higher than logwood not apt for veneer. From this assumption, the changes in the average price index value and in the proportion of timber suitable for veneer were calculated for different age classes, site indexes and silvicultural treatments, considering the yield distribution for different technological and commercial classes used by Montero *et al.* (1992) as well as a diameter distribution model and yield tables that were not available when the previous study was conducted. We analyzed the age at which the average price index increases by less than 3% for a ten-year period, the proportion of trees with a d.b.h. higher than 40 cm and we also took into account other considerations for establishing the rotation age, such as the possible presence of fungal decay in old-growth stands. Finally, we established some criteria for defining rotation ages for the species in the area.

Material and methods

Yield distribution for technological and commercial classes

To apply the proposed methodology we used the same yield distribution for different technological and commercial classes and the information about prices determined by Montero *et al.* (1992). Therefore, we assumed that the price per cubic meter of logwood suitable for veneer is four times higher than logwood not apt for veneer, for the Scots pine wood in Central Spain. Cursory analysis of the current timber market in the study area showed that although the prices have changed, the ratio between the value of the logwood suitable for veneer and the rest of the timber could be very similar to that used by Montero *et al.* (1992), although a more detailed study on the evolution of the timber market in the area in the last years should be made to ensure this assumption. Use of the same yield distribution for technological and commercial classes and of the same price ratio also facilitates comparison of the results obtained in the present work and those obtained by Montero *et al.* (1992).

We then assumed that a tree has timber suitable for veneer when a log of at least 2.5 m in length and 36-37 cm in diameter, with no bark at the mid-point and with no external knots, can be obtained. Consequently, we considered the same distribution of timber production in m^3 over bark and the price index values for different diameter classes (Table 1)

Table 1. Distribution of timber production in m^3 over bark (m^3ob) and price index values for different diameter classes (reproduced from Montero *et al.*, 1992).

Diameter Class (cm)	Total trees	Trees with veneer timber	% trees with veneer timber	Total timber volume (m^3ob) (a)	Volume of veneer timber (m^3ob) (b)	Volume of timber non veneer (m^3ob) (c)	% veneer timber (d)	Total timber value (e)	Price index (f)
30-34	3,164	0	0	1,289	0	1,289	0.0	1,289	1.00
35-39	3,015	102	3.38	2,021	30	1,991	1.5	2,112	1.05
40-44	3,259	515	15.80	3,173	333	2,840	10.5	4,172	1.32
45-49	2,541	965	37.98	3,327	542	2,785	16.3	4,954	1.49
50-54	2,336	1,042	44.61	3,788	777	3,011	20.5	6,118	1.62
55-59	1,576	864	54.82	3,329	802	2,527	24.1	5,736	1.72
60-64	1,128	678	60.11	2,895	773	2,122	26.7	5,214	1.80
65-69	637	422	66.25	1,943	560	1,383	28.8	3,622	1.86
>70	636	448	70.44	2,698	728	1,970	27.0	4,883	1.81
Total	18,192	5,036		24,463	4,546	19,917			

determined by Montero *et al*. (1992) from a sample of 18,192 trees. The total timber value (e) (Table 1) was calculated for different diameter classes as (e) = 4·(b) + (c), and the price index (f) was calculated as (f) = (e)/(a).

The proportion of trees from which at least one veneer log can be obtained begins to be important from d.b.h higher than 40 cm and increases thereafter (Table 1). Consequently, the proportion of timber suitable for veneer also increases with the diameter up to 65-69 cm (28.8%), but then decreases notably in trees over 70 cm diameter, due to more frequent attacks by decay-causing fungi in very old trees (Montero *et al*., 1992). The price index (f) of the timber market therefore varies between 1.00 for 30-34 cm diameter timber not suitable for veneer and 1.86 for 65-69 cm diameter timber, which includes the highest proportion of timber suitable for veneer. The price index also falls in the last diameter class (with trees over 70 cm).

Changes in the average price index for different age classes, site indexes and silvicultural treatments

We calculated the changes in an average price index for different age classes, site indexes and silvicultural treatments. This average price index is a measure of the value of yield that takes into account the volume and price of timber destined for veneer. This timber is of the highest technological quality and is therefore the most valuable type of wood obtained from Scots pine trees.

We used the yield tables developed for natural Scots pine stands in the *Sistema Central* by Rojo-Alboreca & Montero (1996). This growth and yield model includes the regimes of light (C) and heavy thinning (E) defined by Assmann (1970) for five site index classes (defined by dominant heights of 17, 20, 23, 26 and 29 m at 100 years). We also used the diameter distribution model developed by Álvarez-Taboada (2000) and based on the same data from the 104 field plots inventoried for the purposes of constructing yield tables (Rojo-Alboreca & Montero, 1996).

Alvarez-Taboada (2000) fitted the well-known biparametric form of the Weibull distribution function (Weibull, 1951) by the method of moments for estimating the parameters, and by the method of recovering parameters for variables. We used this distribution function (Eq. [1]) to calculate the diameter distribution for age classes ranging from 80 to 180 years, in 10 year intervals, for site indexes and silvicultural treatments. We considered 80 years as the minimum age for reaching quadratic mean diameters that enable production of timber suitable for veneer (as described by Montero *et al*., 1992).

$$F(x) = N \cdot \left(1 - e^{-\left(\frac{x}{b}\right)^c}\right) \quad [1]$$

where: x = upper limit of the diameter class (mm); N = stems/ha (for every site index, silvicultural treatment and age class combination); b = scale parameter of the Weibull function; c = shape parameter of the Weibull function.

The information provided by Eq. [1] is the cumulative frequency in trees/ha with diameter equal to or smaller than x. The amplitude of the diameter class for which the model used was developed was 2 cm, although we used an amplitude of 5 cm in the present study. This difference is due to the fact that we used the same diametric classes as in Montero *et al*. (1992), for which the proportions of logwood suitable for veneer are known.

The values of stems/ha used in Eq. [1] for every site index, silvicultural treatment and age class combination were those defined in the yield tables developed by Rojo-Alboreca & Montero (1996). Finally, we used the values of parameters b and c calculated by Álvarez-Taboada (2000) *i.e.*, b = 294.91848; c = 4.60261.

The diameter distributions generated with Eq. [1] can be consulted in detail in Rojo-Alboreca *et al*. (2014). Once the diameter distributions were generated, the volume of each diameter class was calculated using the volume equations developed by Rojo-Alboreca & Montero (1996) for each site index (Eq. [2]).

$$v = a_1 + a_2 \cdot d + a_3 \cdot d^2 \quad [2]$$

where: v = stem volume (volume above ground level to top diameter 10 cm) over bark (dm^3); d = d.b.h. over bark (cm); a_1, a_2 and a_3 = fitted parameters for each site index, as shown in Table 2.

We used the diameter distribution and volume to generate tables of the distribution of timber production

Table 2. Parameters of Equation [2] and coefficient of determination (R^2) for each site index (Rojo-Alboreca & Montero, 1996).

Site index	a_1	a_2	a_3	R^2
29	180.3488	-29.8955	1.5840	0.9891
26	127.7500	-21.9266	1.3900	0.9786
23	67.8966	-14.2486	1.1322	0.9784
20	68.8793	-14.0749	1.0757	0.9657
17	41.7156	-10.0581	0.8897	0.9713

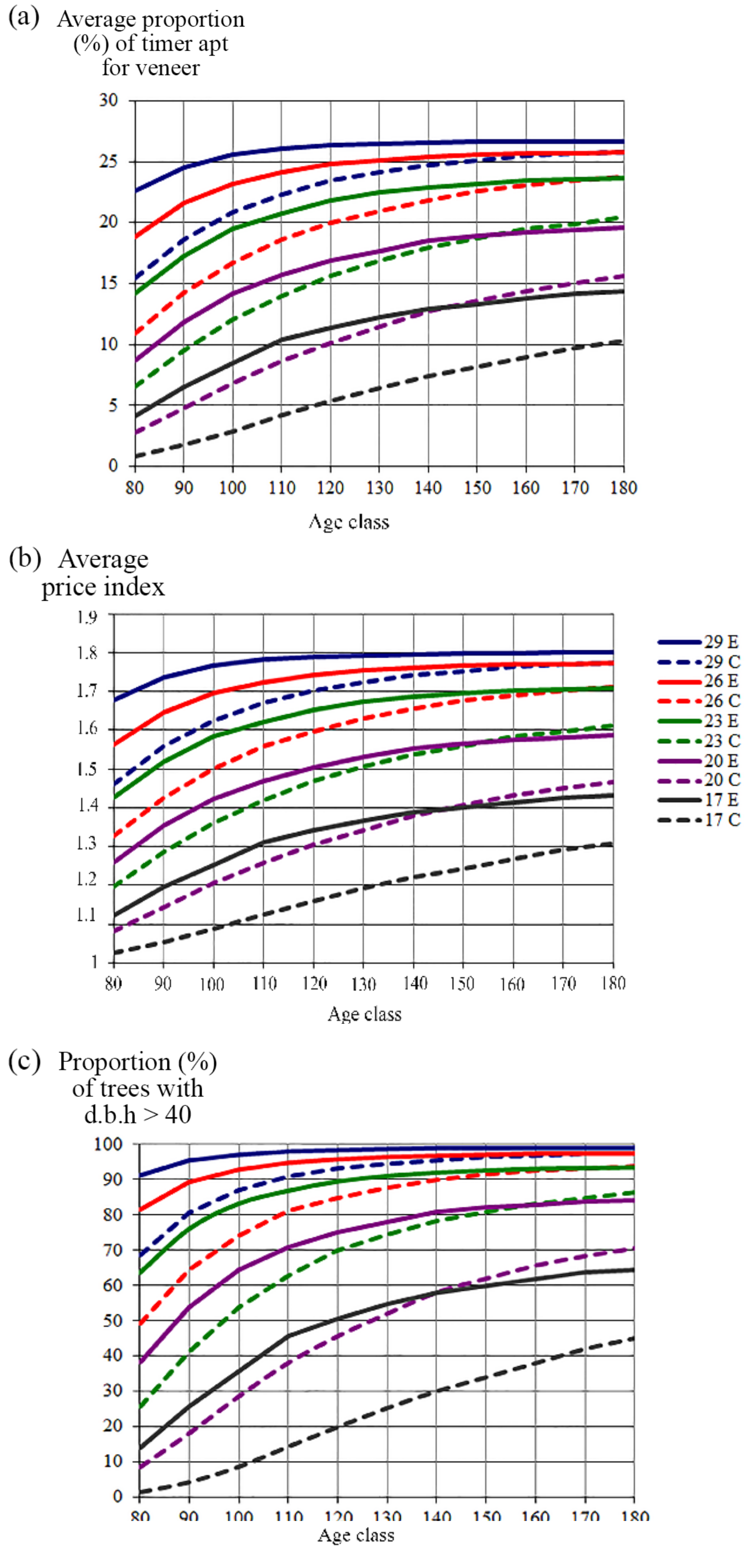

Figure 1. Variation in the average proportion of timber suitable for veneer (a), in the average price index (b), and in the proportion of trees with d.b.h. higher than 40 cm (c) for different age classes, site indexes and silvicultural treatments.

similar to Table 1 for each combination of age class, site index and silvicultural treatment. We used the proportions of timber suitable for veneer and the expressions of the total timber value and price index by diameter classes reported in Table 1. We then calculated the average values of the proportion of timber suitable for veneer and of the price index, for all combinations of age class, site index and silvicultural treatment.

Results and discussion

A total of 110 tables including the distribution of timber production and price index values for different diameter classes and for all combinations of age class, site index and silvicultural treatment were generated. For example, the tables for trees aged 120 years, site index 23 and silvicultural treatments C and E are shown in Tables 3 and 4 respectively.

The variations in the average proportion of timber suitable for veneer and in the average price index for age class, site index and silvicultural treatments are shown in Fig. 1a and Fig. 1b respectively.

As expected, the variations in the average proportion of timber suitable for veneer and in the average price index followed very similar patterns, as the second depends on the first. Both variables increase with the age of the stand and site index, as is logical. They also show an asymptotic trend, which is much less marked in the poorest sites, indicating that the average proportion of timber suitable for veneer (and thus the average price index) stabilizes much earlier in the best sites.

Moreover, treatment E (heavy thinning) always produces higher values of the average price index than treatment C (light thinning) for the same age and site index. This is because heavy thinning leads to wider spacing and thicker (more valuable) trees (Montero *et al*., 2000; Del Río & Montero, 2001).

The average proportion of timber suitable for veneer only exceeds 25% in the two best sites for treatment E (about 95 and 125 years in site index 29 and 26 respectively), and in the best site (SI 29) close to 150 years for treatment C.

The maximum value of the average price index reached is 1.80 (logically for the best site and the heavy thinning treatment E), which indicates that the maximum improvement in the value of these stands that could be obtained by considering the higher price of timber destined for veneer is 80%, although only in exceptional cases.

The average values of the proportion of timber suitable for veneer and of the price index are expected to be somewhat higher than those reported here, as the trees used by Montero *et al*. (1992) to estimate the percentage of timber suitable for veneer in each diameter class were not selected by applying a thinning regime (as proposed in the yield tables used in the present study to determine the diameter distributions).

In order to assess the increases in the average values of the price index, we estimated the total change (for the age range of 80 to 180 years) for different site indexes and silvicultural treatments (Table 5).

The range of improvement for the average price index varied and was larger for light thinning (C) in the age range studied, except for site index 17. However,

Table 3. Distribution of timber production (m^3 over bark or m^3ob) and price index in different diameter classes for trees aged 120 years, site index 23 and silvicultural treatment C (light thinning).

Diameter Class (cm)	Total trees	Total timber volume (m^3ob)	% veneer timber	Volume of veneer timber (m^3ob)	Volume of timber non veneer (m^3ob)	Total timber value	Price index
20-24	6.5	1.87	0.0	0.0	1.87	1.87	1.00
25-29	16.6	8.77	0.0	0.0	8.77	8.77	1.00
30-34	34.8	29.42	0.0	0.0	29.42	29.42	1.00
35-39	60.2	74.75	1.5	1.12	73.63	78.12	1.05
40-44	83.9	144.21	10.5	15.14	129.07	189.64	1.32
45-49	89.3	203.09	16.3	33.10	169.99	302.41	1.49
50-54	66.5	193.34	20.5	39.63	153.70	312.24	1.62
55-59	30.6	111.04	24.1	26.76	84.28	191.31	1.72
60-64	7.5	33.06	26.7	8.83	24.23	59.54	1.80
65-69	0.8	4.21	28.8	1.21	2.99	7.84	1.86
Total	396.61	803.76		125.80	677.96	1,181.16	
Average			15.65				1.47

Table 4. Distribution of timber production (m^3 over bark or m^3ob) and price index in different diameter classes for trees aged 120 years, site index 23 and silvicultural treatment E (heavy thinning).

Diameter Class (cm)	Total trees	Total timber volume (m^3ob)	% veneer timber	Volume of veneer timber (m^3ob)	Volume of timber non veneer (m^3ob)	Total timber value	Price index
20-24	1.0	0.29	0.0	0.00	0.29	0.29	1.00
25-29	3.0	1.60	0.0	0.00	1.60	1.60	1.00
30-34	7.5	6.34	0.0	0.00	6.34	6.34	1.00
35-39	15.8	19.62	1.5	0.29	19.32	20.50	1.05
40-44	28.6	49.23	10.5	5.17	44.06	64.74	1.32
45-49	44.1	100.38	16.3	16.36	84.02	149.47	1.49
50-54	55.6	161.72	20.5	33.15	128.56	261.17	1.62
55-59	53.6	194.29	24.1	46.82	147.47	334.76	1.72
60-64	36.0	159.18	26.7	42.50	116.68	286.68	1.80
65-69	14.9	78.55	28.8	22.62	55.93	146.43	1.86
70-74	3.2	19.85	27.0	5.36	14.49	35.92	1.81
75-79	0.3	2.08	27.0	0.56	1.52	3.77	1.81
Total	263.7	793.13		172.85	620.28	1,311.67	
Average			21.79				1.65

higher values were given for heavy thinning (E) at a particular age, indicating that this treatment yields a price increase before treatment C.

Increases in the price index value were found to be less than 1% before 180 years for all site indexes and heavy thinning, and also for site indexes 26 and 29 and light thinning.

A mean increase of 3.02% in the average price index for a ten-year period within the age range studied (80-180 years), for all site indexes and both silvicultural treatments, was calculated from the data in Table 5. Variations were less than 3% for all site indexes and treatments before 150 years. These differences are shown for different ages in relation to site index and silvicultural treatment in Table 6.

The data included in Table 6 can be considered to indicate the ages after which it would not generally worth maintaining the stand for another 10 years without cutting.

Moreover, according to Montero *et al*. (1992), a shorter rotation age than necessary to achieve a high proportion of trees with d.b.h. higher than 40 cm should not be established. The proportion of trees that fulfil this condition in each age class was therefore calculated for all site indexes and both silvicultural treatments (Fig. 1c).

The silviculture treatment proposed in the yield tables for these stands produces a high proportion of trees in the diameter classes higher than 40 cm in all cases (and therefore an improvement of the price of wood products), but especially for the highest site indexes and the heavy thinning regime (treatment E) (Table 3). A proportion greater than 50% can be obtained for all site indexes and treatments, except for site index 17 when light thinning (treatment C) is applied.

In addition, as expected, the trend for the change in the proportion of trees with a d.b.h. higher than 40 cm (Fig. 1c) is very similar to that observed for the average proportion of timber suitable for veneer in the different age classes, site indexes and silvicultural treatments (Fig. 1a). However, comparison of the two figures shows that the proportion of timber destined for veneer is approximately a quarter of the proportion of trees with a d.b.h. higher than 40 cm in all cases. This means that 75% of the wood of these trees with

Table 5. Variation and maximum values of the average price index for the age range 80-180 years for different site indexes and silvicultural treatments (Treatment C, light thinning; Treatment E, heavy thinning).

Site index	Total variation in the average price index (%)		Maximum value of average price index	
	C	E	C	E
29	31.00	12.53	1.77	1.80
26	38.11	20.71	1.71	1.77
23	41.79	27.89	1.61	1.70
20	38.55	32.47	1.47	1.58
17	28.48	30.77	1.31	1.43

Table 6. Age at which the ten-year increase in the price index value is less than 3% for different site indexes and silvicultural treatments (Treatment C, light thinning; Treatment E, heavy thinning).

Site index	Age		Variation in price index (%)	
	C	E	C	E
29	130	110	2.21	1.57
26	140	110	2.48	2.96
23	150	130	2.12	1.95
20	130	130	2.50	2.50
17	140	120	2.82	2.96

a d.b.h. higher than 40 cm cannot be used to produce veneer, mainly as a result of the presence of fungal-induced decay in old trees, as indicated by Montero *et al*. (1992).

As previously mentioned, the proportions of timber suitable for veneer may actually be higher, and the difference relative to the proportion of trees with a d.b.h. higher than 40 cm may be lower.

Montero *et al*. (1992) estimated that the upper limit of the rotation age should be around 140 years, as at this age a high proportion of trees with a d.b.h. higher than 40 cm and therefore high ratios of veneer timber are achieved, while at ages higher than 140 years, health problems due to fungal attack lead to a decrease in the proportion of wood suitable for veneer. The most common and aggressive fungus affecting trees in the study area is *Fomes pini* Fr.

Considering all of the above, the following criteria could be established for defining the rotation age for Scots pine natural stands in the *Sistema Central*:

1) Rotation age should not be higher or equal than 140 years in any case, to prevent fungal rot.

2) When possible, the rotation age should be less or equal than age at which the ten-year increase in the price index is less than 3%.

3) When possible, the price index should be higher or equal than 1.50 (at least a 50% improvement over the value of the stand without considering the price of veneer timber should be achieved).

Thus, technological, productive and limitations imposed by the criteria regarding sanitary risk were combined. As indicated by Mackay (1944), the use of technological criterion should be combined with the imposition of other criteria or conditions, as it alone can lead to uncertainties.

We propose the rotation ages shown in Table 7, which include a reasonable variation for the site indexes and silvicultural treatments considered.

The rotation ages shown in Table 7 are consistent (at least for the best site indexes) with those proposed by Montero *et al*. (1992), who estimated that the rotation age in the area could be reduced to 120 years by applying a light thinning regime, and even to 100 years by applying a heavy thinning regime. However, even shorter rotation ages than those shown in Table 7 may be possible, considering the possibility that the proportion of wood suitable for veneer would be higher than estimated by Montero *et al*. (1992) if calculated from stands to which intense silvicultural regimes C or E had been applied.

Otherwise, the proposed rotation ages (Table 7) are always higher than the maximum income rotation ages calculated for each site index and silvicultural treatment by Rojo-Alboreca & Montero (1996) (Table 8).

The proposed rotation ages (Table 7) are much more similar to those finally considered by Rojo-Alboreca & Montero (1996), who proposed silvicultural schemes with rotations of 100 and 120 years for heavy and light thinning regimes respectively, based on the multiple uses of these forests and the real needs of the timber market in the area.

Conclusions

The proposed approach is based on technological and productive criteria, with the limitations imposed by sanitary risks. The methodology can be applied to generate rotation ages in relation to different site indexes and silvicultural treatments, provided that the timber market prices and the yield distribution for different technological and commercial classes are known, and that a model of diameter distributions and yield tables for the species in the studied area are available.

Applying the proposed methodology to the natural Scots pine stands in the Sistema Central we found that resulting rotation ages are all much longer than the maximum income rotation ages reported for the

Table 7. Rotation ages proposed and corresponding price indexes for different site index classes and silvicultural treatments (Treatment C, light thinning; Treatment E, heavy thinning).

Site index	C		E	
	Rotation age	Price index	Rotation age	Price index
29	100-110	1.62-1.67	90-100	1.74-1.77
26	110-120	1.56-1.60	100-110	1.70-1.73
23	130	1.51	110-120	1.62-1.65
20	130	1.34	130	1.53
17	140	1.22	140	1.39

Table 8. Maximum income rotation ages for different site indexes and silvicultural treatments (Rojo-Alboreca & Montero, 1996).

Site index	Treatment C (light thinning)	Treatment E (heavy thinning)
29	76	74
26	76	74
23	79	75
20	80	77
17	82	78

species in the study area, but are similar to the rotation ages considered in the usual silvicultural shelterwood schemes proposed, with rotations of 100 and 120 years for heavy and light thinning regimes respectively. As expected, heavy thinning produced a greater number of trees of larger diameter and better technological quality, and earlier than with light thinning.

Considering the resulting rotation ages of between 90-100 and 140 years, periods of regeneration would occur in a broader age range than when considering the criterion of maximum income or the traditional rotation age of 100-120 years for all the site indexes in these stands. Thus a higher diversity of the age classes would be achieved, and the presence of continuous cover would be enhanced.

In order to apply the rotation ages proposed in this work a more detailed study on the evolution of the timber market in the area in the last years should be made to ensure the assumption of the used ratio between the price of the logwood suitable for veneer and the rest of the timber, and it also must be assumed that the prices of different types of wood will be maintained in the same current proportions, although they may vary with demand.

The definition of rotation ages based on the methodology discussed in this work could be complemented by the application of decision-making tools, with which it would also be possible to consider criteria that are not easily quantifiable, such as environmental and social aspects, which would help justify the application of thinning regime and a rotation age in different scenarios and contexts.

Finally, the risk of fire or forest pests and other natural phenomena that may negatively affect the stands must also be taken into account, given the slow recovery inherent in forest systems. This factor becomes even more important when the stands must fulfil a wide variety of social and ecological functions in addition to the purely productive aims, as in the natural Scots pine stands in the *Sistema Central*.

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