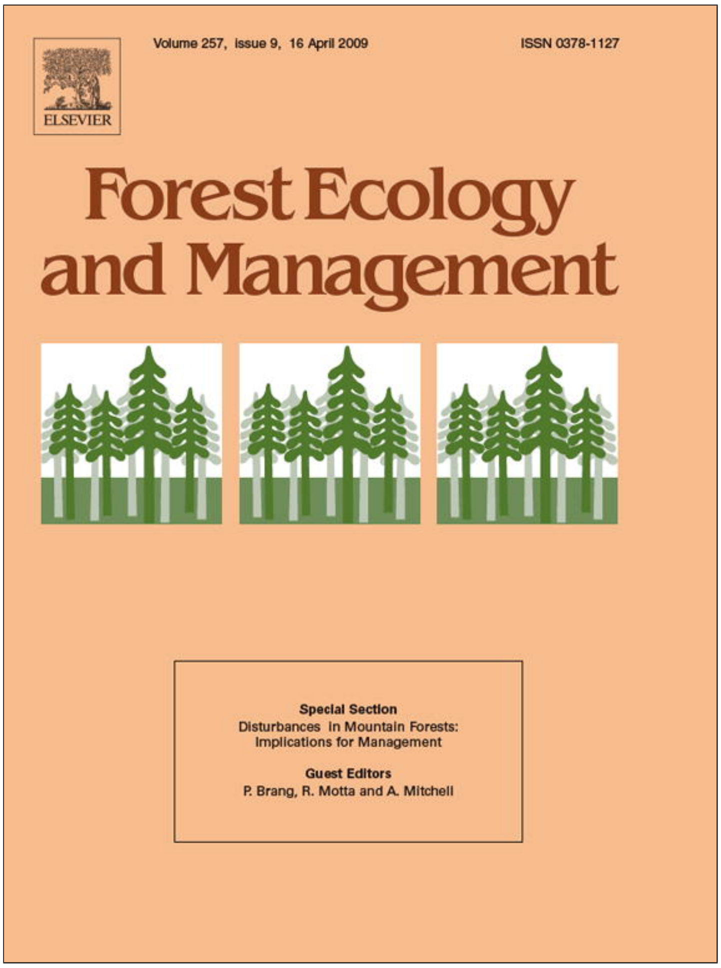

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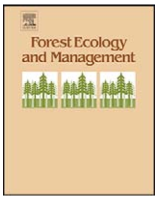

Impacts of thinning on structure, growth and risk of crown fire in a *Pinus sylvestris* L. plantation in northern Spain

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ABSTRACT

We studied the combined effects of thinning on stand structure, growth, and fire risk for a Scots pine thinning trial in northern Spain 4 years following treatment. The thinning treatments were: no thinning, heavy thinning (32–46% of basal area removed) and very heavy thinning (51–57% of basal area removed). Thinning was achieved via a combination of systematic and selective methods by removing every seventh row of trees and then by cutting suppressed and subdominant trees in the remaining rows (i.e., thinning from below). Four years after thinning, mean values and probability density distributions of stand structural indices showed that the heavier the thinning, the stronger the tendency towards random tree spatial positions. Height and diameter differentiation were initially low for these plantations and decreased after the 4-year period in both control and thinned plots. Mark variograms indicated low spatial autocorrelation in tree diameters at short distances. Diameter increment was significantly correlated with the inter-tree competition indices, and also with the mean directional stand structural index. Two mixed models were proposed for estimating diameter increment using a spatial index based on basal area of larger trees (BALMOD) in one model versus spatial competition index by Bella in the other model. As well, a model to estimate canopy bulk density (CBD) was developed, as this variable is important for fire risk assessment. Both heavy and very heavy thinning resulted in a decrease of crown fire risk over no thinning, because of the reduction in CBD. However, thinning had no effect on the height to crown base and thus on the flame length for torching. Overall, although thinning did not increase size differentiation between trees in the short term, the increase in diameter increment following thinning and the reduction of crown fire risks support the use of thinning. Also, thinning is a necessary first step towards converting Scots pine plantations to more natural mixed broadleaved woodlands. In particular, the very heavy thinning treatment could be considered a first step towards conversion of overstocked stands.

1. Introduction

A considerable proportion of the existing stands of Scots pine (*Pinus sylvestris* L.) in Spain are plantations which are a legacy of the large-scale national afforestation programme of the 1950s and 1960s. This is particularly evident in northern and northwestern Spain, where plantations aged less than 70 years cover an area of approximately half a million hectares along with some remnants of ancient pinewoods. As the main objective of these plantations is protection against soil erosion, Scots pine was considered as a suitable, non-site-demanding species, and successful soil preparation techniques were developed. The long-term goal in the afforested areas was to underplant or promote natural regeneration of broadleaved species, as mixed stands were considered to be more stable in the long term (Montero, 1994).

The silviculture of Scots pine plantations in Spain includes the following steps: establishing high initial densities to control light demanding shrubs and to prevent fires; using precommercial thinning at a stand age between 15 and 20 years; first thinning in rows combined with a low thinning in the remaining matrix; using high pruning in productive areas to improve timber quality and increase returns (Rojo et al., 2005); and following with further thinning from below to enhance stand stability against windthrow and snow breakage (Montero et al., 2001).

The management of plantations located in public lands has raised concerns about biodiversity, hydrological effects and risk of fire propagation. It has also been considered a way of artificial promotion of Scots pine in shrub areas where *Quercus pyrenaica*, *Quercus robur* or *Fagus sylvatica* are supposed to be the potential vegetation. Very dense unthinned plantations have also had

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negative effects on the amenity value of the surrounding landscape. For these reasons, the conversion of these stands to a more natural species composition and structure, and the use of alternative management regimes, such as green tree retention (Bravo and Diaz-Balteiro, 2004) or the promotion of resprouting species (González et al., 2006) have been considered in recent years.

Different approaches have been used to study the influence of thinning on forest structure dynamics: spatial individual tree models (Lexer et al., 2000), permanent sample plots (Sullivan et al., 2006) or historic management records (Montes et al., 2005). Results vary depending upon the type and intensity of thinning applied and also with the approach considered in defining the structure (i.e., positions, dimensions or ages of the trees (von Gadow and Hui, 1999)). For example, thinning to wide spacing is an option for increasing spatial or size variability without a major transformation of age structure (O'Hara, 2001).

The possible effect of growth reduction of such alternative management regimes should be studied through models (Hasenauer et al., 1997; Petritsch et al., 2007). Scots pine plantations in northern Spain under traditional silvicultural regimes may be considered as mainly being in the "stand exclusion" phase described by Oliver and Larson (1996). Although a relatively simple structure justifies the use of stand-level growth models in this case (Dieguez-Aranda et al., 2006), the application of alternative management regimes, which increase the small-scale spatial variation, would make more detailed spatio–temporal single-tree analyses desirable (Palahí et al., 2003).

The analysis of alternative regimes should also consider the risks of disturbances that these stands face, notably from fire. The late flowering and the absence of serotinous cones in Scots pine indicate that natural forests of this species did not evolve under conditions involving frequent crown fires (Tapias et al., 2004). However, the occurrence of crown fire in planted areas appears to be increasing, and the area occupied by shrubland and *Pinus pinaster* forest has increased at the expense of *P. sylvestris* in certain regions of Spain, due to more intense fires (Barbéro et al., 1998). The likelihood of these types of fires is clearly related to stand structure, as torching depends on the gap between crown and ground fuels, and active crown fire depends on the continuity of crown fuels (Schaaf et al., 2007). However, little is known about the effect of thinning on fire risk. Pollet and Omi (2002) investigated the on-the-ground effects of fire in adjacent treated and untreated areas and concluded that crown fire severity was mitigated when fuel treatments involving the removal of small diameter trees were applied. Graham et al. (1999) found different results depending on the thinning approach and the management of the thinning brash.

The aim of the present study was to analyze in detail the effects of three thinning treatments on the structure, growth and risk of crown fire of Scots pine plantations. The specific objectives were: (1) to study how thinning influences the structure of the stand; (2) to study the effect of thinning on tree-level competition; (3) to construct a tree-level model for diameter increment based on the competition and structural indices most closely related to growth and (4) to evaluate the effect of thinning on the risk of crown fire.

2. Materials and methods

2.1. Thinning trial

This study is based on data from a thinning trial which is located in a community forest planted with Scots pine in 1957 (Lugo, northern Spain, 43°08′N, 7°05′W). The mean elevation is 855 m, the soil is acidic with more than 80 cm rooting depth, and developed over schists. The average site index at the reference age of 40 years was 20 m, considering the regional model for plantations (Diéguez-Aranda et al., 2005). The study site provides excellent growing conditions for Scots pine. Nine rectangular plots (25 m × 40 m) with a buffer strip of 10 m were established in 2003, and three thinning treatments were allocated at random, but with and unequal number of plots per treatment. Two plots were unthinned (i.e., control plots) to monitor growth and natural mortality of trees without intervention. For the two thinning treatments, every seventh row of trees was removed to facilitate the movement of harvesters along the open strips. The harvester operator then selected trees from the remaining rows in a low thinning. A heavy thinning (HT) was applied to four plots, removing 32–46% of basal area, with an SG-ratio (percent of trees removed divided by percent of basal area removed, see von Gadow and Hui, 1999) of 1.35–1.43. A very heavy thinning (VHT) treatment was applied to three plots, removing 51–57% of basal area, considering an SG-ratio of 1.20–1.25. Thinning residue was piled along the strips and then chipped.

2.2. Tree measurements and biomass estimation

Pine trees were measured in 2003, immediately before thinning (BT), after thinning (AT), and again in 2007, four growth periods after thinning (AT + 4). All the trees with diameter at breast height (1.3 m) (DBH) > 7 cm after thinning were labeled with a number and mapped to an accuracy of ±1 cm using a Nikon DTM 332 total station. Two perpendicular measurements of DBH were taken on each tree and averaged. A Vertex III hypsometer was used to measure total height (H) and height to the base of live crown (HBLC), which was considered as the lower insertion point of at least three consecutive live branches in a tree. Descriptive variables of each tree were also recorded, e.g., if they were alive or dead. Understory cover and average height were estimated for each species in all of the plots.

Crown foliage biomass (CFB) was estimated using equations proposed by Montero et al. (2005) for foliage (FW) and for fine branches and twigs (FBW) using DBH as predictor variable, and summing to obtain CFB. Needles and fine (<2 cm diameter) live or dead branches and twigs were considered as the canopy fuels that would be consumed in a fully active crown fire (Scott and Reinhardt, 2001). In the case of dead trees only FBW was calculated, because the needles had already fallen in most cases. Average canopy length (CL) was calculated as the average crown length (H-HBLC) for all trees in the plot (Cruz et al., 2003). Note that plot canopy volume ($m^3\,ha^{-1}$) can be directly calculated by multiplying CL by 10,000. Following this, canopy bulk density (CBD) was estimated for each plot as the ratio of CFB summed over all trees in the plot and expanded to a per ha value ($kg\,ha^{-1}$) over plot canopy volume.

Defined in terms of its consequences for crown fire initiation, the crown base height (CBH) is the lowest height above the ground at which there is sufficient canopy fuel to propagate fire vertically through the canopy (Scott and Reinhardt, 2001). This definition was considered in setting average HBLC for both live and dead trees as the estimating CBH. For trees that were dead at AT + 4, the HBLC calculated in the first inventory, when the trees were still alive, was used.

The estimated flame length necessary to initiate a crown fire was calculated using van Wagner (1977) as follows:

$$I = (0.01\mathrm{CBH}(460 + 25.9\mathrm{FMC}))^{1.5} \quad (1)$$

$$\mathrm{FL} = 0.0775 I^{0.46} \quad (2)$$

where I is the fire line intensity ($kw\,m^{-1}$), CBH the crown base height (m), FMC the fuel moisture content (%) and FL the flame length (m).

The minimum spread rate to sustain an active crown fire was also estimated using the CBD values ($kg\,m^{-3}$) and the empirically

Table 1
List of the spatial indices and functions used as stand structure measures for nine Scots pine plots in a thinning experiment in northern Spain.

Index	Formula	Explanation	Interpretation
Aggregation	$\mathrm{CE} = \frac{r_A}{r_E}$	$r_E = \frac{1}{2}\sqrt{\frac{A}{N}}$; r_A = average distance among trees, A = stand area, N = tree number	CE < 1 indicates clustering; CE > 1 denotes regularity, CE = 1 in case of random tree positions
Mean directional index	$R_i = \sqrt{\left(\sum_{j=1}^{n} \cos\alpha_{ij}\right)^2 + \left(\sum_{j=1}^{n} \sin\alpha_{ij}\right)^2}$	α_{ij} is the angle between trees i and j and a reference direction	$\bar{R} = 1.799$ in case of random tree positions, $\bar{R} = 0$ in a complete square pattern
Angle index	$\bar{\theta} = \frac{1}{l}\sum_{i=1}^{l} \theta_i$	θ_i = smallest angle between test location and two nearest trees; l = number of sample points on a systematic grid	$\bar{\theta} \sim 90^\circ$ for random, $\bar{\theta} < 90^\circ$ for clustered point patterns, $\bar{\theta} > 90^\circ$ regular point patterns
Height (TH$_i$) and diameter differentiation(TD$_i$)	$T_i = \frac{\sum_{j=1}^{n} 1-(\min(s_i,s_j)/\max(s_i,s_j))}{n}$	s_j = height/diameter tree j, s_i = height/diameter tree i, n = neighbour number, $T_i \in [0, 1]$	T_i = 0–0.3, small differentiation; T_i = 0.3–0.5, moderate; T_i = 0.5–0.7, large
Mark variogram	$\hat{\gamma}(r) = \frac{1}{2N}\sum_{D_{ij}=r} (d_i - d_j)^2$	d_j = diameter tree j, d_i = diameter tree i, D_{ij} = distance between trees I and j, N = tree number in the plot	$\gamma(r)$ describes tree interaction at radius r and gives information on the correlation range.

derived critical mass flow rate of 3 kg m^{-2} min^{-1} proposed by Alexander (cited in Schaaf et al., 2007).

2.3. Spatial indices of woodland structure

The indices used for the nine plots were (see analytical expressions in Table 1):

(1) The aggregation index (CE) of Clark and Evans (1954) compares the average distance between trees and their nearest neighbours (r_A) and the expected mean distance among trees in a completely spatially random (CSR) distribution (r_E). The values of CE, which are calculated per stand, lie between 0 and 2.1491, with the upper boundary indicating strong regularity and the lower indicating a clumped distribution. The expected value under a CSR process is 1. Departure from CSR can be tested using the standard deviation (SD) of r_E in a randomly distributed forest of given density (Kint et al., 2000).

(2) The mean directional index, R_i, (Corral Rivas, 2006) is defined as the sum of the unit vectors from the reference tree i to its n nearest neighbours. This index takes large values in the case of clustering and small ones in the case of regular point patterns.

(3) The angle index, θ_i, (Assunção, 1994) is defined as the smallest of two possible angles formed by a sample point i and the two nearest trees. A systematic grid with a width of 15 cm was used to estimate θ_i, which take values between 0° and 180°.

(4) The diameter and height differentiation indices (TD$_i$ and TH$_i$) provide information on the spatial distribution of tree sizes (Pommerening, 2002). They vary between 0 and 1, with lower values indicating similar sizes and high values indicating variation in diameter or height between neighbouring trees.

(5) The spatial autocorrelation of tree diameters in the plots were explored using the mark variogram $\hat{\gamma}(r)$ (Stoyan and Wälder, 2000), which are second-order characteristics which depend on a distance variable r.

The 'Crancod' software package (Pommerening, 2005) was used to analyze the spatial data. The NN1 technique was employed to adjust edge effects for structural indices; this technique considers a variable buffer zone around the edge of the plot, with a width equal to the distance to the nth nearest neighbour (Pommerening and Stoyan, 2006). For the variogram analysis the edge correction method by Ohser (1983) was used. We computed the structural indices considering $n = 4$ nearest neighbours for R_i, TD$_i$ and TH$_i$.

The probability density function of each index except CE, and for the variogram was estimated using the Epanechnikov kernel, which gives decreasing weights as the deviation from x increases (Diggle et al., 2002), according to a bandwidth or smoothing parameter that was set to 1.3 for R_i, 10 for θ_i and 0.13 for T_i. We also calculated the envelope lines as the mean of the maximum and minimum values of 99 simulations involving random assignment of tree positions to observed trees (for R_i and θ_i) and random permutation of diameters to observed tree positions (for T_i) (Illian et al., 2008, p. 455f.).

Table 2
List of the spatial indices and the corresponding formulae used to analyze the individual growth of Scots pine trees in a thinning experiment in northern Spain.

Non-spatial competition indices		Spatial competition indices	
Index	Formula	Index	Formula
Wykoff et al. (1982) (BAL)	$(\pi/4)\sum_{d_j > d_i} \frac{d_j^2}{S}$	Gerrard (1969)	$\sum_{i \neq j} \frac{O_{ij}}{Z_{ij}}$
Vanclay (1991) (BAL$_R$)	BAL/G	Bella (1971)	$\sum_{i \neq j} \frac{O_{ij} d_j}{Z_{ij} d_i}$
Schröder and Gadow (1999) (BALMOD)	$\frac{1-[1-(\mathrm{BAL}/G)]}{\mathrm{RS}}$	Hegyi (1974)	$\sum_{i \neq j} \frac{d_j}{d_i D_{ij}}$
Ratio basal area/stand basal area	g_i/G	Alemdag (1978)	
Ratio basal area–diameters	$(g_i/G)^{d_i/d_g}$	Martin and Ek (1984)	$\sum_{i \neq j}\left\{\pi\left[\frac{D_{ij} d_i}{d_i + d_j}\right]^2 \frac{d_j}{D_{ij}} / \sum \frac{d_j}{D_{ij}}\right\}$
			$\sum_{i \neq j}\left\{\left(\frac{d_j}{d_i}\right) e^{16D_{ij}/(d_i+d_j)}\right\}$
		Daniels et al. (1986)	$d_i^2 n / \sum_{i \neq j} d_j^2$

d_g is the quadratic mean diameter (cm), BAL is the basal area of larger trees (m^2 ha^{-1}), d_i is the tree DBH (cm), d_j is the DBH of competing trees (cm), S is the plot area (m^2), BAL$_R$ is relative BAL, BALMOD is the modified BAL, G is the basal area (m^2 ha^{-1}), RS is the relative spacing, g_i is the tree basal area referred to surface (cm^2 ha^{-1}), O_{ij} is the overlap of influence zones (m^2), Z_i is the influence zone of tree i (m^2), D_{ij} is the distance between trees i and j (m) and n is the number of competitors.

2.4. Competition indices

Six distance-independent (i.e., non-spatial) competition indices and six distance-dependent (i.e., spatial) competition indices were computed (see Table 2). The competition indices were selected on the basis of the information required for their calculation and on the performance of a larger set of indices evaluated to explain the diameter and height growth of trees in plantations (Crecente-Campo, 2008)

The non-spatial competition indices employed can be divided into two groups: the indices related to the basal area of larger trees (BAL, BAL_R or BALMOD) and the two indices expressed as ratios of tree and stand basal area. Among the spatial competition indices, those of Gerrard (1969) and Bella (1971) are based on the overlap of influence areas, whereas the others are ratios of sizes weighted by distance, with DBH as the variable representing tree size.

The influence zone of each tree was considered as the maximum crown width of the tree growing without competition, and was calculated using the equation proposed by Condés and Sterba (2005). The criterion for selecting competitors for computing the indices was set to the four nearest neighbours, in order to enable comparison with structural indices. In formulating Daniels index (Daniels et al., 1986), n was thus set to 4. All competition indices were calculated after thinning, in order to relate them to the subsequent growth period of 4 years.

2.5. Statistical analysis

The PROC GLM procedure of SAS/STAT® (SAS Institute, 2004) was used to carry out analysis of variance (ANOVA) to test the effects of thinning treatments on individual tree diameter and height growth and individual structural and competition indices, and covariates were considered when necessary. The model used was

$$y_{ijk} = x_{ijk} + \mu + T_k + P_i(T_k) + \varepsilon_{j(ik)} \tag{3}$$

where x_{ijk} is the covariate, μ is the mean value for population, T_k is the effect of thinning, $P_j(T_k)$ is the effect of the plot and $\varepsilon_{j(ik)}$ is the effect of tree j or error term.

The effect of the plot was declared to be random in order to compute the F-test for treatments considering as denominator the mean square of plots within treatment. For pair-wise comparisons, the Tukey's studentized range test was used. The effect used as the error term was declared to be the plot using the option E of the LSMEANS statement. Since most dependent variables were not normally distributed, the variables were rank-transformed when necessary, and the ranks were normalized with the PROC RANK statement before Eq. (3) was employed (SAS Institute, 2004). All references to statistical differences in these cases are thus based on ranked values.

A mixed model (Eq. (4)) was used to model the 4-year periodic diameter increment (id_{ij}) with initial diameter (d_{ij}) and structural and competition indices as fixed explanatory variables. The same was done for height increment. To explore the general form of the model, a linear regression was fitted to the entire set of data and the explanatory variables were selected with a stepwise procedure. The model considered was

$$\ln(id)_{ij} = a_0 + \alpha_i + a_1 \ln d_{ij} + a_2\,\mathrm{CI}_{ij} + a_3\,\mathrm{STI}_{ij} + \varepsilon_{i(j)} \tag{4}$$

The index i denotes the ith plot and j the jth tree, d_{ij} is the initial diameter of tree j in plot i, CI is a competition index, STI is a structural index; a_0, a_1, a_2 and a_3 are fixed effects. The random plot effects (α_i) were assumed to follow a multivariate normal distribution $N(0,G)$ with variance–covariance matrix G and the residual errors $\varepsilon_{i(j)}$, which represent the random tree effect, were assumed to be independent in space based on the results of the experimental variogram.

Fixed and random effects were estimated using the restricted maximum likelihood method with the MIXED procedure of SAS/STAT® (Littell et al., 1996). The contribution of each factor was evaluated by splitting the total variability in diameter increment into the variation component explained by the fixed effects, variation due to random effects, and residual variance.

3. Results

3.1. Effects of thinning on stand structure and competition indices

Average values for each structural index by treatment and by forest type are presented in Table 3. Natural mortality in the control plots was 23.3% on average. This led to important changes in the control plots within the 4 years, moving towards a more

Table 3

Average values of structural and competition indices measured in a Scots pine thinning trial in northern Spain. BT refers to before thinning, or first measurement. AT is just after thinning; and AT + 4 is 4 years after thinning. The p-value refers to the test of thinning effects. Different letters in each row indicate significant differences between means according to the Tukey's test.

Index	p-Value	Control		Heavy thinning		Very heavy thinning	
		BT	AT + 4 years	BT	AT + 4 years	BT	AT + 4 years
CE	–	1.415	1.367	1.450	1.223	1.518	1.110
$\bar{R}$	0.0092	1.196	1.376 b	1.280	1.691 a	1.120	1.655 a
$\bar{\theta}$	0.0010	$115.\mathring{2}$	$111.\mathring{2}$ a	$115.\mathring{4}$	$102.\mathring{8}$ b	$120.\mathring{3}$	$101.\mathring{5}$ b
$\overline{\mathrm{TD}}$	0.0435	0.279	0.226 a	0.236	0.170 b	0.250	0.174 ab
$\overline{\mathrm{TH}}$	0.255	0.104	0.095	0.071	0.069	0.076	0.073

Index	p-Value	AT		
		Control	Heavy thinning	Very heavy thinning
BAL	0.0047	26.46 a	18.12 b	13.25 b
BAL_R	0.065	0.559	0.596	0.592
BALMOD	0.057	2.59	2.26	1.99
g_i/G	0.0057	0.00097 b	0.00153 a	0.00197 a
$(g_i/G)^{d_i/d_g}$	0.0005	0.00114 b	0.00203 a	0.00272 a
Gerrard	0.0062	1.733 a	1.356 b	1.224 b
Bella	0.0037	1.963 a	1.443 b	1.285 b
Hegyi	0.0423	1.567 a	1.278 b	1.252 b
Alemdag	0.0471	6.44 b	9.62 a	10.56 a
Martin and Ek	0.0361	12.19 b	14.83 a	14.64 a
Daniels et al.	0.203	1.063	1.036	1.074

random spatial distribution (CSR) and to lower height and diameter differentiation based on all of the indices analyzed.

For the control and HT plots, the Clark and Evans index indicated a more regular spatial distribution that differed significantly ($p < 0.0001$ and 0.0017, respectively) from a random spatial distribution. For the VHT plots, results differed by plot, with plot 1 appearing to be randomly dispersed ($p = 0.575$), whereas the null hypothesis of a CSR could not be rejected for plots 9 and 10 ($p = 0.017$ and 0.0089, respectively). The *F*-test proposed by Clark and Evans (1954) revealed highly significant differences between thinning treatments in terms of spatial distributions ($p < 0.0001$).

The mean directional index showed significant differences among treatments and means differed significantly for thinned and unthinned plots (Table 3). As this index has been proposed recently, comparison is difficult since there are not very many reported values in the literature. There was, however, a clear trend towards increasing index values in 4 years for the control plots, and a similar trend in the thinned plots to values in the range of 1.6–1.7, quite close to CSR. These effects are even more apparent in the probability density functions of the mean directional index (R_i) (Fig. 1). The distributions show much larger variance and are flatter after the thinning. A marked proportion of trees in the thinned plots have R_i values higher than 2.5, representative of trees in the edges of rows removed by thinnings.

Average values of the angle index (θ_i) were lower in the thinned plots, with values quite close to those representative of random distributions (90°). The same trend is apparent in the probability density functions shown in Fig. 2. While the majority of angles between neighbouring trees were larger angles before the thinning there is an increasing tendency towards a more uniform distribution of angles as a result of thinning that continued 4 years after the thinning. The heavier the thinning the stronger the tendency towards random tree positions.

The TD_i was also affected by thinning treatment, right after thinning and also 4 years after thinning, as shown by the significant differences in means (Table 3), with a trend of decreasing differentiation. The analysis of the probability density function of the diameter differentiation provided further results, as can be seen in Fig. 3: the variance rather decreases and the distributions shift to the left. Thinning left no trees with TD_i values higher than 0.4, and the percentage of trees with TD_i higher than 0.3 remained important only in the control plots. The fact that the diameter differentiation distribution does not deviate from the random envelopes even before thinning may be explained by the lack of spatial correlation of diameters at this stage of stand development, being this attributable to a compensation of the competition and microsite effects on tree diameters. TH_i was not significantly affected by thinning.

The results of the mark variogram analysis are shown in Fig. 4. There was a distinctive difference between the control plots and the very heavy thinned plots. In the first case, there was no marked difference between the first and the second measurements, as a result of mortality and growth. The field variance did not change at all. As a result of VHT and after 4 years, the overall field variance decreased, i.e., the diameters became more homogeneous. The curves associated with the HT treatment showed an intermediate tendency. There was a weak spatial autocorrelation in tree sizes. However, it is remarkable that the VHT led to negative autocorrelation of tree diameters up to a distance of 2 m.

The results of the effect of thinning on competition indices are shown in Table 3. There is a marked variation in the non-spatial indices that depend directly on the stand density, always tending to values showing a reduction in competition right after thinning, although those measured as relative values were not affected by thinning (BALMOD and BAL_R). The effect on spatial competition indices was clearer in the case of those based on overlapping influence areas.

3.2. Individual growth in relation to structure and competition

The average diameter increment in the thinned plots was 1.68 cm in 4 years, and in the control plots 1.30 cm. Even so, the

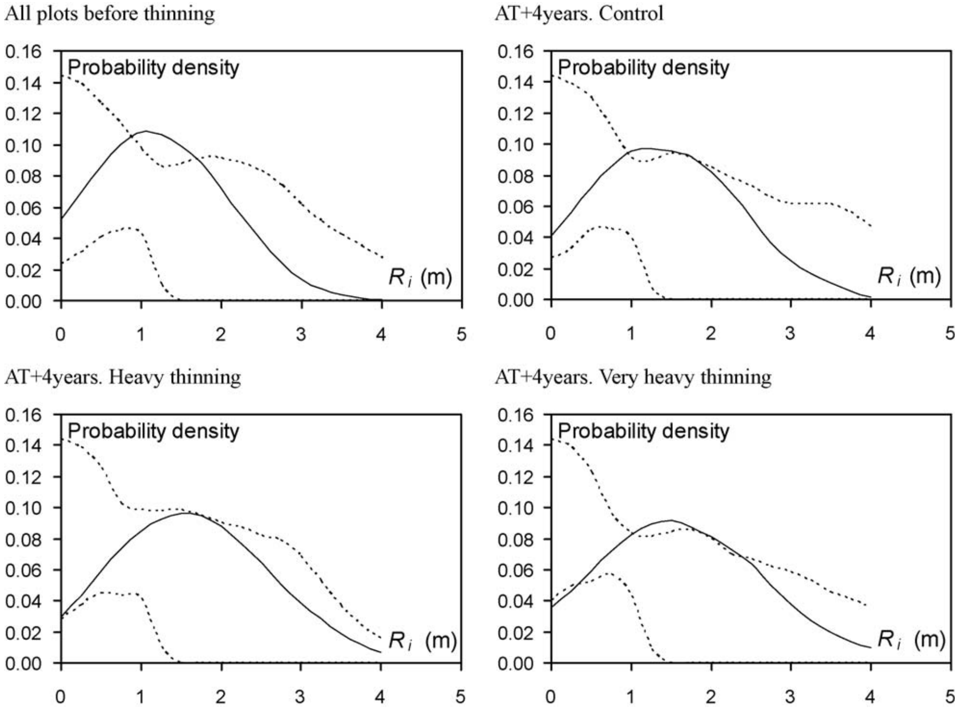

Fig. 1. The probability density functions of the mean directional index R_i estimated using the Epanechnikov kernel for different thinning treatments in a Scots pine trial in northern Spain. BT is before thinning, AT is after thinning, and AT + 4 is 4 years after thinning. Dashed lines are envelopes estimated as the mean of the maximum and minimum values of 99 simulations involving random assignment of tree positions to observed trees.

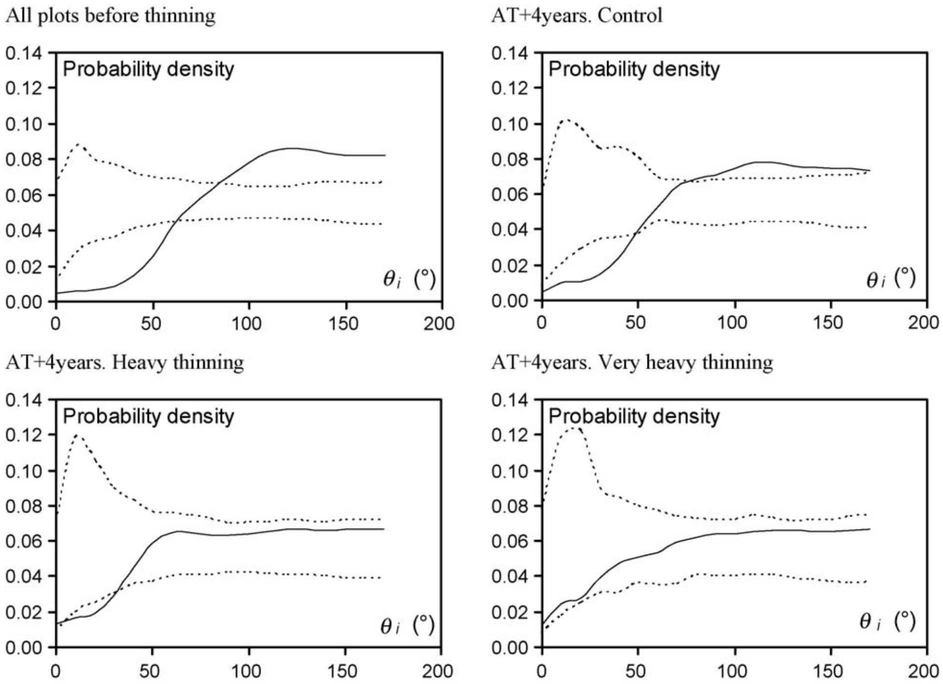

Fig. 2. The probability density functions of the angles index θ_i estimated using the Epanechnikov kernel for different thinning treatments in a Scots pine trial in northern Spain. See explanations in Fig. 1.

analysis of covariance (Eq. (3)) indicated that individual diameter increment was greatly influenced by the initial diameter, as may be expected, but thinning effects were not significant ($p = 0.244$). Also, the variance among plots was significantly different from zero. LSMEANS were -0.34 for the control plots, 0.166 for HT and 0.092 for VHT. Thinning treatment did not have a significant effect on height growth ($p = 0.654$).

The only structural index that was significantly correlated with diameter growth was R_i ($\hat{\rho} = 0.132$, $p = 0.018$). All the competition indices evaluated were highly significantly correlated with diameter growth, although the clearest relationships were with BALMOD ($\hat{\rho} = -0.459$, $p < 0.0001$) among the non-spatial indices, and Bella ($\hat{\rho} = -0.388$, $p < 0.0001$) and Daniels ($\hat{\rho} = 0.376$, $p < 0.0001$), among the spatial indices. The spatial indices based on overlapping influence areas appeared to be more related to diameter increment. Height growth was not related to any structural or competition index. The question arises regarding the possibility of explaining growth with a set of three indices,

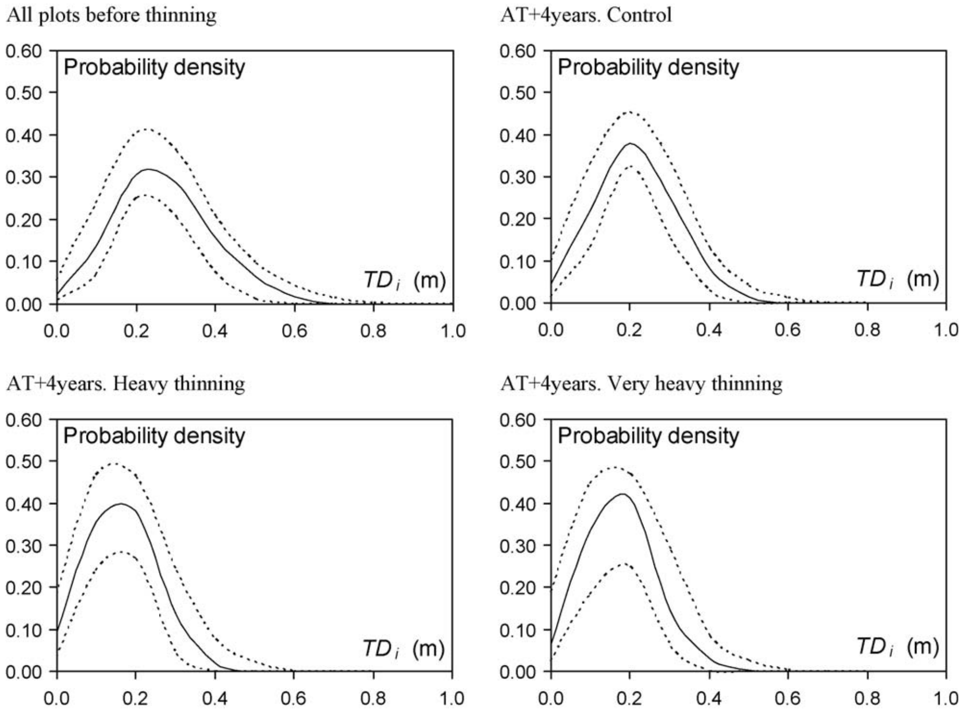

Fig. 3. The probability density functions of the DBH differentiation TD_i estimated using the Epanechnikov kernel for different thinning treatments in a Scots pine trial in northern Spain. See explanations in Fig. 1.

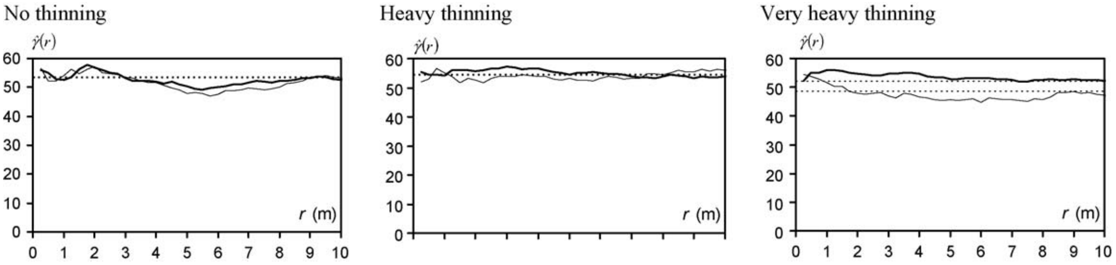

Fig. 4. Mean mark variograms $\hat{\gamma}(r)$ per treatment in a Scots pine thinning trial in northern Spain. The thick line refers to before thinning, whereas the thin line refers to 4 years after thinning. Average values are represented as dashed lines.

representative of the general conditions of competition (using BALMOD), the specific competition conditions for a tree depending on the proximity of competitors (using a distance-dependent index), and the R_i as an index representative of the direction of competition and of the stand structure.

Evaluation of the models based on Eq. (4) to predict diameter increment indicated that no structural index was significant ($p < 0.05$) given the other variables, although R_i had a p-value of 0.114. STI was then removed and two mixed models were fitted. In the first (Model 1), the index by Bella (1971) was included as the competition index (CI in Eq. (4)), requiring spatial information about the plots; the other (Model 2) included BALMOD for which no spatial information is needed. The use of both indices did not produce improve the model and as there is a strong correlation between these two competition indices, it was no longer possible to have reliable parameter estimates. Table 4 shows the results of fitting the spatial and non-spatial models. For both of these models, interestingly, the variance among trees was much higher than the variance among plots.

In the case of Model 1, the variation explained by the fixed effects was 30.0%, with an additional 7.4% explained by the random plot effects. In the case of Model 2, the variation explained by the fixed effects was 30.5%, with an additional 12.8% explained by the random plot effects. A comparison with local stand growth models (Diéguez-Aranda et al., 2006) showed their failure to estimate the overall reduction in basal area growth, higher as thinning is heavier. This growth decrease was derived from the reduction in stand closure and the trend towards a less regular spatial distribution.

3.3. *Effects of thinning on the risk of crown fire*

Table 5 shows the values of the most important variables influencing the risk of crown fire before and 4 years after thinning. The average CBD before thinning for the whole site was close to 0.5 kg m^{-3}, a large value which indicates high risk of crown fire (see Cruz et al., 2003). After 4 years there was a slight increase of 6% of CBD in the control plots, whereas the HT resulted in a decrease of 39.8% and the VHT reduced the CBD by 57.3%. The differences between treatments were even clearer when the minimum spread rate calculated as necessary to maintain an active crown fire was taken into account. Whereas the average value for the whole site before thinning considering a fuel moisture content of 70% was 6.2 m s^{-1}, the mean value 4 years after thinning for control plots was very similar (6.4 m s^{-1}) and increased to 10.1 m s^{-1} after heavy thinning and to 14.4 m s^{-1} (i.e., 2.3 times higher) after the VHT.

In the case of CBH, there was a general increasing trend for all the treatments from AT to AT + 4, which was greater in thinned than in control plots (1.2 and 1.5 m for HT and VHT, respectively, compared with 0.9 m for the control). The slight increase in CBH for the control plots was due to the presence of standing dead trees, even though HBLC increased in these plots by as much as 1.75 m in only 4 years (data not shown). Even so, the type of thinning applied did not appear to have a positive effect in terms of increasing CBH. In the same way, the flame length calculated for torching to be initiated did not differ clearly between treatments, even though torching was less likely for the whole site 4 years after thinning.

It is also important to indicate that, after 4 years, thinning did not lead to an increase in the understory cover or height. An increase in understory height would have reduced the gap length between understory materials and the crown base, resulting in a greater chance of crown fires. However, more information is needed to better assess the effects of thinning on gap length.

The evaluation of CBD in each of the nine plots before and after thinning and 4 years produced a set of 18 measurements that were used to fit an equation for predicting CBD using basal area and trees per ha, in the form predicted ln CBD = $\beta_0 + \beta_1$ ln $G + \beta_2$ ln N (Cruz et al., 2003). The parameter estimates were $\hat{\beta}_0 = -6.098(0.192)$, $\hat{\beta}_1 = 0.767(0.106)$ and $\hat{\beta}_2 = 0.329(0.065)$, with adjusted R^2 = 0.979

Table 4
Estimates and associated standard errors (S.E.) for fixed effects and variances of random effects for diameter increment models (Eq. (4)) including the index by Bella (1971) in Model 1 and including BALMOD in Model 2 as competition indices, but excluding any stand structural variables. *T*-tests test the hypothesis that the coefficient is equal to zero, whereas *Z*-tests test the hypothesis that the variance of the random effect is equal to zero.

Model 1. Explanatory variable Bella index

Fixed effect	Estimation	S.E.	*T*-test	*p*
a_0	−3.167	0.522	−6.06	0.0003
a_1	1.163	0.153	7.60	<0.0001
a_2	−0.150	0.040	−3.69	0.0002

Model 2. Explanatory variable BALMOD index

Fixed effect	Estimation	S.E.	*T*-test	*p*
a_0	−6.485	1.257	−5.16	0.0009
a_1	2.209	0.430	5.13	<0.0001
a_2	−0.084	0.048	−1.73	0.0845

Model 1. Explanatory variable Bella index

Random effect	Estimation	S.E.	*Z*-test	*p*
Var (α_i)	0.039	0.022	1.79	0.0364
Var (ε_{ij})	0.314	0.018	16.99	<0.0001

Model 2. Explanatory variable BALMOD index

Random effect	Estimation	S.E.	*Z*-test	*p*
Var (α_i)	0.050	0.027	1.83	0.0334
Var (ε_{ij})	0.318	0.019	17.02	<0.0001

Table 5
Average values and range (in brackets) of variables relevant to assess the risk of crown fire in a thinning experiment with Scots pine in northern Spain. BT is before thinning, AT is after thinning, and AT + 4 is 4 years after thinning.

Treatment	Canopy bulk density (CBD, kg m^{-3})		Minimum spread rate for active crown fire (m s^{-1})		Crown base height (CBH, m)		Flame length for torching (FL, m)	
	BT	AT + 4 years	BT	AT + 4 years	BT	AT + 4 years	BT	AT + 4 years
Control	0.44 (0.42–0.44)	0.46 (0.45–0.47)	6.8 (6.5–7.1)	6.4 (6.4–6.4)	12.7 (12.5–12.9)	13.5 (13.2–13.9)	3.9 (3.8–3.9)	4.0 (4.0–4.1)
Heavy thinning	0.50 (0.40–0.59)	0.30 (0.27–0.36)	6.1 (5.1–7.5)	10.1 (8.3–11.2)	12.7 (11.6–13.8)	13.9 (12.4–14.7)	3.9 (3.6–4.1)	4.1 (3.8–4.3)
Very heavy thinning	0.51 (0.41–0.59)	0.22 (0.16–0.26)	6.0 (5.0–7.3)	14.4 (11.7–19.2)	12.2 (11.7–12.9)	13.7 (13.0–14.6)	3.7 (3.7–3.9)	4.1 (3.9–4.3)

and RMSE = 0.052 kg m^{-3}. Even though this equation was fitted using localized data, the equation may have broader applicability to assess the effects of a reduction in tree number and basal area on CBD.

4. Discussion

There is increasing evidence that the spatial pattern of tree positions and sizes should be added to the traditional assessments used in forestry to describe stands in order to provide guidance for multi-purpose management of forests (Pommerening, 2002). This particularly applies to plantations which are being converted to more natural stands to meet a stated primary management goal. The plantation in which the thinning trial was established for the present study is overstocked with a regular spatial distribution and a restricted range of diameters and heights. It serves as an example of a type of structure commonly found in plantations where tending operations and prethinning fellings have been restricted due to a lack of funding.

The initial values of diameter differentiation before thinning treatments indicated little differentiation and were close to those calculated for natural Caledonian pinewoods and plantations by Mason et al. (2007). The results for the control plots suggest that non-intervention management at this stem exclusion stage of development would cause more stand homogenization in the short term. This is in disagreement with the observed long-term trend to increase size differentiation in ageing Scots pine stands (Kint, 2005), but is a result of very intense asymmetric competition and mortality. The thinned plots also showed a trend from right after thinning to 4 years after thinning of decreasing diversity in tree size, although less apparent than in the control plots, as a result of the thinning from below of the remaining matrix. Montes et al. (2005) also found that low thinning carried out to homogenize inter-tree distances in clusters of natural regeneration lowered stand structure and microstructure diversity. The height differentiation values were much lower than for diameter for both control and thinned plots and before and after treatments, and showed a stronger trend towards homogeneity. The TH_i values were lower than those obtained for natural stands in Central Spain managed by shelterwood or individual tree selection fellings (Montes et al., 2005), and also lower than those reported by Kint (2005).

The thinning treatments applied have an important effect on the spatial distribution of tree positions, with a clear trend for heavily thinned plots towards a more random spatial distribution, closer to that expect in naturally regenerating stands, right after treatment and continuing to 4 years following treatment. This may indicate a good starting point for conversion to a more natural spatial pattern, if successive thinnings of more than 50% pine basal area are applied as supported by Kint (2005). Kint (2003) used CE to show that Scots pines aged 70 to 160 years in forest reserves tended towards a random pattern in the case of lower stand densities. This trend may strongly depend on the type of thinning applied, as Kint et al. (2000) showed a tendency towards regularity in mixed stands of oak (*Q. robur*) and Scots pine thinned to release future crop trees and respace clusters. The two thinning intensities evaluated in this study can be considered a preparatory stage towards conversion. The HT treatment led in fact to a current structure at 4 years after treatment that is in fact close to structural class B of Kint (2005), whereas the VHT has tended towards structural class A, where there is clear likelihood of birch (*Betula pubescens*) regeneration.

The results of growth after thinning indicated that the effect of thinning on individual growth is not yet significant. Similar results of spatial and non-spatial competition indices for estimating periodic diameter growth could be attributed to the overstocked and regular initial state of the plantation. Davies and Pommerening (2008) recently found that spatial variables can contribute to effective models of crown size of Sitka spruce (*Picea sitchensis*) and birch in mixed stands, especially in overstocked conditions. The very heavy thinning produced an important short-term decrease on stand basal area growth, whereas heavy thinning represents a good balance between reduction of stand growth and promotion of individual diameter growth. This is in agreement with the long-term results of thinning experiments in Central Spain (del Río et al., 2008), which reported a volume growth loss of 18% for the heavier thinning treatment applied.

Selective thinning (in the sense of crown thinning with designation of frame or crop trees) would promote greater differentiation in sizes (Sevilla, 2005), but this would probably cause more mortality among dominant trees (Bravo-Oviedo et al., 2006) and even more important, higher risk of crown fire. González et al. (2005) showed that an increase in the risk level from 2% to 5% of 5-year fire probabilities led to optimal application of earlier and heavier low thinnings. In fact, several of the principles proposed for fuel reduction treatments, such as reduction of surface fuels and increased height of the live crown could be attained more easily by low thinning (Agee and Skinner, 2005). Comparison of the present and previous results (González et al., 2006) reveals that management of plantations aimed at conversion to more diverse structures in areas at such risk from forest fires should first attempt to acquire variation in tree spatial positions. Then, by opening enough space in a further stage, the promotion of a broadleaved understory can reduce the fire occurrence. Details to obtain rapid seedling recruitment both for broadleaves and pines are presented by Edwards and Mason (2006).

Scots pine has proved to be one of the more sensitive of European pine species to crown damage and mortality caused by heat. Several studies have highlighted the importance of tree size to withstand surface fire (Fernándes et al., 2008). Thin the plantations with the objective of reducing crown fire likelihood and promoting diameter growth of remaining trees could be then consider as a major goal of management. Reduction of crown fire risk is especially important for reducing fire severity near human settlements. The application of a heavy selective crown thinning would lead to the maintenance of crown base heights similar to those observed before thinning, because not removed small trees free of competition would probably survive. If we consider the factor representative of gap/ladder fuels in the crown fire initiation term of the fuel characteristics classification system (Schaaf et al.,

2007) we would conclude that the likelihood of a crown fire would be higher if overtopped trees remain after thinning, as in the case of selective thinning. Thus, the heavy low thinning combined with row removal applied in the current forest practices in the region, could be considered appropriate after the results of this study.

5. Conclusions

The thinning treatments have clear effects on the mean values and distribution of structural indices accounting for tree positions and size differentiation. There is a general trend towards a more random spatial distribution and lower diameter and height differentiation, which is strongly enhanced by the thinning treatments. The mean directional index is related to growth and can be an interesting structural index to be included in single-tree growth models. The VHT tested here could be considered as a first step where conversion is a present management goal, with further opening of gaps being necessary. HT is a possible way to maintain pine productivity, delay the conversion decision and make more flexible the future management. It balances between the promotion of diversity in tree positions, enhancement of single-tree diameter growth and reduction of vertical and horizontal continuity of crown fuels. Thinning did not significantly affect individual diameter or height growth 4 years after thinning.

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