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RESEARCH ARTICLE

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Influence of thinning intensity and canopy type on Scots pine stand and growth dynamics in a mixed managed forest

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Abstract

Aim of the study: We analysed the effects of thinning intensity and canopy type on Scots pine growth and stand dynamics in a mixed Scots pine-beech forest.

Area of the study: Western Pyrenees.

Material and methods: Three thinning intensities were applied in 1999 (0, 20 and 30% basal area removed) and 2009 (0, 20 and 40%) on 9 plots. Within each plot, pure pine and mixed pine-beech patches are distinguished. All pine trees were inventoried in 1999, 2009 and 2014. The effects of treatments on the tree and stand structure variables (density, basal area, stand and tree volume), on the periodic annual increment in basal area and stand and tree volume, and on mortality rates, were analysed using linear mixed effects models.

Main Results: The enhancement of tree growth was mainly noticeable after the second thinning. Growth rates following thinning were similar or higher in the moderate than in the severe thinning. Periodic stand volume annual increments were higher in the thinned than in the unthinned plots, but no differences were observed between the thinned treatments. We observed an increase in the differences of the Tree volume annual increment between canopy types (mixed < pure) over time in the unthinned plots, as beech crowns developed.

Research highlights: Moderate thinning is suggested as an appropriate forest practice at early pine age in these mixed forests, since it produced higher tree growth rates than the severe thinning and it counteracted the negative effect of beech on pine growth observed in the unthinned plots.

Keywords: competition; *Fagus sylvatica* L.; *Pinus sylvestris* L.; forest management; mortality; Mediterranean forest.

Abbreviations used: U, unthinned plots; M, moderate thinning; S, severe thinning; MC, mixed beech-pine; PC, pure pine; UM, unmanaged mixed beech-pine; UP, unmanaged pure pine; MM, mixed beech-pine in moderate thinning; MP, pure pine in moderate thinning; SM, mixed beech-pine in severe thinning; SP, pure pine in severe thinning; PAI, periodic annual increment; PAIBA, periodic basal area annual increment; PAIV, periodic stand volume annual increment; $i\bar{v}$, periodic tree volume annual increment; N, density; BA, basal area; V, stand volume; $\bar{v}$, tree volume; Dg, quadratic mean diameter; DBH, diameter at breast height; Q_x, x% percent quartiles.

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Introduction

Pure coniferous forests have been historically favoured in the European temperate zone for management reasons (Spiecker, 2003), and because of a higher volume growth expectation (Pretzsch, 2005). However, the view of forests as a simple source of wood products is nowadays mostly outdated and forest policies aim to achieve a sustainable management of forest ecosystems (MCPFE, 1993). Conversion to near-natural and often, mixed broadleaved-coniferous forests is therefore being considered (Spiecker, 2003), due to the multiple benefits that mixed woodlands may provide, such as greater diversity, protection from disease, resistance to abiotic stress or stability to disturbances (Kelty, 1992; Pretzsch, 2005). Additionally, mixed forests do not necessarily lead to a decrease in stand productivity when compared to pure stands if beneficial inter-specific processes occur (Kelty, 1992). Several studies on the effects of mixture on the forest yield have been carried out (e.g. Kelty, 1992; Pretzsch, 2005; Pretzsch & Schütze, 2009; Pretzsch *et al.*, 2010), but little is known about inter-specific processes in mixed Scots pine (*Pinus sylvestris* L.)-beech (*Fagus sylvatica* L.) forests, and particularly in Mediterranean areas (but see Primicia *et al.*, 2013; Río *et al.,* 2014).

Spiecker (2003) suggested that the structure of mixed stands may be maintained and improved by management practices like thinning, which has been also recommended as a necessary first step in the conversion process from pure Scots pine plantation to mixed broadleaved forests (Crecente-Campo *et al.*, 2009). Thinning reduces the stand density and promotes the growth of the remaining trees by decreasing the competition for the resources (Valinger, 1992; Larson *et al.*, 2001), and by enhancing the photosynthetic capacity of the crown due to an increase of the foliar mass of the remaining trees and of the light reaching the low parts of the crown (Aussenac, 2000). Additionally, thinning may also affect tree growth through the alteration of microclimatic conditions. Thus, even though forest floor evaporation may rise after thinning due to higher soil temperature from increased radiation reaching the forest floor, soil humidity may also increase due to greater throughfall (Ma *et al.,* 2010). For instance, Breda *et al.* (1995) observed a longer growing season, and therefore, higher tree growth, of canopy trees after thinning caused by the reduction of summer drought stress in a *Quercus petraea* stand in France. Several studies have been focused on the effects of thinning on tree growth in Scots pine pure stands (e.g. Montero *et al.*, 2001; Mäkinen & Isomäki, 2004; Mäkinen *et al.*, 2005; Río *et al.*, 2008; Crecente-Campo *et al.*, 2009; Novak *et al.*, 2011), but just few studies have tackled the same issue in mixed woodlands (e.g. Primicia *et al.*, 2013).

The natural distribution of Scots pine (*Pinus sylvestris* L.) and beech (*Fagus sylvatica* L.) overlap in south and central Europe, where large pure Scots pine forests are being transformed into mixed Scots pine- beech stands (Bolte *et al.*, 2007). In the south-western Pyrenees (e.g., Navarre), mixed Scots pine-beech forests constitute a common vegetation type, where it accounts for over 40 % of the mixed stands (Gobierno de Navarra, 2010). In high-productive mixed Scots pine- beech stands in this area, Scots pine generally constitutes the main tree species; its natural regeneration being the final objective of the forest management. Beech was usually eliminated to promote Scots pine growth in traditional silvicultural practices, but nowadays, the maintenance of beech in the understorey is becoming frequent, since among other benefits, managed mixed pine–beech forests apparently produce higher quality of Scots pine wood than pure stands. Nevertheless, there is evidence that beech may negatively affect pine growth in this area through competition (Primicia *et al.*, 2013; Primicia *et al.*, 2014). Therefore, the main objective of this study was to evaluate the effects of thinning intensity and canopy type (pure pine *vs.* mixed beech-pine) on the development of the stand and tree structure and growth of Scots pine. Our hypothesis is that the negative effect of beech on pine growth will be affected by thinning intensity.

Material and methods

Study Area

The study area is located in Aspurz (42º 42’ 31’’ N, 1º 08’ 40’’ W), in the western Spanish Pyrenees, Navarre (Figure 1). It is located in one of the most productive Scots pine forests in Spain (Puertas, 2001), which site index is 29 m at 80 years. The forest is an even-aged mixed stand dominated by Scots pine, naturally regenerated in the mid-1960s after strip-like clear- cutting, with mean dominant tree height of 20.4 m in 2014. Beech is the second most abundant tree species, being very abundant in the understorey (< 2 m) at certain mixed areas. However, it also occurs as an upper continuous canopy layer including the four crown classes (Smith, 1986), where competition between beech and pine crowns is evident. Additionally, some isolated beech individuals can be found between this upper layer and the understorey. In 2008, beech had a mean crown cover of ca. 38% and mean beech age was 35-40 years. The study site is North-oriented and it is located at a mean altitude of 642 m, a mean slope of 7 % and it develops on a Haplic Alisol (Blanco, 2004). The climate is classified as a cold wet Mediterranean type with water deficit usually in July and August, and frequent frosts in winter and early spring. Mean annual precipitation is 921 mm and mean annual temperature, 12.0 ºC (data from nearby Navascués station located at 2.7 km from the study site, 42º 43’ 06’’ N, 1º 06’ 55’’ W, 615 m; period 1984- 2014).

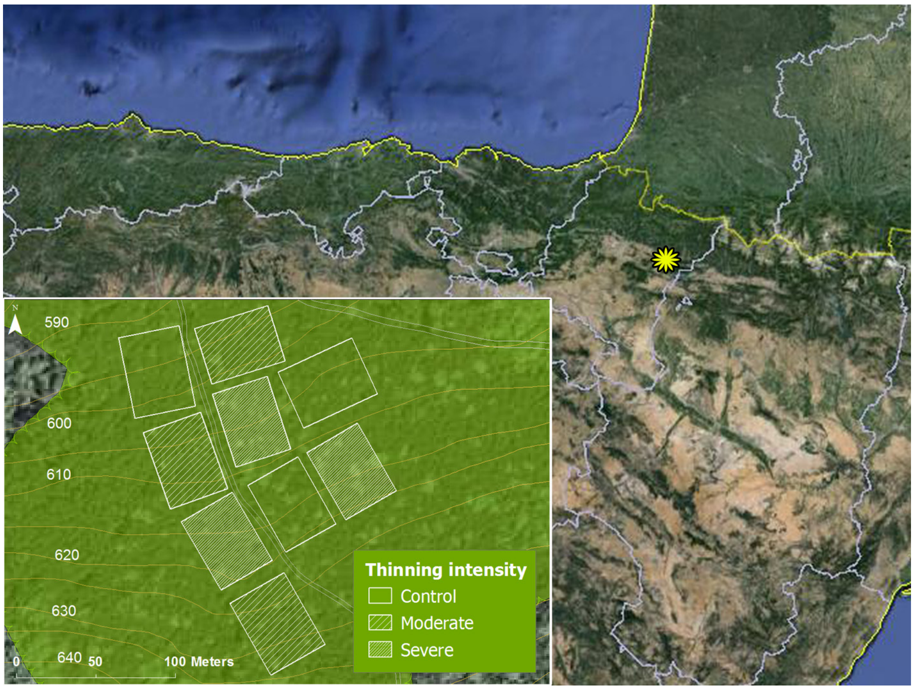

Figure 1. Map of the study site location and distribution of plots with different thinning treatments on the slope.

Experimental design

Nine rectangular plots (30 m x 40 m) were included in the experimental design, installed by the Servicio Forestal del Gobierno de Navarra following a complete randomized block design (Andrew, 1986). Three different thinning intensities (3 thinning intensities *x* 3 replicates) were applied in November 1999 (0, 20 and 30% basal area removed, hereafter unthinned-U -, moderate-M- and severe-S- thinning) and March 2009 (0, 20 and 40%). The first thinning was carried out removing mainly suppressed or intermediate trees, and some dominant or codominant trees with malformed stems. During the second thinning, mainly subdominant or dominant trees were removed, as most trees were in the upper strata as the result of the stand dynamics and the first thinning. The highest thinning intensity was increased up to the 40 % of the basal area during the second thinning in accordance to the silvicultural trends applied on similar surrounding stands at that moment. Similarly, following the silvicultural guidelines applied in Navarre on mixed stands with beech as secondary species, only Scots pine trees were thinned. In 1999, stumps were left on the ground, and logs and most branches from the felled trees were left outside the plot limits. In 2009, stumps and branches, the latter cut into pieces, were left on the forest floor but the stems, including the bark, were removed from the experimental area. The same treatments were applied in a buffer zone of 5-10 m around the plots.

Within each plot, two discontinuous subplots can be distinguished based on the crown cover of beeches taller than 2 m: mixed beech- pine and pure pine subplots (hereafter abbreviated as MC and PC subplots). Six treatments are thus determined: UM (unmanaged mixed beech-pine), UP (unmanaged pure pine), MM (mixed beech-pine in moderate thinning), MP (pure pine in moderate thinning), SM (mixed beech-pine in severe thinning) and SP (pure pine in severe thinning). The experimental design can be thus specified as a split-plot (von Ende, 2001) with three replicates of six subplots (Table 1). Data on beech tree cover is not available for 1999, but comparison between beech cover data in 2003 and 2008 suggests that mixed canopy area has remarkably spread over the plots since the onset of the experiment.

The study site was considered as a pure pine forest due to the low presence of beech by the foresters who set up the experimental plots in 1999. However during the course of our studies in the site we have shown that beech cover is expanding in the stand and that beech has a great effect on forest nutrient cycling (see Primicia *et al.*, 2014). Therefore, the main aim of this study was to study the effect of beech presence on the dynamics of Scots pine growth. Pure beech plots have been lately installed near the experimental site to model the development of whole stand growth in future analyses.

Table 1. Evolution of the mean main stand variables (means ± SE) in the six different treatments.

Treatment	Before thinning 1999			Before thinning 2009						2014 Inventory		
	Pinus sylvestris L.			*Pinus sylvestris* L.			*Fagus sylvatica* L.			*Pinus sylvestris* L.		
	N	Dg	BA	N	Dg	BA	N	Dg	BA	N	Dg	BA
UM	3156 ± 521	12.4 ± 1.0	36.6 ± 1.6	1947.4 ± 343.8	16.5 ± 1.0	40.4 ± 1.9	1448 ± 300	6.0 ± 0.6	4.1 ± 1.3	1369.6 ± 194.5	18.5 ± 1.0	36.1 ± 1.3
UP	3768 ± 869	11.6 ± 0.6	45.5 ± 3.1	2086.6 ± 291.5	17.0 ± 0.6	49.8 ± 2.5				1478.8 ± 117.1	19.8 ± 0.5	43.3 ± 1.4
MM	2942 ± 174	10.7 ± 0.9	30.8 ± 1.9	1611.4 ± 139.0	16.4 ± 1.2	36.1 ± 1.0	765 ± 158	7.5 ± 0.6	3.5 ± 0.4	980.3 ± 110.1	19.2 ± 1.5	30.1 ± 2.6
MP	4209 ± 369	12.8 ± 1.3	43.8 ± 2.0	2107.2 ± 140.5	17.6 ± 1.1	46.9 ± 0.3				1201.6 ± 55.3	19.4 ± 1.0	37.6 ± 2.2
SM	3948 ± 529	11.6 ± 0.4	34.9 ± 3.7	1738.5 ± 243.6	16.9 ± 0.6	35.6 ± 2.2	675 ± 113	9.3 ± 1.2	5.8 ± 1.3	965.6 ± 136.7	20 ± 0.7	27.3 ± 1.7
SP	5268 ± 517	10.5 ± 0.6	45.1 ± 0.9	2361.2 ± 272.7	15.7 ± 0.8	45.1 ± 1.7				1154.4 ± 157.9	19.1 ± 1.0	32.4 ± 1.3

Abbreviations: N, tree density (tree ha^{-1}); Dg, quadratic mean diameter (cm); BA, basal area (m^2 ha^{-1}); UM, unthinned mixed canopy; UP, unthinned pine canopy; MM, moderate thinning mixed canopy; MP, moderate pine canopy; SM, severe thinning mixed canopy; SP, severe thinning pine canopy. Data of *Fagus sylvatica* trees was only available for 2009.

Data gathering and processing

In 1999, all alive and standing dead Scots pine trees within the plots were labelled and their relative coordinates calculated using a compass and the Vertex III hypsometer (Haglöf, Sweden). Two perpendicular measurements of their diameter at breast height were taken and the measuring height was marked to reduce the error when comparing with the following measurements. The inventory was repeated in 2009 (before the second thinning) and in 2014. The variables measured during each inventory are shown in Table 2. Stem volume equations were derived from a sample of 229 Scots pine trees covering all diameter classes felled down in 1999 and 2009 (n = 200 and n = 29 trees for 1999 and 2009, respectively). The best-fitted model was selected as that showing the lowest Akaike Information Criterion (Burnham & Anderson, 2002) and highest R^2adj values once the assumptions of normality and homoscedasticity were satisfied (Suppl. Table S1 [online supplement]). To analyse Scots pine mortality in the study plots, we used data on standing dead trees (snags) recorded in 1999 and data on both standing and lying dead (logs) trees recorded in the 2009 and 2014 inventories. Mean mortality rates (frequency, basal area) and periodic annual increments (PAI) in basal area (PAIBA), stand volume (PAIV), and in tree volume ($i\bar{v}$) were calculated for the two periods determined by the three inventories (1999-2009 and 2009-2014).

Statistical analysis

All statistical analyses were performed using the R software (R Core Team, 2013). The effects of thinning intensity and type of canopy on the tree and stand structure variables (density, N; basal area, BA; stand volume, V; tree volume, $\bar{v}$ data before thinnings), PAIBA, PAIV, $i\bar{v}$, and on mean mortality rates, were assessed using linear mixed effects models following a split-plot design with a repeated measure (Pinheiro & Bates 2000) using the *nlme* package (Pinheiro *et al.*, 2009). We used thinning intensity, canopy type and the inventory year (or period for PAI variables and mortality rates) as fixed effects. To analyse the PAI variables, we also included the quadratic mean diameter (Dg) into the models as a fixed effect, to account for the influence of the stand structure on growth and

Table 2. Field data gathered during each inventory.

Year of inventory	Measured Scots pine variables
1999	Diameter at breast height (DBH) of all alive and standing dead trees Age (n = 30 stumps/ plot) Mean height (n = 30 trees/ plot) Dominant height (n = 12 trees/ plot) Trees measurement for volume equations construction (total n = 200 trees)
2009	DBH of all alive and standing and lying dead trees Trees measurement for volume equations construction (total n = 29 trees)
2014	DBH of all alive and standing and lying dead trees Mean height (trees measured in 1999 and still alive, total n =198) Dominant height (n = 12 trees / plot)

mortality rates. We choose Dg because it was the stand variable most correlated with the PAI variables. We did not include the dominant height, like in other studies, because due to the proximity and situation of the study plots on the same slope, no differences in site quality can be expected. As random effects, we included subplot (for variables at the stand scale) or tree nested in subplot (tree variables), since they can be considered as a random representation of the population. An autoregressive correlation structure of first order was included to account for the repeated measures on the same subplot or tree (Pinheiro & Bates, 2000). For instance, to analyse $i\overline{v}$, a variable calculated at the tree scale, the proposed model was stated as follows:

$$i\overline{v} = I + \mathrm{Dg} + \text{thinning} * \text{canopy} * \text{period} + \\ + \text{tree:subplot} + \text{corAR (tree:subplot)}$$

where: $i\overline{v}$ represents the Tree volume annual increment; *I* is the intercept; Dg is the subplot quadratic mean diameter; thinning and canopy represent the study treatments; period is the sampled period for which $i\overline{v}$ has been estimated; tree:subplot, a random term specifying the effect of individual trees nested within each subplot; and corAR (tree:subplot), the autoregressive correlation structure to account for the repeated measures on each tree within each subplot.

The appropriateness of the random and correlation structures was analysed by comparing nested models with and without the structures with the likelihood ratio test using the restricted maximum likelihood estimation procedure. The significance of the fixed effects was analysed by comparing nested models with and without the fixed terms using the maximum likelihood estimation procedure (Zuur *et al.*, 2009).

To analyse whether the effects of treatments on the Tree volume annual increment ($i\overline{v}$) depended on tree size, we used linear mixed effects models fitted to the data set split into four classes based on the 25%, 50%, 75% and 100% percent quartiles (Q_{25}, Q_{50}, Q_{75}, and Q_{100}, respectively) of the tree diameter at breast height (DBH) at the beginning of the study. Thus, the data set was split into four classes: Q_{25}, Q_{50} - Q_{25}, Q_{75} - Q_{50}, and Q_{100} - Q_{75}. The proposed models were similar to the one stated above, but in this case we used the initial DBH instead of quadratic mean diameter as covariate.

Results

Influence of thinning intensity and canopy type on Scots pine stand structure

Evolution of the main stand variables in the different thinning treatments are shown in Suppl. Table S2 ([online supplement]). Scots pine density and basal area were lower in thinned than in unthinned plots only after the second thinning ($P < 0.001$, Table 3, Figure 2a), while stand volume was higher ($P < 0.01$, Table 3) in U than in M and S plots, although differences were mainly observed in 2014 (295 ± 14, 253 ± 17 and 222 ± 11 $m^3\ ha^{-1}$ in U, M and S plots, respectively, Figure 2a). Tree volume decreased with increasing thinning intensity at the beginning of the study, but in 2014, it was highest in the M plots ($P < 0.001$, Table 3, Figure 2a). Scots pine basal area and stand volume was significantly ($P < 0.001$) higher in pine than in mixed canopy (Figure 2b). Differences between canopy types for pine density decreased over time (PC > MC, $P = 0.09$, Figure 2b), except for tree volume, which was similar between canopy types at the beginning of the experiment, but it was higher in PC than in MC at the end of the study ($P < 0.05$, Figure 2b).

Table 3. Likelihood ratio test and significance of treatments (thinning intensity, canopy type) and year on Scots pine stand and tree variables (N, pine density; BA, basal area; V, stand volume; $\overline{v}$, tree volume) in 1999, 2009 and 2014 (data before thinnings), and on mortality rates (frequency, Nd; basal area, BAd), and periodic annual increment in basal area (PAIBA), stand volume (PAIV) and tree volume ($i\overline{v}$). Abbreviations: Dg, quadratic mean diameter. Significant effects ($P < 0.05$) are shown in bold, marginally significant effects ($P < 0.1$) are shown in italics.

Variable	Stand structure variables					Mortality rates		Periodic annual increment		
	N	BA	V	$\overline{v}$	Variable	Nd	BAd	PAIBA	PAIV	$i\overline{v}$
					Dg	0.2201	0.4027	**0.0002**	**<.0001**	**0.0676**
Thinning (TI)	0.8648	0.1448	**0.0088**	0.1774	Thinning (TI)	**<.0001**	**0.0003**	**0.0033**	**0.0076**	**0.0080**
Canopy (C)	0.1939	**<.0001**	**<.0001**	0.0204	Canopy (C)	*0.0845*	0.9158	0.6155	0.3703	0.5135
Year (Y)	**<.0001**	**<.0001**	**<.0001**	**<.0001**	Period (P)	*0.0631*	*0.0602*	0.1202	0.2175	**<.0001**
TI: C	0.5354	0.5592	0.7343	0.1094	TI: C	*0.0864*	0.2896	*0.0697*	*0.0865*	*0.0721*
TI: Y	**<.0001**	**0.0010**	0.2185	**<.0001**	TI: P	**0.0458**	0.1413	0.1300	**0.0444**	**0.0000**
C: Y	*0.0905*	0.1966	0.1002	**0.0086**	C: P	0.6135	0.5872	0.6273	0.5238	**0.0085**
TI: C: Y	0.4311	0.8783	0.7928	**0.0009**	TI: C: P	0.5714	0.9403	0.6789	0.6586	0.5004

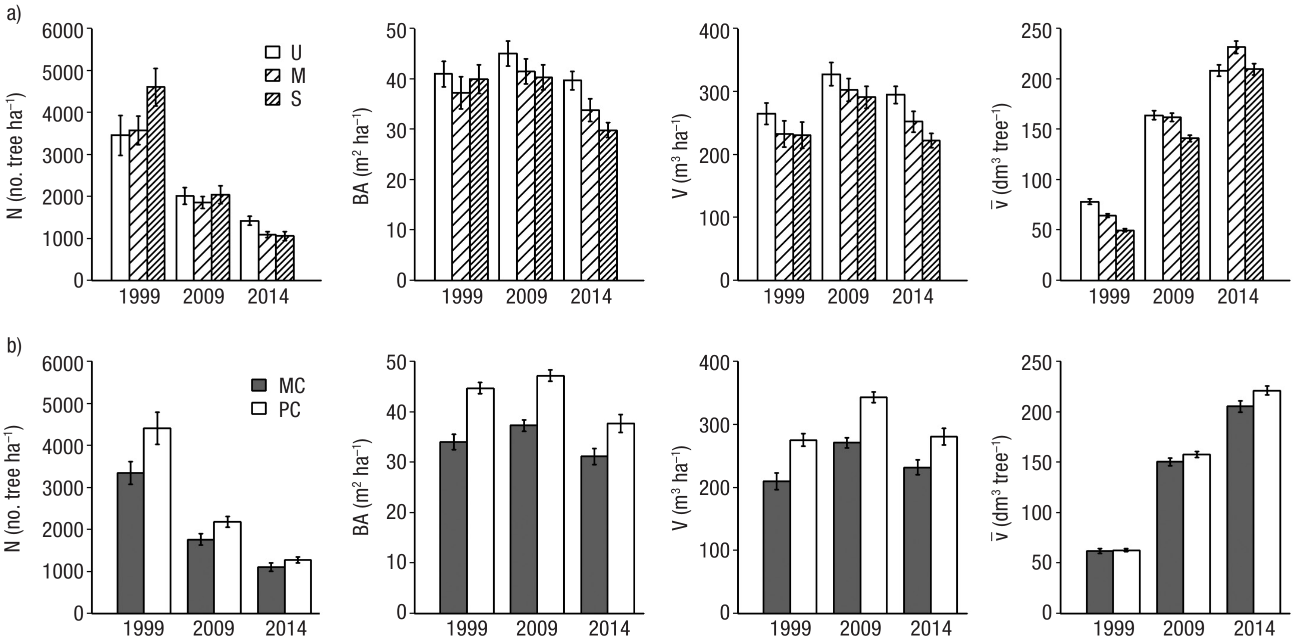

Figure 2. Mean (± SE) Scots pine density (N), basal area (BA) and stand (V) and tree ($\bar{v}$) volume by thinning intensity (*a*) and canopy type (*b*) in 1999, 2009 and 2014 (data before thinnings). Abbreviations: U, unthinned plots; M, moderate-thinned plots; S, severe-thinned plots; MC, mixed beech-pine canopy; PC, pure pine canopy.

In 1999, the number of snags was similar in the severe than in the unthinned plots (Figure 3). Mortality rates (frequency) was significantly influenced by the interaction between thinning intensity and period ($P < 0.05$, Table 3), since higher rates occurred in U plots compared to M and S plots during the first period, but higher values were observed in U and M plots than in S plots during the second period (Figure 3). Basal area mortality rates increased from S plots, followed by M plots, and reaching the highest values in U plots ($P < 0.001$).

Influence of thinning intensity and canopy type on Scots pine growth and mortality rates

Both periodic annual increments in basal area and in stand volume decreased with increasing the quadratic mean diameter ($P < 0.001$, Table 3), and they were significantly higher in the thinned than in unthinned plots ($P < 0.001$). In unthinned plots, a decrease in the stand volume occurred after the second thinning due to natural pine mortality.

Tree volume annual increment ($i\bar{v}$) was always lowest in U plots, and while it was similar in thinned plots during the first study period, it was lower in S than in M plots during the second study period ($P < 0.001$, Table 3, Figure 4a). Tree volume annual increment was similar between canopy types during the first study

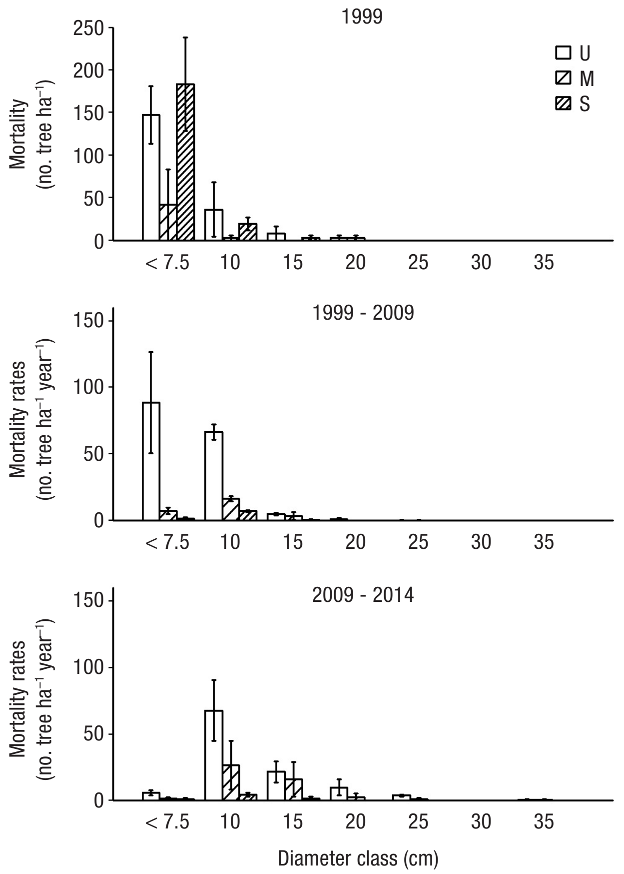

Figure 3. Mean (± SE) number of Scots pine standing dead trees in 1999 and mean (± SE) mortality rates during 1999- 2009 and 2009-2014 in unthinned (U), moderate (M) and severe (S) thinned plots per diameter class.

period, but it was lower in MC than in PC during the second period (Figure 4b). Nevertheless, the reduction of $i\overline{v}$ in the MC was not observed in the thinned plots (*P* =0.07, Table 3, Figure 4c). The effect of treatments on $i\overline{v}$ was influenced by tree size, being the biggest trees (DBH comprised between Q_{50} and Q_{100}) the most influenced ones by treatments (Table 4, Figure 5). Tree volume annual increment of the smallest trees (Q_{25}) showed practically no differences among thinning intensities, while bigger trees (DBH comprised between Q_{50} and Q_{100}) showed higher $i\overline{v}$ in M plots, followed by S plots, and finally, by U plots, especially during the second study period (Figure 5). Tree volume annual increment of all trees except the smallest ones was higher in PC than in MC, although the effects frequently depended on the study period, as differences between canopy types increased after the second thinning.

Table 4. Likelihood ratio test and significance of treatments (thinning intensity, canopy type) and period on Scots pine tree volume annual increment ($i\overline{v}$) of trees with different size based on the diameter at breast height (DBH) at the beginning of the study. Abbreviations: Q_{25}, Q_{50}, Q_{75}, and Q_{100} trees with DBH comprised in the 25%, 50%, 75% and 100% percent quartiles, respectively. Significant effects (*P* < 0.05) are shown in bold, marginally significant effects (*P* < 0.1) are shown in italics.

	Tree volume annual increment ($i\overline{v}$)			
	Q_{25}	**Q_{50} - Q_{25}**	**Q_{75} - Q_{50}**	**Q_{100} - Q_{75}**
DBH	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Thinning (TI)	**0.007**	**<.0001**	**<.0001**	**0.002**
Canopy (C)	0.952	0.230	**0.025**	*0.054*
Period (P)	0.156	0.297	**0.003**	**<.0001**
TI: C	0.654	0.098	0.228	0.126
TI: P	**0.007**	**<.0001**	**<.0001**	**<.0001**
C: P	0.819	**0.013**	**0.029**	0.555
TI: C: P	0.234	0.367	0.567	**0.011**

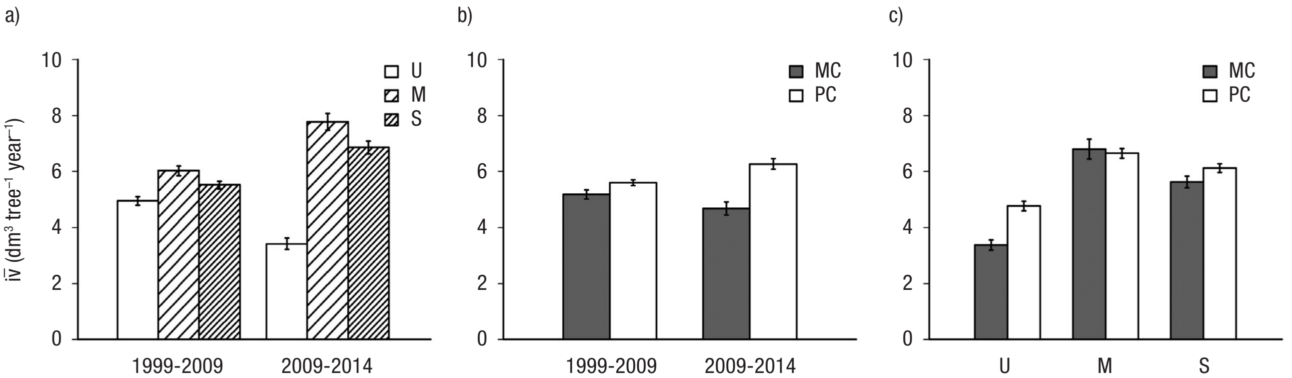

Figure 4. Effects of thinning intensity *x* period (*a*), canopy type *x* period (*b*), and thinning intensity *x* canopy type (*c*) on the Tree volume annual increment ($i\overline{v}$) of Scots pine (means ± SE). Abbreviations: UM, unthinned mixed canopy; UP, unthinned pine canopy; MM, moderate thinning mixed canopy; MP, moderate pine canopy; SM, severe thinning mixed canopy; SP, severe thinning pine canopy; U, unthinned plots; M, moderate-thinned plots; S, severe-thinned plots; MC, mixed beech-pine canopy; PC, pure pine canopy. Only significant effects of treatments are shown.

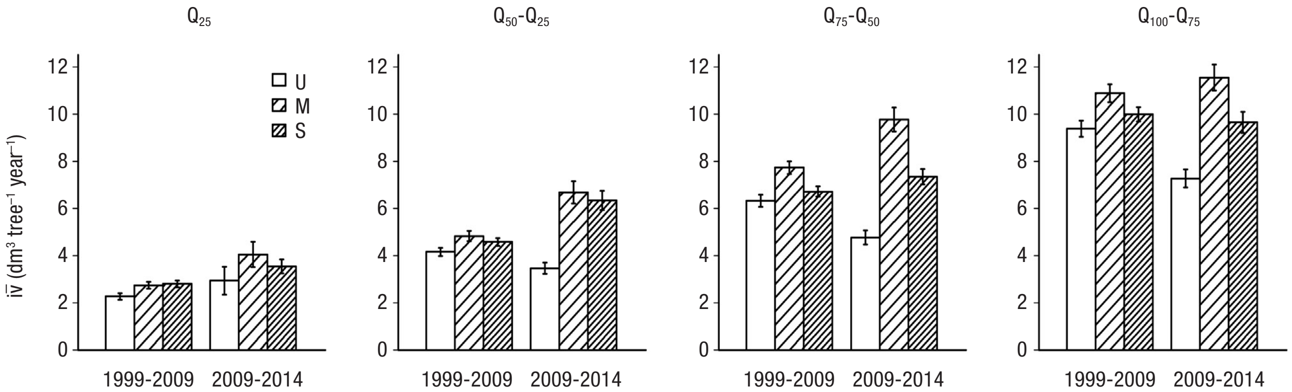

Figure 5. Effects of thinning intensity *x* period on the tree volume annual increment ($i\overline{v}$) of Scots pine (means ± SE) of different size based on the diameter at breast height (DBH) at the beginning of the study. Abbreviations: Q_{25}, Q_{50}, Q_{75}, and Q_{100} trees with DBH comprised in the 25%, 50%, 75% and 100% percent quartiles, respectively; U, unthinned plots; M, moderate-thinned plots; S, severe-thinned plots.

Discussion

Stand and tree growth and development of Scots pine is highly influenced by thinning intensity

The tree volume annual increment ($i\overline{v}$) of Scots pine was slightly enhanced after the first thinning, but no differences were observed between M and S plots. Primicia *et al.* (2013) also found a weak and temporary effect of the first thinning on the tree ring width of dominant and codominant pines in the same study site. Although thinning from below in Scots pine stands appears to particularly enhance the growth of intermediate trees (Río *et al.*, 2008), we observed that the biggest trees (DBH comprised between Q_{50} and Q_{100}) were the most responsive ones to the first thinning. In the study site, the initial stand structure of Scots pine was greatly variable among plots (lower pine density with higher quadratic mean diameter, higher tree and stand volume in unthinned than in thinned plots). Additionally, high natural pine mortality occurred in U and M plots after the first thinning, highlighting a strong competition among trees. Both the initial variability in the stand structure and the disparities in the mortality rates may have disguised to some extent the effects of the first thinning on $i\overline{v}$.

After the second thinning, $i\overline{v}$ was highest in the M plots, especially in the case of the biggest trees, contrastingly to the results obtained in previous studies, where increment in diameter increased with increasing thinning intensity (Montero *et al.*, 2001; Mäkinen & Isomäki, 2004). In Mediterranean sites, thinning could enhance tree growth by improving the tree water status (Bréda *et al.*, 1995; Ma *et al.*, 2010; Molina & del Campo, 2012), since tree growth is usually mainly limited by water deficit (Sabaté *et al.*, 2002). However, in our study plots, soil moisture was higher in unthinned than in thinned plots even 9 years after the first thinning, probably due to higher transpiration rates in the latter (Primicia *et al.*, 2013). Additionally, wind speed within the stand and evaporation may also increase following thinning, enhancing the transpiration rates of individual trees (Aussenac, 2000). Therefore, the trees water balance might have been negatively affected by the severe- thinning treatment. The higher $i\overline{v}$ in M than in S plots after the second thinning could be related to a fertility decrease because of nutrient loss in the highest thinning intensity. In the study site, the main nutrient limiting Scots pine growth appears to be phosphorus (Primicia *et al.*, 2014), whose reserves are susceptible to overexploitation (Blanco *et al.*, 2005). In this context, we suggest that the decrease in soil fertility is mainly due to a reduction in litterfall after thinning. For instance, during the first 30 months after thinning in 1999, the percentage of P returns for total aboveground litterfall in thinned relative to control plots ranged from 16.9% (M plots) to 22.3% (S plots; Blanco *et al.*, 2008). Prescriptions for forest thinning in high-productive Scots pine stands following the economic criteria and adapted to our region (exploitation cycle of 80 years, first thinning at 20- 25 years, rotation length of 10 years, removal of 30% of the basal area; Río & Montero, 2001; Puertas, 2003) could indeed result in a significant net phosphorus loss in the study site at the long term (Blanco *et al.*, 2005). Current forest thinning practices applied on surrounding similar stands should be consequently verified from an ecological perspective at the long term.

Thinning treatments enhanced the periodic stand volume annual increments, even though no differences between M and S plots were found. The differences between unthinned and thinned plots were especially notable after the second thinning, as a decrease in the stand volume occurred because of natural pine mortality in the unthinned plots. In the thinned plots, the yield reduction by thinning is counteracted by the enhancement of individual tree growth, resulting in lower stand density but bigger tree size. However, a reduction in either stand or merchantable volume and stand growth has been frequently observed following moderate to very heavy thinning, although it was also absent after light thinning or in control plots in other Scots pine stands few years after thinning (Montero *et al.*, 2001; Mäkinen & Isomäki, 2004; Mäkinen *et al.*, 2005; Río *et al.*, 2008; Crecente-Campo *et al.*, 2009).

Effect of the canopy type on Scots pine stand and tree growth and development

Beech presence apparently caused a reduction in the Tree volume annual increment, agreeing with previous results (Primicia *et al.*, 2013; Río *et al.*, 2014). In our study site, characterized by summer water deficit, the negative effect of beech on $i\overline{v}$ may have been related to the beech root system, since it is highly competitive for water and nutrient resources (Curt & Prevosto, 2003). The importance of light in competition in mixed Scots pine-beech forests in the same region has been also highlighted (Río *et al.*, 2014), where size-asymmetric competition (resource uptake depends on the relative sizes of the competitors) is apparently stronger than size-symmetric competition (resource uptake is independent of the relative sizes of the competitors, Schwinning & Weiner, 1998). The reduction of the Tree volume annual increment due to beech presence gradually increased during the study period, related to beech crown development. Nevertheless, this decrease in $i\overline{v}$ in the mixed compared to the pure canopy did not happen in the thinned plots. Primicia *et al.* (2013) also observed that Scots pine growth was higher in PC than in MC in the same study site 9 years after the first thinning, but only in the unthinned plots. They suggested that these results were related to differences among treatments (thinning intensity *x* canopy type) in the tree water status, tree size and tree-to-tree competition.

The differences in Scots pine density between canopy types found at the onset of the experiment (PC > MC) decreased over time. This pattern could have been partly due to Scots pine mortality in the MC, or due to an unequal thinning intensity within plots. Although the thinned trees were broadly randomly distributed within the plots, some Scots pines near the beech trees were maintained to better study the inter-specific processes between both species and to homogenize the stand structure between canopy types.

Conclusions

A slight enhancement of the Scots pine tree volume annual increment was observed after the first thinning, but no differences between the thinned treatments were found. A more noticeable increase of tree volume annual increment was recorded after the second thinning, when it was highest in the moderated- thinned plots, leading to a higher cumulative tree volume in the intermediate than in the heaviest thinning intensity at the end of the study. The biggest trees were always the most responsive ones to thinning. While Scots pine tree volume annual increments were similar between canopy types during the first study period, a reduction in the tree growth rates occurred in the mixed compared to the pure pine canopy during the second period. However, this decrease in the Scots pine growth rates due to beech presence was absent in the thinned plots. Conclusively, in this area and in terms of wood production, moderate thinning could be an appropriate forest practice at early pine age, as it produced bigger-sized stems and similar periodic stand volume annual increments than the severe thinning. Furthermore, it counteracted the negative effect of beech on pine growth observed in the unthinned plots. The consistency of these patterns should be nevertheless verified as the following thinnings are carried out.

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