Modelling silvicultural and economic alternatives for Scots pine (*Pinus sylvestris* L.) plantations in north-western Spain

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Summary

Two silvicultural alternatives for Scots pine (*Pinus sylvestris* L.) plantations in north-western Spain were simulated and compared. One corresponded to the current management practice applied in the region and the other was an intensive silvicultural regime. Both alternatives were described by a specific combination of plantation density, precommercial treatments, thinning pattern and rotation age. Stand development of each silvicultural alternative was generated using a regional growth and yield model implemented in a simulator called GesMO, for three site qualities that represented poorest, intermediate and best sites found in the region. Different timber grades associated with each alternative were predicted, and estimates of costs and selling prices were used to predict a cash flow pattern for each of the simulated alternatives. The alternatives were ranked using the criterion of net present value of an infinite series of rotations. Sensitivity analysis, in terms of basic prices, discount rate and rotation length, was also carried out. In addition, the effects of risk of fire on net revenues were evaluated. For the present regional market conditions the results showed that the currently applied alternative is not the best one if the main aim is profit maximization. For very poor quality sites the proposed schedules are uneconomical for all silvicultural alternatives.

Introduction

According to the third Spanish National Forest Survey, Scots pine (*Pinus sylvestris* L.) stands occupy nearly 63 000 ha in Galicia (north-western Spain) (Xunta de Galicia, 2001a). This species is mainly present in pure stands, but sometimes also in mixture with native maritime pine (*Pinus pinaster* Ait.) and exotic Monterey pine (*Pinus radiata* D. Don). Most of the Scots pine stands are situated in the mountainous areas of the provinces of Lugo and Ourense.
All Galician Scots pine stands occur in plantations under 60 years old, and nearly half of them are 30–55 years old. The proposed rotation ages are 70–80 years in the better quality sites (Martínez et al., 1997a; Rodríguez-Soalleiro and Vega, 1998), and therefore no final harvests have yet been carried out in those stands. However, in the next few years a large increase in harvests from thinning operations and final cuttings is expected.

Most Galician Scots pine plantations are under communal ownership, and they are generally managed by the Regional Forest Service. Until recently, only a very small proportion of the Scots pine plantations in Galicia have been managed with application of an appropriate silvicultural regime. Nowadays, there are still many stands younger than 40 years in which no silvicultural interventions have taken place after planting, except perhaps low pruning up to 2.0 m of both dead and green branches to improve accessibility in the stand and to reduce the risk of forest fire (Arenas and Rojo, 1998).

Precommercial thinning is considered as an important tool for the development of Scots pine stands (Salminen and Varmola, 1990; Petterson, 1993; Kuliesis and Saladis, 1998; Varmola and Salminen, 2004). Despite these findings, precommercial thinnings have generally been avoided in Galician plantations due to the costs involved. The first thinning is usually delayed until the last possible moment, very often until a stand is at least 30 years old, when commercial timber can already be obtained using mechanized harvesting, to make sure that the operation is profitable or at least self-financing. This course of action produces and maintains a large number of dead trees in the stands, which provide brush control. The first thinnings are usually carried out in a semi-systematic way, removing every seventh or thirteenth row (depending on the slope), while the remaining rows are thinned selectively from below, removing in total up to 40 per cent or more of the trees (Arenas and Rojo, 1998; Rodríguez-Soalleiro and Vega, 1998; Vignote et al., 2001b). The current high demand for fibreboard and small size sawmill products in Galicia makes delaying the first thinning profitable, so that low and even high pruning, i.e. further pruning stages to a height up to 6 m, can be afforded. In a small proportion of the stands, two or three thinnings have been carried out to date, although in some high pruning has also been carried out (Arenas and Rojo, 1998).

Until recently all Spanish growth and yield research in Scots pine has been done in natural stands (García-Abejón, 1981; García-Abejón and Gómez-Loranca, 1984; García-Abejón and Tella, 1986; Rojo and Montero, 1996; Bravo, 1998; Río and Montero, 2001; Palahí et al., 2002). The resulting recommendations are not applicable to the most productive plantations in Galicia, where site qualities and growth rates vary widely (Martínez et al., 1997b).

According to Clutter et al. (1983), a simple approach in drawing up an idealistic silvicultural regime is to specify a set of silvicultural alternatives, simulate the development of each alternative using a flexible growth-projection system, then select the best alternative using specified decision criteria. In this way, forest managers can use those management guidelines for practical planning purposes. Recent studies have been made of the profitability of different silvicultural alternatives for maritime pine and Monterrey pine plantations in Galicia (Rodríguez-Soalleiro et al., 2000, 2002), and two feasibility studies of silvicultural schedules for Scots pine have also been carried out in other regions of Spain (Díaz-Balteiro and Romero, 1995; Bravo and Díaz-Balteiro, 2004), although both are related to natural stands. However, this type of study has not been carried out for Scots pine plantations in Galicia, despite the relatively large area occupied by the species and its economic importance in the region.

The objective of the present study was therefore to evaluate silvicultural treatment schedules for Scots pine plantations in Galicia. We focused exclusively on two silvicultural alternatives, the first representing the management methods applied at present in Galicia and the second representing intensive treatment for Scots pine plantations. Both alternatives were simulated by using a growth and yield model recently developed for the species in the study area (Diéguez-Aranda, 2004), which has been implemented in the GesMO program (Castedo, 2004; Diéguez-Aranda, 2004). The differences in growth and yield were analysed, including and excluding the risk of forest fire, to find which alternative is the most desirable on the basis of economic criteria.
Methods

Silvicultural alternatives

A large number of silvicultural schedules can be proposed for a given species by varying the age, weight and type of thinning, and the rotation age. Selection of the most appropriate timing and intensity of silvicultural operations depends on the production strategy. In the present study we selected the only two reasonable alternatives for managing Scots pine plantations in Galicia. The first was based on the treatments applied at present, under economic restrictions (alternative A). The second used a more intensive silviculture scheme that can be applied in the artificial stands of the species in Galicia (alternative B), following the suggestions of Martínez et al. (1997a) and Rodríguez-Soalleiro and Vega (1998).

Both alternatives corresponded to a planting density range of 1800–2000 stems per hectare (e.g. 2 × 2.5 m or similar), where the higher planting densities are usually associated with poor quality sites.

Alternative A: low-cost silviculture

This alternative is characterized by the maintenance of a high density of trees during the first years, without pre-commercial thinnings, with the only operation in the juvenile phase being brush control at stand ages of 2 and 4 years. A third brush control can be applied when low pruning is carried out.

The first thinning is mechanized and is carried out in a semi-systematic way, removing every seventh row (15 per cent of the trees), then thinning the remaining rows selectively from below and removing 25 per cent of the trees. This first thinning is delayed until the age in which the removable volume reaches at least 70 m³ ha⁻¹, a value quoted from González-Romero (2001) and Vignote et al. (2001a) for carrying out self-financing mechanized thinnings in artificial stands of Scots pine in nearly all regions of Spain.

Afterwards, two intermediate thinnings are carried out, in this case standard thinnings from below and moderate (C grade of severity; Assmann, 1970), removing 30 per cent of the stem number. The condition in applying these thinnings is again to remove at least 70 m³ ha⁻¹, but it is also necessary to wait until at least 10 years after the previous thinning and also between the last thinning and clearcutting, to have a considerable effect on the remaining trees (Montero, 1994; Cañellas et al., 2000). The rotation age is different for different site qualities.

Taking into account a usual log length of 2.5 m, low pruning of all the stems to a standardized height of 2.6 m is proposed. The pruning should be carried out when the stand mean height reaches 6–6.5 m, to avoid reduction in growth when >40 per cent of the living crown is removed (Uotila and Mustonen, 1994). The aims of low pruning are to reduce the risk of forest fire and to improve wood quality of the first log. To produce two knot-free logs, high pruning – to a height of 5.5 m – of those trees expected to reach rotation age should be carried out at a stand mean height higher than 14 m, for the same reason.

Alternative B: intensive silviculture

The intensive alternative also begins with brush control at stand ages of 2 and 4 years. A precommercial thinning is carried out when a dominant height of 5–6 m is reached, to obtain a compromise between volume production and merchantable removal, as suggested by Varmola and Salminen (2004). This is carried out in a mechanized and semi-systematic way, similar to the first thinning in alternative A: every seventh row is systematically removed (around 15 per cent of the stems), and the remaining rows are selectively thinned from below, until removal of a total of 40 per cent of the trees. This resembles the tending in young Scots pine stands in other countries (Beck, 2000).

Thereafter four more thinning operations are carried out. The intermediate thinnings are selective from below and are moderate, removing 30 per cent of stems. The intervals between thinnings are 10 years, with the exception of the intervals between the third and the fourth thinning and between the fourth thinning and the final cut (15 years each). This schedule is consistent with that proposed by Martínez et al. (1997a), and similar to that suggested by Rodríguez-Soalleiro and Vega (1998). In this alternative the rotation age also differs according to site quality. The pruning scheme is similar to that described in alternative A.
**Growth simulation**

An appropriate simulation model is required to evaluate silvicultural treatment schedules over time for different treatment options. Such a model has been developed for Scots pine plantations in north-western Spain by Diéguez-Aranda (2004). The model can be classified as a variable-density whole stand model in which stand volume is aggregated from mathematically generated diameter classes. A two-stage process that first predicts future stand density and then uses this information to estimate future stand volume allows predicting growth by subtraction (Davis et al., 2001).

In the model, the initial stand conditions at any point in time are defined by three state variables (number of trees, basal area and dominant height), and are used to estimate stand volume, classified by timber assortments, for a given projection age. The model uses three transition functions expressed as algebraic difference equations and incorporates a function for predicting initial basal area, which can be used to establish the starting point for the simulation. Once the state variables are known for a specific age, a distribution function is used to estimate the number of trees in each diameter class, by recovering the parameters of the Weibull function, using the moments of first and second order of the distribution (arithmetic mean diameter and variance, respectively). By using a generalized height–diameter function to estimate the height of the average tree in each diameter class, combined with a taper function that uses the above predicted diameter and height, it is then possible to estimate the total or merchantable stand volume, which depends on specified log dimensions.

The model has the following components:

**Site index system**

The development of the dominant height and site classification were modelled using the algebraic difference form of the differential function proposed by McDill and Amateis (1992):

\[
H_{0_2} = \frac{51.39}{1 - \left(1 - \frac{51.39}{H_0_1} \right)^{1.277}} \tag{1}
\]

where \(H_0_1\) and \(A_1\) represent the predictor dominant height (metres) and age (years), and \(H_{0_2}\) is the predicted dominant height at age \(A_2\). In selecting the base age, it was found that a base age of 40 years was best for predicting dominant height at other ages.

**Reduction in tree number (natural mortality)**

The equation used to model natural mortality is:

\[
N_2 = \left[ N_1^{-1.5896} + 1.138 \times 10^{-9} (S/1000) \times (A_2^{-3.3079} - A_1^{-3.3079}) \right]^{-1/1.5896} \tag{2}
\]

where \(N_2\) is the number of trees per hectare at age \(A_2\), \(N_1\) is the number of trees per hectare at age \(A_1\), and \(S\) is the site index (m), estimated using equation (1) for a reference age of 40 years.

**Basal area growth**

The following modification of the Korf function (cited in Lundqvist, 1957) was selected for basal area initialization:

\[
B = 92.40 e^{-0.1593/S} \times 1.369 \tag{3}
\]

where \(B\) is basal area (m² ha⁻¹) at age \(A_1\), and \(S\) is the site index (m) estimated using equation (1) at a reference age of 40 years. Equation (3) should only be used when no inventory data are available. The corresponding function for basal area projection is:

\[
B_2 = 92.40 \left( \frac{B_1}{92.40} \right)^{(A_1/A_2)^{0.366}} \tag{4}
\]

where \(B_2\) is basal area (m² ha⁻¹) at a given projection age \(A_2\), and \(B_1\) is basal area (m² ha⁻¹) at age \(A_1\).

**Diameter distribution**

The equation selected for predicting the arithmetic mean diameter for use in the parameter recovery approach is:

\[
d = d_g - e^{-1.294 + 0.000187N + 0.0363H_0} \tag{5}
\]

where \(d\) is the arithmetic mean diameter (cm), \(d_g\) is the quadratic mean diameter (cm), \(N\) is the number of trees per hectare and \(H_0\) is the dominant height (m).

**Height estimation for diameter classes**

The model selected is a modification of the function proposed by Gaffrey (1988):

\[
h = 1.3 + (H_0 - 1.3) e^{7.197 \left( \frac{1}{d_0} - \frac{1}{d} \right)} \tag{6}
\]

\(d_0\) and \(d\) are the quadratic mean diameter (cm) at age \(A_1\) and \(A_2\) respectively.
where \( h \) is the total height (m) of the subject tree, \( d \) its diameter at breast height (cm), and \( H_0 \) (m) and \( d_0 \) (cm) are dominant height and dominant diameter (average values of the 100 thickest trees per hectare) of the stand where the subject tree is included, respectively.

**Total and merchantable volume estimation**

For total and merchantable volume estimation of the average tree in each diameter class, the compatible system proposed by Fang et al. (2000) was selected. It is constituted by the following components.

**Taper function:**

\[
d_i = c_1 \sqrt{h_b(k-h_i/b_i)(1-q)^{(k-\beta)/\beta} \alpha_1 t_1 + \alpha_2 t_2} \tag{7}
\]

where \( I_1 = 1 \) if \( p_1 \leq q \leq p_2 \); 0 otherwise

\( I_2 = 1 \) if \( p_2 < q \leq 1 \); 0 otherwise

\( p_1 \) and \( p_2 \) are relative heights (\( h_i \) over \( h \)) and \( h_i \) over \( h \), respectively, both from ground level where the two inflection points of the model occur

\[
\beta = (h_1 - h_i)/b_i b_1 t_1^{\alpha_1} \tag{7a}
\]

\[
\alpha_2 = (1 - p_2) b_2/b_3 \tag{7b}
\]

\[
q_0 = (1-h_i/h)^{k/b_i} \tag{7a}
\]

\[
q_1 = (1 - p_1) h_i/b_i \tag{7b}
\]

\[
q_2 = (1 - p_2) h_i/b_2 \tag{7b}
\]

\[
c_1 = \sqrt{a_0 d^{a_1} b_i^{a_2-k/b_i}} \tag{7b}
\]

**Merchantable volume equation:**

\[
v_i = c_2 h_i^{k/b_i} [b_i q_0 + (I_1 + I_2) (b_2 - b_1) q_1 + I_2 (b_3 - b_2) \alpha_1 q_2 - \beta(1-q)^{k/b_i} \alpha_1^{I_1+I_2} \alpha_2^{I_2}] \tag{8}
\]

**Volume equation:**

\[
v = a_0 d^{a_1} b_i^{a_2} \tag{9}
\]

The following notation was used: \( d \) = diameter at breast height (cm) over bark; \( d_i \) = top diameter at height \( h_i \) (cm) over bark; \( h \) = total tree height (m); \( h_i \) = height above the ground to top diameter \( d_i \) (m); \( h_{st} \) = stump height (m); \( v \) = total tree volume (m³) over bark; \( v_i \) = merchantable volume (m³) over bark, i.e. the volume above ground level to top diameter \( d_i \); \( a_i \), \( b_i \), \( p_i \) = regression coefficients to be estimated, where \( i = 1, 2, 3;\ldots\);

\( k = \pi/40000 \), metric constant to convert from diameter squared in cm² to cross-section area in m²; \( q = h/h_i \).

The model has been implemented in a stand growth simulator called GesMO (Castedo, 2004; Diéguez-Aranda, 2004). It allows simulation of different types of thinnings (systematic, selective from below or semi-systematic) using the methodology proposed by Alder (1979) and successfully applied in diverse studies, most of them referring to thinnings from below (Lemm, 1991; Gadow and Hui, 1997; Castedo, 2004). GesMO takes into account the variation of the diameter distribution due to thinnings (Álvarez et al., 2002). It also allows calculation of the incomes gained in the harvest operations (thinnings and clearfellings), selection of the log lengths, the log top diameters and the prices of each timber grade.

As the model was based primarily on data from stands of ages ranging between 10 and 60 years, predictions of site index for stands <10 years old should not be made, since, for younger ages, erratic height growth may lead to erroneous classifications. However, the model may be used with caution for ages above 60 years, because the behaviour of the different components was evaluated and found to be logical for ages close to the rotation length (for the best results, \( \sim 70-80 \) years).

The most important limitation of the model is that it does not consider the later effect of thinning and pruning before the trees fully occupy the additional space that has been made available to them. This effect does not seem to be important in our case since very heavy thinnings were not considered (García, 1990).

**Yield tables generated**

GesMO was used to simulate a yield table for each silvicultural alternative (A and B) and three
productivity levels: poorest (site index of 8 m at 40 years), intermediate (site index 13), and best sites (site index 18) (Tables 1 and 2).

Equation (2), which accounts for natural mortality, was only applied until the age of the first operation in which some trees are removed (first thinning in alternative A and precommercial thinning in alternative B).

High pruning was not applied in either of the alternatives in site index 8 because using the indicated requirement it would be carried out at a stand age of >70 years. In site indices 13 and 18, high pruning was brought forward to ages of 40 and 30 years, respectively, in alternative A, to coincide with the age of the semi-systematic first thinning, and to ages of 38 and 32 years, respectively, in alternative B, to coincide with the age of the second thinning. The number of stems subjected to high pruning in alternative B was similar to the number of trees removed in the fourth thinning and in the final cut.

Timber grades

Three timber grades corresponding to 2.5-m log lengths were considered:

- Grade I: logs with a top diameter <18 cm, usually destined for the fibre-board industry, but also used for small dimension sawmill products. It was assumed that branches and logs with a top diameter of <7 cm are residues left in the forest.
- Grade II: logs with a top over-bark diameter of between 18 and 35 cm, for use as sawn timber, both knot-free or knotty logs.
- Grade III: defect-free and branchless logs with a top over-bark diameter of >35 cm, for the production of veneer.

Economic evaluation

The financial criterion used to evaluate each regime was Faustmann’s hypothesis (Faustmann, 1849). The net present value of an infinite series of rotations (NPVIS) was calculated to predict the present value of future incomes (Peyron \textit{et al}., 1998). This value is also referred to in the literature as the land expectation value (Bright and Price, 2000). Assuming that the net present value of each successive rotation is the same, the NPVIS associated with a given cash flow sequence can be calculated, using a continuous time formulation, as follows:

\[
NPVIS = \sum_{t=0}^{\infty} C_t \left( e^{-it} \right) = \frac{NPV_{first}}{1-e^{-iT}} \tag{10}
\]

where \( C_t \) is the net cash flow at age \( t \) calculated on the basis of plantation costs, silvicultural costs, annual management costs and harvesting revenues; \( i \) is the discount rate; \( NPV_{first} \) is the net present value of the first crop, i.e.

\[
NPV_{first} = \sum_{t=0}^{T} C_t \left( e^{-it} \right) \tag{10a}
\]

and \( T \) is the length of the rotation.

The basic discount rate considered in the present study for calculating the NPVIS values was 0.03 (3 per cent). Discount rates of 0.02 and 0.04 were also used in a sensitivity analysis.

Values of the internal rate of return (IRR) were also calculated on the basis of \( NPV_{first} \) as an indicator of the capital productivity.

Stumpage prices of different timber grades were defined on the basis of prices obtained at timber auctions carried out in recent years by the Galician Forestry Administration, as well as information provided by Galician Forest industrialists. The stumpage prices associated with each defined grade applied here were: Grade I, 18 € m\(^{-3}\); Grade II, 50 € m\(^{-3}\); and Grade III, 90 € m\(^{-3}\).

In accordance with the Regional Government’s most recent subsidy prices, the regeneration costs per hectare were assumed to be 2000 € for all the alternatives, the mechanized brush control 300 € per hectare, and the low pruning of whole stems 400 € per hectare. The assumed costs of low pruning plus brush control (alternative A) were 550 € per hectare. The cost per hectare of the high pruning was calculated for each specified schedule (depending on the number of trees pruned), and ranged between 450 and 550 € per hectare. The precommercial thinning costs were assumed to amount to 800 € per hectare, including brush control and residue treatment, and were only applied in alternative B.

The per hectare bare land value is implicitly included in equation (10). The annual management costs in the region were generally assumed to amount to 30 € per hectare (Rodriguez-Soalleiro \textit{et al}., 2002).
Table 1: Generated stand development in alternative A (low cost silviculture)

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>$H_p$ (m)</th>
<th>$N_{stems} (stems ha^{-1})$</th>
<th>$d (cm)$</th>
<th>$g (m^2 ha^{-1})$</th>
<th>$v (m^3 ha^{-1})$</th>
<th>Yield from thinning</th>
<th>$N_{stems} (stems ha^{-1})$</th>
<th>$g (m^2 ha^{-1})$</th>
<th>$v (m^3 ha^{-1})$</th>
<th>$v_{ac} (m^3 ha^{-1})$</th>
<th>Main crop after thinning</th>
<th>Total crop</th>
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Note: MAI = Main crop after thinning, CAI = Total crop.
Table 2: Generated stand development in alternative B (intensive silviculture)

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<th>Yield from thinning</th>
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<td>268.3</td>
<td>319.5</td>
<td>0</td>
<td>0 0.0 319.5</td>
<td></td>
</tr>
</tbody>
</table>

$N_{vac}$, $d_t$, $g_{vac}$, $v_{vac}$, $MAI$, $CAI$. Downloaded from https://academic.oup.com/forestry/article-abstract/78/4/385/646031 by guest on 16 December 2018.
Table 2: Continued

| Age (years) | $H_0$ (m) | $N$ (stems ha$^{-1}$) | $d_g$ (cm) | $g$ (m$^2$ ha$^{-1}$) | $v$ (m$^3$ ha$^{-1}$) | $N$ (stems ha$^{-1}$) | $g$ (m$^2$ ha$^{-1}$) | $v$ (m$^3$ ha$^{-1}$) | $v_{w}$ (m$^3$ ha$^{-1}$) | $N$ (stems ha$^{-1}$) | $g$ (m$^2$ ha$^{-1}$) | $v$ (m$^3$ ha$^{-1}$) | $v_{w}$ (m$^3$ ha$^{-1}$) | MAI (m$^3$ ha$^{-1}$) | CAI (m$^3$ ha$^{-1}$) |
|-------------|-----------|---------------------|----------|-----------------|----------------|---------------------|----------------|-----------------|----------------|---------------------|----------------|----------------|-----------------|----------------|----------------|----------------|
| 30          | 14.0      | 671                 | 24.3     | 31.2            | 190.6         | 0                   | 0.0             | 0.0             | 23.7           | 671                 | 31.2            | 190.6         | 214.2           | 7.14            | 14.02           |
| 32          | 14.8      | 671                 | 25.5     | 34.2            | 220.1         | 201                 | 7.4             | 47.0            | 70.7           | 470                 | 37.1            | 281.7         | 352.3           | 8.81            | 14.46           |
| 40          | 18.0      | 470                 | 31.7     | 37.1            | 281.7         | 0                   | 0.0             | 0.0             | 70.7           | 329                 | 30.6            | 241.0         | 379.8           | 9.04            | 13.73           |
| 42          | 18.7      | 470                 | 32.6     | 39.3            | 309.2         | 141                 | 8.8             | 68.2            | 138.9          | 329                 | 38.7            | 341.2         | 480.0           | 9.60            | 12.61           |
| 50          | 21.5      | 329                 | 38.7     | 38.7            | 341.2         | 0                   | 0.0             | 0.0             | 138.9          | 231                 | 34.5            | 329.7         | 564.2           | 9.90            | 12.07           |
| 57          | 23.6      | 329                 | 41.5     | 44.6            | 425.4         | 98                  | 10.1            | 95.7            | 234.6          | 231                 | 36.9            | 362.7         | 597.1           | 9.95            | 11.38           |
| 60          | 24.4      | 231                 | 45.1     | 36.9            | 362.7         | 0                   | 0.0             | 0.0             | 234.6          | 231                 | 43.9            | 467.3         | 701.7           | 10.02           | 10.25           |
| 70          | 26.9      | 231                 | 49.2     | 43.9            | 467.3         | 0                   | 0.0             | 0.0             | 234.6          | 231                 | 43.9            | 467.3         | 701.7           | 10.05           | 10.40           |
| 72          | 27.4      | 231                 | 49.9     | 45.2            | 489.1         | 231                 | 45.2            | 489.1           | 723.5          | 0                   | 0.0             | 0.0             | 723.5           | 10.05           | 10.40           |
Additionally, a sensitivity analysis was carried out for all the calculations by altering the current prices for the timber grades ±20 per cent and the rotation age ±5 years.

Because there is a high risk of fire in the region, the risk of a plantation being destroyed was also considered. A risk valuation was used, using the standard probabilistic approach in three stages (Bright and Price, 2000): (i) evaluation of the NPV<sub>first</sub> of different possible outcomes; (ii) weighting of each NPV<sub>first</sub> by the probability of the outcome; and (iii) summing the probability-weighted NPV<sub>first</sub>.

Data on the probability of fire occurring were obtained from Rodriguez-Soalleiro et al. (2002) and Castedo (2004), and were derived from the Regional Government statistics (Xunta de Galicia, 2001b). For precommercial stands the probability of fire destruction is 0.078, and it is assumed that this will induce crop replacement, on average, at 10 years after plantation. For commercial stands, the probability of fire occurring is 0.022 for each 10-year period, and the hazard was allocated to the middle of the period. Using the prices for burnt timber auctions, the reduction in the crop sale value was calculated as 70 per cent of the current prices for each timber grade defined. According to the same source the average relationship between profitable and total timber was estimated to be 0.85.

The cumulative conditional probabilities of the crop reaching a particular age and the summed discounted probability of death (A) were calculated as follows:

\[
A = \frac{P_i}{e^{\beta_i}} + \frac{P_{i+1}(1-P_i)}{e^{\beta_{i+1}}} + \frac{P_{i+2}(1-P_{i+1})(1-P_i)}{e^{\beta_{i+2}}} + \ldots + \frac{1((1-P_{i+1})(1-P_{i+2}) \ldots (1-P_T))}{e^{\beta_T}}
\]  

where \( P_i \) is the probability of crop destruction by fire at age \( i \), and \( T \) is the rotation age.

The land expectation value under fire hazard (NPVIS<sub>i</sub>) is thus:

\[
\text{NPVIS}_i = \text{(NPVIS}_{\text{first},i}/(1-A)
\]

where NPVIS<sub>first,i</sub> is the net present value of the first rotation considering the probability of fire.

**Results**

**Stand development and yield production**

Rotation ages simulated in alternative A varied from 67 years (best) to 109 years (poorest) (Table 1). Rotation ages in alternative B were more uniform, with only a difference of 15 years between the extreme site qualities (Table 2). In both silvicultural schedules the rotation age of the intermediate site index was closer to the best than to the poorest site quality. Rotation ages were rather similar for the intermediate site quality (81 and 78 years in alternatives A and B, respectively); there was a difference of 5 years (67 and 72 years) for the best site index, and rotation ages were very different for the poorest site index (109 and 87 years). The rotation age was lower in alternative A than B only for the best site quality (Tables 1 and 2).

The percentage of the total volume production removed by successive thinnings during the rotation can be used as an index of thinning intensity (Lanier, 1986). The corresponding values were 38.8, 34.9 and 32.0 per cent over the whole rotation for site indices of 8, 13 and 18, respectively, in alternative A, and 33.1, 32.9 and 32.4, respectively, in alternative B. Thinnings were more intense in alternative A than in B, especially at the poorest quality site, even though alternative B seemed a priori to be a more intensive alternative than A (Tables 1 and 2). Figure 1 shows the changes in basal area over the whole rotation.

The mean annual increments (MAI) at rotation age in both alternatives were very similar for all site qualities, with differences of between 6 and 19 per cent in favour of alternative A (Tables 1 and 2).

The number of trees that reached clearfelling age in alternative A was between 1.5 and 1.8 times the number of trees in alternative B, as expected in a schedule in which fewer thinnings are included. The predicted diameter distributions at clearfelling (Figure 2) show higher proportions of thicker trees in alternative B. In alternative A very few trees exceeded a diameter of 50 cm (only at the best site quality), and between 40 per cent and 44 per cent of the trees (depending on the site qualities) were <35 cm, the minimum diameter for the production of veneer. Alternative B produced a very different stand.
composition, with 29 per cent and 50 per cent of trees with diameter of >50 cm for the intermediate and best site quality, respectively.

Alternative B produced trees with an average volume at clearfelling that was 1.04 times larger than that of alternative A in the poorest site productivity class, 1.54 times in the intermediate class and 1.84 times in the best class. The proportions of the different timber grades at clearfelling for both silvicultural alternatives are shown in Table 3. The highest values of timber grades II and III were obtained, as expected, with alternative B, whereas alternative A produced high percentages of low-dimension wood (grade I).

Economic profitability

Figure 3 shows NPVIS for each alternative, excluding the risk of fire. Taking into account a current discount rate of 3 per cent, only the best site quality in both alternatives provided economic profits (NPVIS > 0), with alternative B achieving 22 per cent more profit than alternative A. If prices increased (+20 per cent) the intermediate site quality in each alternative would also produce profits, with alternative B always producing higher profits. A price decrease (~20 per cent) would maintain the profitability in the best site quality for both alternatives, but with a reduction of about 59–64 per cent in monetary terms when compared with current prices.

With a discount rate of 2 per cent, best and intermediate site qualities would provide profits, in most cases high when compared with the current discount rate (e.g. nearly four times higher in site index 18), again in favour of alternative B. With higher prices (+20 per cent), an increase in the profitability of intermediate and best qualities would be produced, as expected, and would provide profits even with the poorest site quality in alternative A. With lower prices (~20 per cent) only the best and intermediate site quality in each alternative would be profitable.

An increase in the discount rate to 4 per cent would only produce profits in the best quality sites in both alternatives when prices increased by 20 per cent.

The IRR values were 1.72, 2.61 and 3.55 for site indices 8, 13 and 18, respectively, in alternative
A, and 1.56, 2.84 and 3.87, respectively, in alternative B. As expected, according to the NPVIS results, only the best site quality in both alternatives had an IRR higher than 3 per cent (the current discount rate).

The sensitivity analysis involving varying the rotation length by ±5 years showed slight variations in the NPVIS values (Figure 4). The lengthening of the rotation age did not provide better economic results for any of the alternatives for discount rates of 3–4 per cent. Nevertheless, the contrary was true for a discount rate of 2 per cent, except for site index 18 in alternative B. Apparently the fixed rotations were close to the maximum profitability rotation ages.

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Discussion
The advantage of alternative A was a large saving in precommercial thinning costs, although there
was a high associated mortality in the stands, with values between 28 and 38 per cent depending on site quality. According to Assmann (1970), *Pinus sylvestris* has a striking capacity to make acceptable growing space by self-reduction of surplus numbers in the juvenile stages, thereby avoiding large growth and yield stagnation in the stand.

In terms of the combinations of prices and discount rate that produced profits, alternative B always provided better results than A for the two best site qualities. This is true even with higher costs associated with the application of precommercial thinnings in alternative B; therefore those costs may be considered as an investment in the yield and improvement in quality of the stands (Montero, 1994; Cañellas et al., 2000). These results indicate the convenience of concentrating intensive first thinning programmes only in intermediate and best productivity sites.

The superiority of alternative B corresponds to the relatively high proportion of valuable timber obtained, which is an indication that the current price patterns favour silvicultural treatments that improve stand conditions in the most productive plantations. These results are consistent with those obtained in other studies related to the importance of precommercial thinning in the future development and growth of Scots pine stands (see e.g. Salminen and Varmola, 1990; Petterson, 1993; Kuliesis and Saladis, 1998; Varmola and Salminen, 2004). They are, however, not consistent with the silvicultural practices currently applied in Scots pine plantations in Galicia, i.e. alternative A.

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Figure 4. Sensitivity analysis by increasing and reducing the rotation length 5 years in alternatives A (low-cost silviculture left) and B (intensive silviculture right).

Figure 5. Economic results including and excluding the risk of forest fire in alternatives A (low-cost silviculture left) and B (intensive silviculture right).
In general, low economical feasibility was obtained in the present study, in agreement with the findings of Díaz-Balteiro and Romero (1995) for natural stands of Scots pine in central Spain. However, Bravo and Díaz-Balteiro (2004) analysed silvicultural alternatives in a natural stand of Scots pine in northern Spain, combining intensive management practices with the retention of a portion of the stand in the final cutting in some cases, and the extension of the rotation to fulfil non-timber objectives in other cases, showing its feasibility in comparison with traditional management. However, the results cannot be easily compared with those of the present study because of the great difference between natural and artificial stands (Martínez et al., 1997b) and also because of the higher timber prices considered in the former study. The price of Scots pine timber destined for use as veneer (grade III) is certainly much higher in other parts of Spain (Montero et al., 1992, 2001), but in Galicia the prices of the defined timber grades are similar to those obtained for maritime pine. At the moment there is not an important market for Scots pine timber in the region, because of the above-mentioned average age of the plantations. This fact should perhaps be taken into account when considering the results obtained in the present study.

Referring to results including forest fire hazard, alternative B also seems better than A, even with the generally negative feasibility found, because early application of silvicultural treatments to control stand density implies effective prevention of forest fire.

The results also show that it would be necessary to continue with Regional Government subsidies for silvicultural operations to increase the profitability of Galician Scots pine plantations, even in the best quality sites, taking into account that they are mainly privately owned, and especially in areas with a high risk of forest fire. It is also evident that another alternative to improve profitability of plantation forestry is to search for any possible way of reducing the costs associated with stand establishment.

The proposed schedules are uneconomical for the poorest site quality in both alternatives (with the exception of alternative A when using the lower discount rate and the higher prices). Then, it seems reasonable that these stands should be managed with no production goals, focusing on aspects such as protection, recreation and preservation of biodiversity. It should be pointed out that significant natural regeneration of native hardwood trees under Scots pine stands in the region has been observed, and it may be profitable to create mixed stands. This would be done only where the Scots pine stands are planted in optimal sites, because in some cases they have been planted at very low altitudes (<500–700 m) or in wet soils in Galicia.

Consideration of these results has been limited to clearfelling options. However, transition from plantation forestry to selective harvesting systems may be a long-term option with ecological benefits (Malcolm, 1997; Kerr, 1999), even considering the green tree retention in the final cutting (Curtis, 1997; Franklin et al., 1997; Valkonen et al., 2002; Bravo and Díaz-Balteiro, 2004).

The analysis carried out in the present study has only focused on economic criteria concerning timber. Other economic criteria such as mushroom production were not considered, although they can provide even higher profits than timber in Scots pine stands (Díaz-Balteiro et al., 2003). Multiple-use aspects such as protection, recreation and nature conservation are of increasing importance, especially in the mountainous areas in which Scots pine plantations are mainly situated in Galicia. These non-economic aspects should be considered in future studies, even in the most productive sites.

Optimization techniques have been used to simultaneously optimize thinning and rotation ages for Scots pine stands (see e.g. Gerasimov and Khlustov, 1996; Miina, 1996; Brukas and Brodie, 1999; Bræze and Bulte, 2000; Hyytiäinen and Tahvonen, 2002; Lu and Gong, 2003). The silvicultural schedules considered in the present paper are certainly not the only possible ones for Scots pine plantations in north-western Spain. However, the approach followed in this study was to compare an existing silvicultural schedule with a realistic alternative that may actually be adopted in practice. An additional analysis of feasible alternatives, based on an evaluation of specific regional objectives, constraints and customs, would be necessary to complete the present study and to expand the conclusions to other areas. Another important task for future research related to Scots pine plantations in Galicia would be to integrate these alternatives into different strategic
and tactical planning models. According to Gadow and Puumalainen (2001), using optimization techniques or methodologies involving multiple criteria would make it possible to evaluate scenarios of forest development that represent specific combinations of treatment schedules for different stands (with known ages, site conditions and densities) within a given area, and to establish the optimal solution for each case.

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