

New approach to knowledge of rotation age for *Pinus sylvestris* L. natural stands in the Spanish Central Range

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Abstract

Aim of study: To present a new contribution to the knowledge of rotation age for Scots pine (*Pinus sylvestris* L.) natural stands in Central Spain by silvicultural treatments (light and heavy thinnings) and site indexes, based on productive and economic aspects.

Area of study: The Spanish Central Range, and specifically the provinces of Segovia and Madrid.

Material and methods: Considering the yield in volume and the price of veneer timber for these stands (the best technological quality wood and therefore of higher value for this species), the evolution of an average price index value and of the average percentage of veneer timber were calculated and analyzed by age classes, site indexes and silvicultural treatment, based on the yield distribution by technological and commercial classes, on a model of diameter distributions and on yield tables. We also analyzed the age at which the price index rises less than 3%, the percentage of trees with d.b.h. > 40 cm and take also into account other considerations such as the possibility of fungal rots in old growth stands. Based on all this information we establish the following criteria to defining rotation ages: (i) Rotation age should not be ≥ 140 years in any case; (ii) When it is possible, rotation age should be $\leq$ age at which the ten-years increase of the price index is < 3%; and (iii) When it is possible, price index should be ≥ 1.50 .

Main results: We propose rotation ages ranging between 100-140 years for different site indexes with light thinnings and between 90-140 years for heavy thinnings. This proposal includes a logical escalation by the analyzed five site indexes and by the two silvicultural treatments.

Research highlights: Technological and economic criteria with the limitations imposed by sanitary risks were combined to establish the rotation ages.

The rotation ages estimated in this work are always much higher than the maximum income rotation ages reported for the species in the study area, but they are similar to the rotation ages considered in the silvicultural schemes proposed for Scots pine natural stands in the Spanish Central Range, with rotations of 100 and 120 years for heavy and light thinnings regimes respectively.

Key words: Scots pine, price index, veneer timber, yield tables, diameter distributions

Introduction

Scots pine (*Pinus sylvestris* L.) stands occupies an area of nearly 1,280,000 ha in the Iberian Peninsula, of which about 90,000, most of them natural stands, are in the Spanish Central Range (Montero *et al.*, 2008).

The economic importance of *Pinus sylvestris* forests of the Spanish Central Range is given by the approximately 100,000 m³ of sawn timber (with a high proportion of good quality) cut annually and used to supply several sawmills, which also are an important source of employment in the area. However, the environmental, landscaping and social benefits of these forests are increasingly appreciated, so they play an essential role in the biological balance and the social development of the territory (Montero *et al.*, 2001).

The silvicultural management of natural stands of *Pinus sylvestris* is well-known in Spain and specifically in the study area (Montero *et al.*, 2001; 2008), which constitutes a solid basis for analyzing treatment possibilities. This management method is mainly based on periodic compartments with silvicultural treatments by shelterwood systems for regular or semiregular stands, or two-time final cutting for regular stands, in both cases with natural regeneration, and rotation usually varies between 100 and 120 years (Montero *et al.*, 2008).

Determining rotation age for a species in an area is a very important subject, which gives rise to great controversy both in research (forestry economics) and in the practical application of forest management. Numerous methods have been developed, based on mathematical, economic and financial criteria (Clutter *et al.*, 1983; Davis *et al.*, 2001), and a description and explanation thereof, with application to Scots pine in the Spanish Central Range, can be found in Montero *et al.* (2001).

Only a few other studies focused on determining the optimal rotation of the species in the Spanish Central Range, mainly those of Montero *et al.* (1992), Diaz-Balteiro and Romero (1995) and Rojo-Alboreca and Montero (1996).

Montero *et al.* (1992) used the universally known fact of as the stand's age increases, the size of the trees and technological quality of the timber increases and a unit price increase occurs, simultaneous to the growth in volume, which is usually called "growth in quality" (Mackay, 1944). Authors determined the percentage of timber suitable for veneer (the best technological quality wood and therefore of higher value for this species) by diameter classes (d.b.h. classes) from a large sample of 18,192 trees (measured in medium site index stands) with a d.b.h. over 30 cm (all trees cut for exploitation during a five years period in a forest of the area). Then, a unit price index by d.b.h. classes was also calculated, based on the timber market conditions at that time for Scots pine in the Central Range. Results were applied to a sample of 29 plots inventoried in medium site index stands, with few or no silvicultural

interventions (as was usual in the area). These plots were placed into four age classes: 80-100, 100-120, 120-140 and 140-160 years. The evolution of the average price index was obtained for stands of the four age classes. This information allowed limiting *Pinus sylvestris*'s technological rotation to around 140 years under the found and studied ecological and silvicultural conditions of the stands. Anyway, Montero *et al.* (1992) estimated that the rotation age in the area could be reduced to 120 years applying an intensive light thinnings regime, and even to 100 years applying an intensive heavy thinnings regime.

It should be noted that Montero *et al.* (1992) did not use a growth and yield model (such as yield tables) or a diameter distribution model, since they were not available at that time for the species in Central Spain.

Díaz-Balteiro and Romero (1995) concluded a low overall profitability of the species in strictly financial terms and under the assumptions used, involving restocking from an initial situation of agricultural land. This hypothesis makes irrelevant the results of this study for the forests of the study area, which are mostly natural and capitalized stands.

Rojo-Alboreca and Montero (1996) developed yield tables, including regimes of light and heavy thinnings, for Scots pine in the Central Range, based on the data from 104 field plots inventoried and 39 sample trees cut and measured. The maximum income rotation ages derived from these yield tables ranged for the established five site index classes between 82 and 76 years for the light thinnings regime, and between 78 and 74 for the heavy thinnings regime. Large differences found regarding technological rotation ages proposed by Montero *et al.* (1992) are mainly due to the silviculture proposed in the yield tables (Rojo-Alboreca and Montero, 1996) is much more intensive (even for the light thinnings regime) than those found on field plots used in the first study. Anyway, considering the multiple use of these forests and the real needs of the timber market in the area, Rojo-Alboreca and Montero (1996) concluded that rotation of 100 and 120 years for heavy and light thinnings regimes respectively should be most appropriate than aforementioned maximum income rotation ages. For that reason they ended their study proposing silvicultural schemes for each thinnings regime using those values of rotation ages.

Should be mentioned that exist previous yield tables for Scots pine in the Central Range (García-Abejón and Gómez-Loranca, 1984), but in which the proposed thinnings regime was based on a simulation from the values of the Hart-Becking index and not on actual thinnings data, as in the case of yield tables of Rojo-Alboreca and Montero (1996).

The rotation age of the species in other areas of Spain was also studied in some works, such as in Palahí and Pukkala (2003) and González *et al.* (2005) for the stands in the province of

Girona (north-east Spain), or in Rojo-Alboreca *et al.* (2005) for the Scots pine plantations in Galicia (north-west Spain), but none of these studies are applicable to the *Pinus sylvestris* natural stands of the Spanish Central Range.

The objective of this work is to present a new contribution to the knowledge of rotation age for Scots pine natural stands in the Spanish Central Range by silvicultural treatments (light and heavy thinnings) and site indexes, based on productive and economic aspects. For this purpose, the evolution of an average price index value and of the percentage of veneer timber will be calculated and analyzed by age classes, site indexes and silvicultural treatments, based on the yield distribution by technological and commercial classes used by Montero *et al.* (1992), but also based on a diameter distribution model and on yield tables, which were not available when the previous study was conducted. We will analyze the age at which the average price index rises less than 3% for a ten-years period, the percentage of trees with d.b.h. > 40 cm and we will take also into account other considerations to set the rotation age, such as the possibility of fungal rots in old growth stands. Considering all mentioned above we will establish some criteria to defining rotation ages for the species in the area.

Materials and methods

Yield distribution by technological and commercial classes

We used the yield distribution by technological and commercial classes and the information about prices used by Montero *et al.* (1992). A cursory analysis of the current timber market in the study area shown that although prices have changed, the ratio used by Montero *et al.* (1992) between the value of the logwood suitable for veneer and the rest of the timber is substantially like today. For that reason, we decided to use the same yield distribution by technological and commercial classes applied in such work, which moreover facilitates the comparison between the results obtained by Montero *et al.* (1992) and those obtained in the present work. Therefore, we assume that a tree contains timber for veneer when can be obtained at least a log of 2.5 m long and 36-37 cm in diameter without bark at its mid point, in which there are no external knots, and we also assume that the price per m³ of logwood suitable for veneer is four times higher than logwood not apt for veneer. Consequently, we assume the distribution of timber production in m³ over bark and the price index values by diameter classes (Table 1) elaborated by Montero *et al.* (1992). In Table 1 the total timber values (e) were calculated by diameter classes as $(e) = 4 \cdot (b) + (c)$, and the price index values (f) were calculated as $(f) = (e)/(a)$.

Table 1. Distribution of timber production in m³ over bark and price index values by diameter classes (Montero *et al.*, 1992).

Diameter Class (cm)	Total trees	Trees with veneer timber	% trees with veneer timber	Total timber volume (m ³ ob) (a)	Volume of veneer timber (m ³ ob) (b)	Volume of timber non veneer (m ³ ob) (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
46-49	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			

As shown in Table 1, the percentage of trees from which at least one veneer log can be obtained begins to be remarkable from d.b.h > 40 cm and it increases with the diameter. Consequently, the percentage of veneer timber also increases with the diameter up to the 65-69 cm class (28.8%), but then it drops noticeably in trees over 70 cm diameter, due to the more frequent fungi attacks causing woodrot in very old trees. Therefore, the timber market's price index value (f) varies between 1.00 for 30-34 cm diameter timber not suited to veneer and 1.86 for 65-69 cm diameter timber, which contain the higher % of veneer timber, and the price index also falls in the >70 cm diameter class.

Evolution of the average price index value by age classes, site indexes and silvicultural treatments

We calculated the evolution of an average price index value by 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 veneer timber, which is the best technological quality wood and therefore of higher value for this species.

To do that, we used the yield tables developed for Scots pine natural stands in the Central Range by Rojo-Alboreca and Montero (1996). This growth and yield model includes regimes of light (C) and heavy thinnings (E), both for five site index classes (defined by dominant heights of 17, 20, 23, 26 and 29 m at 100 years). And we also used the diameter distribution model developed by Álvarez-Taboada (2000), precisely based on the same data from the 104 field plots inventoried for the elaboration of the yield tables by Rojo-Alboreca and Montero (1996).

Álvarez-Taboada (2000) adjusted 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 (Equation 1) to calculate the diameter distribution for age classes ranging from 80 to 180 years, in 10 years intervals, by site indexes and silvicultural treatments. As Montero *et al.* (1992), we consider 80 years as the minimum age for to reach quadratic mean diameters that allow getting veneer timber.

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

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 Equation 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, but we used in the present work an amplitude of 5 cm. This difference is because we used the diametric classes related in the work of Montero *et al.* (1992), for which the percentages of logwood suitable for veneer are known.

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

The diameter distributions generated with Equation 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 and Montero (1996) for each site index (Equation 2).

$$v = a_1 + a_2 \cdot d + a_3 \cdot d^2 \text{ [Equation 2]}$$

where:

v = stem volume (volume above ground level to top diameter 10 cm) over bark (dm³).

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.

Table 2. Parameters of Equation 2 and coefficient of determination (R^2) for each site index (Rojo-Alboreca and 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

From the diameter distribution and volume we generated tables of distribution of timber production similar to Table 1 for each combination of age class, site index and silviculture treatment, using the percentages of timber suitable for veneer and the expressions of the total timber value and price index by diameter classes reported in Table 1. Then, we calculated the average values for the percentage of veneer timber and for the price index, for all combinations of age classes, site indexes and silvicultural treatments.

Results and discussion

A total of 110 tables with the distribution of timber production and price index values by diameter classes, for all the combinations of age classes, site indexes and silvicultural treatments, were generated. As examples, the tables for 120 years age class, site index 23 and silvicultural treatments C and E are shown in Tables 3 and 4 respectively.

Table 3. Distribution of timber production (m³ over bark) and price index values by diameter classes for 120 years age class, site index 23 and silvicultural treatment C (light thinnings).

Diameter Class (cm)	Total trees	Total timber	% veneer	Volume of	Volume of	Total timber	Price index
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		volume (m ³ ob)	timber	veneer timber (m ³ ob)	timber non veneer (m ³ ob)	value	
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
46-49	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 (m³ over bark) and price index values by diameter classes for 120 years age class, site index 23 and silvicultural treatment E (heavy thinnings).

Diameter Class (cm)	Total trees	Total timber volume (m ³ ob)	% veneer timber	Volume of veneer timber (m ³ ob)	Volume of timber non veneer (m ³ ob)	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
46-49	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

The evolution of the average percentage of veneer timber and of the average price index by age classes, site indexes and silvicultural treatments are respectively shown in Figures 1 and 2.

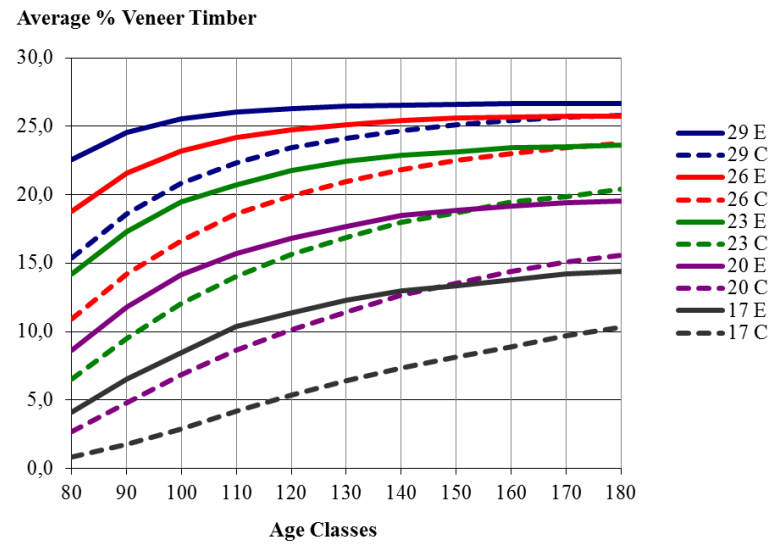


Figure 1. Evolution of the average percentage of timber veneer by age classes, site indexes and silvicultural treatments.

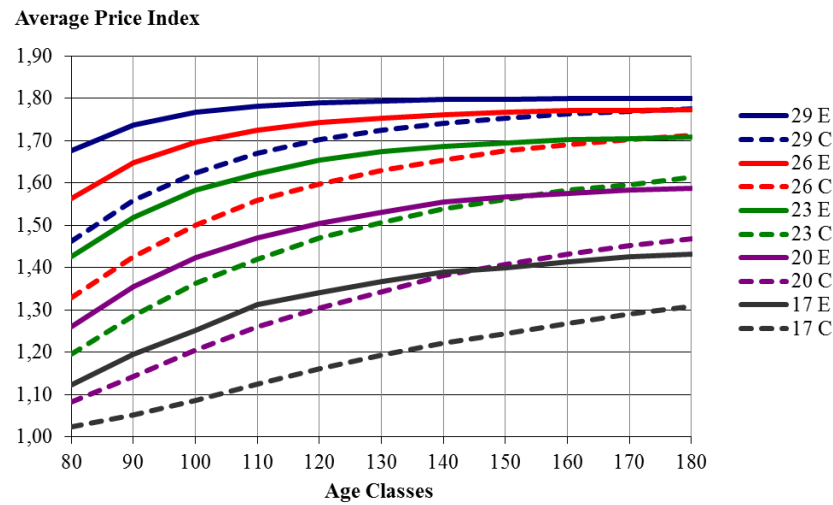


Figure 2. Evolution of the average price index by age classes, site indexes and silvicultural treatments.

As expected, the average percentage of veneer timber and the average price index show a very similar behavior pattern, as the second depends on the first. Both variables show a rising trend as does the age of the stand and the site index, as it is logical. They also show an asymptotic trend, much less marked in the worst site indexes, indicating that the average percentage of veneer timber (and thus the average price index) stabilizes much earlier in the best site indexes.

Moreover, treatment E (heavy thinnings) always produces higher values of the average price index than treatment C (light thinnings) for the same age and site index. This is because heavy thinnings make trees grow more widely spaced and then stand include thicker trees (Montero *et al.*, 2000; Del Rio and Montero, 2001), which are the most valuable.

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

The maximum value reached by the average price index is 1.80 (logically for the best site index 29 and the heavy thinnings treatment E), which means that the maximum improvement that could be obtained in the value of these stands by considering the higher price of veneer timber is 80%, although in exceptional cases.

Anyway, it is expected that both the average values of the percentage of veneer timber as of the price index are actually somewhat higher than those presented here, since 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 work to determinate the diameter distributions.

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

Table 5. Variation in the range 80-180 years and maximum values of the average price index by site indexes and silvicultural treatments.

Site index	Total variation in the average price index (%)	Maximum value of average price index
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	Treatment C (light thinnings)	Treatment E (heavy thinnings)	Treatment C (light thinnings)	Treatment E (heavy thinnings)
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

As shown, the improvement range for the average price index ranges from treatments, being larger for light thinnings (C) in the age range studied, except for the site index 17. However, for a particular age larger values are given for heavy thinnings (E), indicating that this treatment results in a price increase before the C treatment.

It was found that increases of the price index value are less than 1% before 180 years in all site indexes for heavy thinnings, and also for light thinnings in site indexes 26 and 29.

From the data in Table 5 a 3.02% medium increase in the average price index for a ten-years period within the age range studied (80-180 years), for all site indexes and the two silvicultural treatments, can be calculated. Variations were found less than 3% in all site indexes and treatments before 150 years. These differences are presented at different ages by site indexes and treatments as shown in Table 6.

Table 6. Age at which the ten-years increase of the price index value is less than 3%, by site indexes and silvicultural treatments.

Site index	Age		Price index variation (%)	
	Treatment C (light thinnings)	Treatment E (heavy thinnings)	Treatment C (light thinnings)	Treatment E (heavy thinnings)
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

It could be considered that the data of Table 6 indicate the ages from which, on average, would not compensate to keep the stand without cutting another 10 years.

Moreover, according to Montero *et al.* (1992), should not set a shorter rotation age than necessary to achieve a high proportion of trees with d.b.h. > 40 cm, so it was calculated the percentage of trees that fulfill this condition in each age class for all site indexes and both silvicultural treatments (Figure 3).

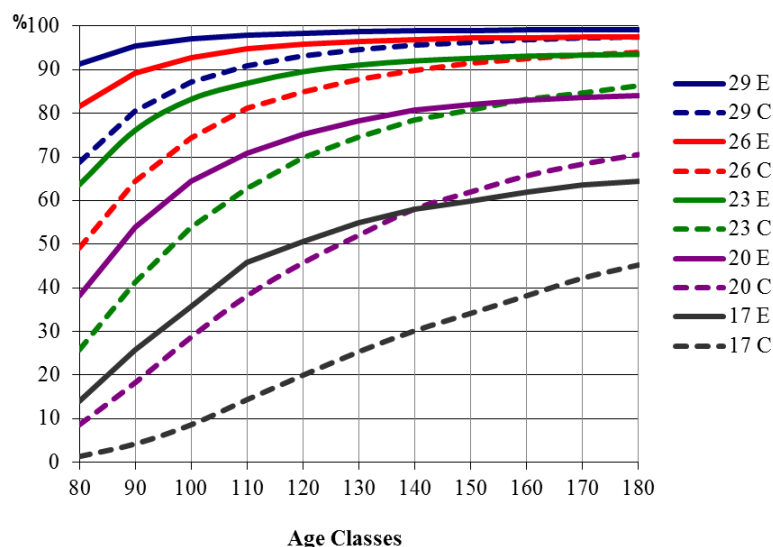


Figure 3. Evolution of the percentage of trees with d.b.h. > 40 cm by age classes, site indexes and silvicultural treatments.

As shown in Figure 3, the silviculture proposed in the yield tables for these stands results in a high proportion of trees in the diameter classes > 40 cm in all cases (and therefore an improvement of the price of wood products), but especially in the highest site indexes with heavy thinnings (treatment E). A percentage higher than 50% can be getting in all site indexes and treatments, except for site index 17 when light thinnings (treatment C) are applied.

In addition, as expected, the trend of the evolution of the percentage of trees with d.b.h. > 40 cm (Figure 3) is very similar to that of the average percentage of veneer timber by age classes, site indexes and silvicultural treatments (Figure 1). However, comparing the two figures shows that the percentage of veneer timber is approximately a quarter of the percentage of trees with d.b.h. > 40 cm in all cases. This means that 75% of the wood of these trees with d.b.h. > 40 cm can not to use as veneer, mainly due to fungal rots in old trees, as indicated Montero *et al.* (1992).

Anyway, as previously mentioned, the values of the percentage of veneer timber could be actually higher, so these differences with the percentage of trees with d.b.h. > 40 cm may be lower.

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

Considering all mentioned above, the following criteria could be established to defining the rotation age for Scots pine natural stands in the Spanish Central Range:

- 1st) Rotation age should not be ≥ 140 years in any case, to prevent fungal rots.
- 2nd) When it is possible, rotation age should be $\leq$ age at which the ten-years increase of the price index is < 3%.
- 3rd) When it is possible, price index should be ≥ 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, economic and limitations imposed by the sanitary risk criteria were combined. As Mackay (1944) indicates, the use of technological criterion should be combined with the imposition of other criteria or conditions, as it alone can lead to uncertainties.

Applying these criteria we propose the rotation ages shown in Table 7, which include a reasonable escalation by the analyzed site indexes and silvicultural treatments.

Table 7. Rotation ages proposed and corresponding price indexes by site index classes and silvicultural treatments.

Site index	Treatment C (light thinnings)		Treatment E (heavy thinnings)	
	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

Rotation ages shown in Table 7 are consistent (at least in the best site indexes) as proposed by Montero *et al.* (1992), who estimated that the rotation age in the area could be reduced to 120 applying an intensive light thinnings regime, and even to 100 years applying an intensive heavy thinnings regime. However, the rotation ages shown in Table 7 could be even lower, due to the already mentioned possibility that the percentage of wood suitable for veneer estimated by Montero *et al.* (1992) were higher if calculated from stands that had been applied intense silvicultural regimes C or E.

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 and Montero (1996), shown in Table 8.

Tabla 8. Maximum income rotation ages by site indexes and silvicultural treatments (Rojo-Alboreca and Montero, 1996).

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

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

Conclusions

Rotation ages proposed for Scots pine natural stands in the Spanish Central Range by site indexes and silvicultural treatments are presented based on technological and economic criteria, but also with the limitations imposed by sanitary risks. As expected, applying heavy thinnings a greater number of trees with larger diameter and better technological quality is achieved, and also this is achieved previously regarding the application of light thinnings.

It must be assumed that the prices of different types of wood are to be maintained in the same current proportions, which may vary with demand.

The definition of rotation ages based on the criteria discussed in this work could be complemented with the application of decision-making tools (Howard, 1991; Kangas and Kangas, 2005; Diaz-Balteiro and Romero, 2008; Ananda and Herath, 2009). Thus it would be possible to consider not easily quantifiable criteria such as environmental, social, etc., that would help justify the application of a thinnings regime and a rotation age in different scenarios and contexts.

Accepting the proposed rotation ages between 90-100 and 140 years, then periods of regeneration would occur in a broader age range than those for the criterion of maximum income or for the traditional rotation between 100 to 120 years for these stands. Thus a better structural diversity would be achieved, while the presence of continuous cover would be enhanced.

Finally, the risk of fire or forest pests and other natural phenomena that can affect negatively should not be forgotten, given the slow recovery inherent to forest systems. This factor becomes worse consequences when the stands meet a wide variety of social and ecological functions in addition to the purely productive, such as Scots pine natural stands in the Spanish Central Range.

References

- Álvarez-Taboada M.F. 2000. Caracterización de las distribuciones diamétricas de *Pinus sylvestris* L., en la Sierra de Guadarrama. Proyecto Fin de Carrera. E.P.S. de Lugo. Universidade de Santiago de Compostela, 290 p.
- Ananda J., Herath G. 2009. A critical review of multi-criteria decision making methods with special reference to forest management and planning. *Ecol. Econ.* 68(10): 2535–2548.
- Clutter J.L., Fortson J.C., Pienaar L.V., Brister G.H., Bailey R.L. 1983. Timber management: A quantitative approach. John Wiley & Sons, Inc. 333 pp.
- Davis L.S., Johnson K.N., Bettinger P., Howard T.E. 2001. Forest Management. Mc Graw Hill, New York. 804 pp.
- Del Río M., Montero G. 2001. Modelo de simulación de claras en masas de *Pinus sylvestris* L. Monografías I.N.I.A. Forestal, nº 3. Ministerio de Ciencia y Tecnología, Madrid. 114 pp.

- Díaz-Balteiro L., Romero C. 1995. Rentabilidad financiera de especies forestales arbóreas de crecimiento medio y lento en el vigente marco de ayudas públicas. *Revista Española de Economía Agraria* 171: 85-108.
- Díaz-Balteiro L., Romero C. 2008. Making forestry decisions with multiple criteria: A review and an assessment. *For. Ecol. Manage.* 255: 3222-3241.
- García-Abejón J.L., Gómez-Loranca J.A. 1984. Tablas de producción de densidad variable para *Pinus sylvestris* L., en el Sistema Central. Comunicaciones I.N.I.A. Serie: Recursos Naturales, nº 29, Madrid. 36 pp.
- González J.R., Pukkala T., Palahí M. 2005. Optimising the management of *Pinus sylvestris* L. stand under risk of fire in Catalonia (north-east of Spain). *Ann. For. Sci.* 62: 493-501.
- Howard A.F. 1991. A critical look at multiple criteria decision making techniques with reference to forestry applications. *Can. J. For. Res.* 21(11): 1649-1659.
- Kangas J., Kangas A. 2005. Multiple criteria decision support in forest management. The approach, methods applied, and experiences gained. *For. Ecol. Manage.* 207(1-2): 133-143.
- Mackay E. 1944. Fundamentos y métodos de la ordenación de montes. Primera parte: Conceptos fundamentales. Ordenación teórica. Escuela de Ingenieros de Montes. Madrid.
- Montero G., Rojo-Alboreca A., Alía R. 1992. Determinación del turno de *Pinus sylvestris* L. en el Sistema Central. *Montes* 29: 42-48.
- Montero G., Del Río M., Ortega C. 2000. Ensayo de claras en una masa natural de *Pinus sylvestris* L. en el Sistema Central. *Invest. Agr.: Sist. Recur. For.* 9(1): 147-168.
- Montero G., Rojo-Alboreca A., Álvarez-Taboada M.F., Del Río M. 2001. Aspectos selvícolas y económicos de los pinares de *Pinus sylvestris* L. en el Sistema Central. *Estudios Agrosociales y Pesqueros* 193: 27-56.
- Montero G., Del Río M., Roig S., Rojo-Alboreca A. 2008. Selvicultura de *Pinus sylvestris* L. In: Serrada R., Montero G., Reque J.A. (Eds.). *Compendio de selvicultura aplicada en España*. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria, Ministerio de Educación y Ciencia. Fundación Conde del Valle de Salazar. pp 503-534.
- Palahí M., Pukkala T. 2003. Optimising the management of Scots pine (*Pinus sylvestris* L.) stands in Spain based on individual-tree models. *Ann. For. Sci.* 60: 105–114.
- Rojo-Alboreca A., Montero G., 1996. El pino silvestre en la sierra de Guadarrama. Ministerio de Agricultura Pesca y Alimentación, Madrid. 293 pp.

- Rojo-Alboreca A., Diéguez-Aranda U., Rodríguez-Soalleiro R., Gadow K. von. 2005. Modelling silvicultural and economic alternatives for Scots pine (*Pinus sylvestris* L.) plantations in north-western Spain. *Forestry* 78(4): 385-401.
- Rojo-Alboreca A., Álvarez-Taboada M.F., Álvarez-González J.G., Gorgoso-Varela J.J., Montero G. 2014. Distribuciones diamétricas para las tablas de producción de *Pinus sylvestris* L. en la Sierra de Guadarrama. *Foresta* 61: 34-49.
- Weibull W. 1951. A statistical distribution function of wide applicability. *J Applied Mechanics* 18 (3): 293-297.