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EFFECTS OF THE FIRST THINNING ON THE GROWTH AND CONE PRODUCTION OF STONE PINE (*PINUS PINEA* L.) STANDS IN THE NORTHERN PLATEAU (SPAIN)

Por DANIEL MORENO FERNÁNDEZ

Tutoras:

Mariola Sánchez-González

Isabel Cañellas Rey de Viñas

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Que es mi barco mi tesoro,
que es mi dios la libertad,
mi ley, la fuerza y el viento,
mi única patria, la mar.

La Canción del Pirata, José de Espronceda

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Índice

Índice de tablas

Índice de figuras

Abstract

Edible stone pine (*Pinus pinea* L.) nut is the forest product which provides the highest incomes to the owners of stone pine forests. In spite of this, there is a lack of knowledge concerning forest management alternatives when the main stand objective is edible nut. The objective of this work is to evaluate the effect of first thinning on growth and cone production in an artificially regenerated stand located in the Northern Plateau (Spain) in order to determine optimum intensity. A thinning trial was installed in 2004 to compare two thinning regimes (heavy and moderate) and a control treatment. From 2004 to 2012 an inventory of forest attributes was carried out 6 times and the cone crop was harvested annually. In order to evaluate the effect of thinnings on growth we used repeated measures analysis of variance using a mixed model approach. With regards to cone production we first estimated the probability of finding cones in a tree by applying a generalized mixed model and then estimate cone production using a mixed model, including climatic variables in both models. We found that thinning has a positive influence on tree diameter and height increment, quadratic mean diameter and cone production. We recommend early silvicultural treatments in stone pine stands to favor the development of trees and larger edible pine nut production.

Key words: mixed models, logistic regression, non-wood products, edible nut, Mediterranean area, early treatments

Resumen

El piñón del pino piñonero (*Pinus pinea* L.) es el producto que más beneficios reporta a los propietarios de estas masas forestales. Sin embargo, aún quedan muchas preguntas acerca de la selvicultura a seguir para masas cuya función preferente es la producción de piñón. En este trabajo se estudia el efecto de la primera clara sobre el crecimiento y la producción de piña en una masa repoblada en la provincia de Valladolid (España) para tratar de determinar cuándo se deben comenzar las claras y con qué intensidad. Con dicho objetivo, en 2004 se instaló un dispositivo permanente en el que se comparan tres tratamientos distintos, dos regímenes de claras (fuerte y moderada) y un tratamiento control. Desde 2004 a 2012 se realizaron 6 inventarios y se recogió la piña anualmente. Para evaluar el efecto de las claras en el crecimiento tanto a nivel de masa como de árbol individual se realizó un análisis de la varianza de medidas repetidas aplicando modelos mixtos. En el caso de la producción de piña, en primer lugar se estimó la probabilidad de que un árbol produzca piñas aplicando un modelo mixto generalizado, y a continuación se estimó la producción de piña mediante un modelo mixto, incluyendo en ambos casos variables climáticas. Encontramos influencia positiva de las claras en el crecimiento en diámetro y en altura a nivel de árbol individual, en el diámetro cuadrático medio, en el peso de la cosecha de piñas y en la posibilidad de encontrar piñas en un árbol. Se recomienda aplicar tratamientos selvícolas tempranos para fomentar el desarrollo de los pies así como la producción de piña.

Palabras clave: modelos mixtos, regresión logística, productos no maderables, piñón comestible, área mediterránea, claras tempranas.

Introduction

Stone pine (*Pinus pinea* L.) is a species native to the Mediterranean area. Natural or afforested stone pine stands occupy more than 400,000 ha in Spain (Montero *et al*., 2008). Traditionally, the management of stone pine stands has tried to combine multiple objectives: edible pine nut production, timber, firewood, recreational use, landscaping and protection against wind erosion on sandy soils. However, pine cones provide high incomes to the forest owners, often than that associated with timber or firewood, due to the fact that pine nuts are currently highly prized (average price of 2,100 € t^{-1}) in international markets (Mutke *et al*., 2005). Edible nuts have become the most important forest product in many rural areas. Sustainable development of the stone pine forest and the surrounding rural areas requires more intensive management of forest resources in order to achieve maximum value per tree.

For these reasons, when nut production is the main goal the target of stone pine management, thinnings must aim low densities to encourage crown development and to avoid overlaps and regression of the crowns. Also, thinnings must promote tree cone production even if this means a reduction in productions per unit area in order to reach greater yield in harvest operations. If there is a delay in thinning treatments or they are too light, productions will not be commercial until the stand is at least 60 years old (Montero *et* *al*., 2008). The first thinning must be carried out achieving low densities since the beginning of fructification (15-25 years old) (Montero *et al*., 2008).

There are some scientific works which report that fellings favor seed production in pine species, such as *Pinus sylvestris* L. (Karlsson, 2000), *Pinus ponderosa* Dougl. Ex P.&C. (Krannitz and Duralia, 2004) or *Pinus resinosa* (Sol. Ex Aiton) (Cooley, 1970). The effects of density on cone production in managed stands have been studied in *Pinus pinea* L stands (e.g. Calama *et al*., 2008). However, there are not any studies which have analyzed thinning schedules and the goal densities for each site index and age in the case where the edible pine nut is the main stand aim.

However, large crops fluctuate significantly over the years. The fluctuation is attributed to meteorological conditions (Calama *et al*., 2011; Mutke *et al*., 2005) and is associated with the secondary effect of exhaustion of resources caused by large crops (Mutke *et al*., 2005). Climate conditions affect the physiological cone development, and therefore cone production, in the course of its long reproductive cycle, which takes 3 years. Hot points of cone development are bud formation and flower survival; all of them are closely related to rainfall (Mutke *et al*., 2005). In addition, both cone and seed production for a given year, are also conditioned by the vigor and health of the tree, its size, the loss of seed through pests or predation, soil attributes, mainly water soil retention, and the attributes of the stand, especially, the stand density (Calama *et al*., 2008; Calama *et al*., 2011).

Diameter is positively correlated with crown size (Ciancio *et al*., 1986) and cone production (Krannitz and Duralia, 2004; Calama *et al*., 2008; Calama *et al*., 2011). Since trees of larger diameter produce the most of the cones, increased cone production may be a longer-term benefit of thinning (Krannitz and Duralia, 2004). Therefore, large diameters will be required to maximize cone and edible nut productions per tree. Tree growth is regulated by thinning which controls of stand density (Mäkinen and Isomäki, 2004b). There are many studies about the thinning intensity and growth response, mainly in Northern conifers (e.g. Mäkinen and Isomäki, 2004a and 2004b; Slodicak *et al*., 2005). In the Mediterranean basin, several thinning experiments have been carried out on other pines (e.g. Montero *et al*., 2001; Del Río *et al*., 2008). However, there is less information about the effect of first thinning (Gordo *et al*., 2009).

Objectives

The main objective of this study is to analyze the effect of the first thinning on growth at single tree and stand levels, and on cone production, while taking climatic variables into account, for stone pine stands established through artificial regeneration in the Northern Plateau, which is one of the most important areas for the species in Spain. Considering our data series, the results of this work might be useful in order to determinate the optimum goal density after first thinning. We hypothesize that diameter growth and cone production will be higher in thinned stands than in control stands. Also, we expect to find a positive correlation between cone production and precipitation.

Materials and methods

Experimental design

A thinning trial with permanent plots was installed in the Pinar y Dehesa de Abajo forest (Valladolid province, Northern Plateau, Spain) (Figure 1) in 2004. The trial is located in a pure *P. pinea* stand established 20 years ago through artificial regeneration. Annual precipitation in the area is 408 mm and average annual temperature is 11 ºC. The stand is on sandy flat soil at an altitude of around 743 meters above sea level. This area is in the climatic limit of the species because of the shortage of precipitation and the extremely high summer temperatures.

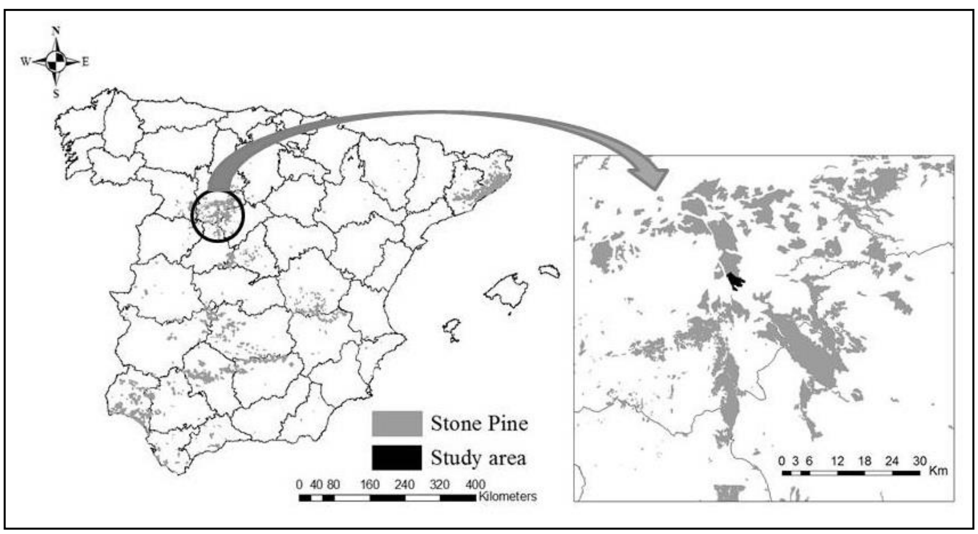

Figure 1. Distribution of *Pinus pinea* stands in Spain and location of the study area.

The thinning trial was carried out using a randomized complete block design, with three blocks and three treatments per block. The plots, nine 2500 m^2 adjacent squares (50 m x 50m), were thinned from below immediately after trial establishment eliminating small trees, trees with badly shaped crowns, twisted stems, less vigorous and dominated trees providing remaing trees enough growing space and water and nutrients which are scarce in these sandy soils. Selection of future or elite trees was rejected because the stand was too young at the installation moment. Three treatments were tested: heavy thinning (goal density: 275 trees ha^{-1}), moderate thinning (goal density: 350 trees ha^{-1}) and control (517 trees ha^{-1}). Due to the differences in dominant height three blocks were established. The dominant heights of the blocks I, II and III were 6.68 m, 7.20 m and 7.82 m respectively. The block effect is due to the difference of sand stored in the soil which is related to the water retention in the soil. The average attributes of the stand treatments are shown in Table 1.

Table 1. Average attributes of the stand treatment before and after thinning treatment at the installation year and quantification of the thinning developed.

	Before thinning				Stand removed			After thinning			
	Ho	N	Dg	G	N	Dg	G	Ho	N	Dg	G
Treatment											
Control	7.13	517	15.18	9.34	-	-	-	7.13	517	15.18	9.34
Moderate	7.09	456	15.50	8.59	104	11.17	1.00	7.09	352	16.55	7.59
Heavy	7.48	521	15.54	9.87	239	12.45	2.92	7.48	282	17.69	6.95

Ho=dominant height (m), N=density (trees ha^{-1}), Dg=quadratic mean diameter (cm) and G=basal area (m^2 ha^{-1}).

All trees in the nine plots are identified in order to facilitate data gathering. Six inventories (2004, 2007, 2009, 2010, 2011 and 2012) were carried out and the following data was collected: diameter at breast height (dbh) of all trees, the height of 30 trees proportionally situated throughout the diametric distribution, and the height of the 10 thickest trees per plot in order to estimate the dominant height (*Ho*).

In addition, cones from the trees used to calculate the average height were collected (30 trees per plot proportionally situated throughout the diametric distribution), counted and quantified their fresh weight each autumn between 2005 and 2012. They were classified into healthy and unhealthy cones. Unhealthy cones were attacked by *Dioryctria mendacella* Stgr. (Lepidoptera) and *Pissodes validirostris* Gyll. (Coleoptera).

Dependent variables

The effect of different thinning intensities on growth was evaluated by analyzing both stand and average tree attributes as dependent variables. The variables analyzed were: *di*, tree diameter increment (mm year^{-1}) (diameter increment of each single tree); *hi*, height increment (cm year^{-1}) (height increment of each single tree); *Ho*, dominant height (m); *HoI*, dominant height increment (cm year^{-1}); *Dg*, quadratic mean diameter (cm); *DgI*, quadratic mean diameter increment (cm year^{-1}); *G*, basal area (m^2 ha^{-1}) and *GI*, basal area increment (m^2 ha^{-1} year^{-1}).

In order to evaluate the effect of the three treatments on the cone production, the following variables were analyzed: *n_healthy* (number of healthy cones per tree); *w_healthy* (weight of healthy cones per tree).

Statistical analysis

The available data consisted of repeated observations of a variable taken from the same tree, block and plot during different years. Measurements taken on the same tree are more highly correlated than measurements taken on different trees, and measurements taken closer in time on the same tree are more highly correlated than measurements taken further apart in time. This pattern of correlation between observations implies that assumptions about error variance being independent and homogenous are no longer valid (Wolfinger, 1996; Littell *et al*., 2000). The analysis of repeated measurements requires that correlations between the observations made on the same subject be taken into account as well as possible heterogeneous variances among observations on the same tree over time. In this study this is achieve using a mixed linear model specifying a model for the covariance structure of the data.

Thinning effects on growth

The hypotheses of no differences among thinning treatments averaged over the six inventories, and whether their effects change over time or not was tested using the following analysis of variance (ANOVA) mixed model:

$$y_{ijkl} = \mu + w_i + h_j + wh_{ij} + b_l + s_{lk} + bh_{lj} + \varepsilon_{ijkl} \qquad (1)$$

where y_{ijkl} indicates the value of the response variable taken in the sampling unit (tree or plot) k with treatment i, located in a block l; μ represents the intercept of the model or overall mean; w_i is the fixed effect treatment i; h_j is the fixed time effect (periods between inventories for increments and inventories for growth); wh_{ij} is the fixed interaction effect corresponding to treatment i and time j; b_l is the random effect of block l; s_{lk} is the random sampling unit effect k in block l and bh_{lj} is the random interaction corresponding to blocks and time j. b_l ,s_{lk}, and bh_{lj} are random effects following a normal distribution with mean zero and variance σ_b^2, σ_s^2 and σ_{bh}^2 respectively. Finally, ε_{ijkl} is a random error term defining within-subject pattern of variability. In the case of tree diameter increment (*di*) the diameter at the beginning of the period (d_{kj}), i.e., previous diameter inventory was taken as covariate.

Model *(1)* represents the complete model. The simplest structure, including only the fixed part of the model and without random effects was compared with more complicated models with random structures. Contrasts were performed by applying restricted log-likelihood test after restricted maximum likelihood (REML) estimation. Variance-covariance structures for within-subject observations were then evaluated on the basis of the log-likelihood ratio test and Akaike´s Information Criterion (AIC): variance components (VC), compound symmetry (CS), autoregressive order 1 (AR-(1)), Huyhn-Feldt (H-F) and unstructured (UN). In order to explore the data in more detail, significant ANOVA-effects were further investigated usinge Tukey’s post-hoc test. All analyses were carried out using SAS 9.2 Proc MIXED (SAS, 2009).

Thinning effects on cone production

As stated above, cone crops fluctuate over the years and fluctuation can be mainly attributed to meteorological conditions of the three years reproductive cycle. Stone pine bud formation takes place 3 years before cone maturation (Mutke *et al*., 2005), and therefore thinning effects (more resources availability) do not appear until 3 years after thinning treatment i.e., cones harvested in 2005 and 2006 came from female flowers sprouted in 2003 and 2004 and buds were formed the previous year during 2002 and 2003 respectively, before thinning treatment. To take these two issues into account, we evaluate the influence of thinning treatment on cone production by a linear mixed model including in the modeling data number and the weight of healthy cones per tree and year from 2007 to 2012 and rainfall variables related to key points of cone formation and development. The number and weight of healthy cones do not follow a normal distribution because of the dramatic number of zeros, 81.41 % from 2007 to 2012. First, a logistic regression was used to estimate the probability of finding a cone in a tree according to thinning intensity, and then, the influence of treatment on crop was evaluated only for the non-zero events.

We used logistic regression to model the probability that a tree *i* produces at least one cone in a single year *j*. The dependent variable *n_healthy* (number of healthy cones per tree) was transformed into a binary variable logged bin where value "1" implies *n_healthy* > 0 and "0" implies *n_healthy*=0. We used a Generalized Linear Mixed Model with a logit link function, random effects and repeated measures to test the effects of explanatory variables on the binary cone production data. Let π_k be the probability of *n_healthy* > 0 and 1- π_k as the probability that a tree produces no cone. Odds is defined as $\pi/(1-\pi)$.

$$\log it(\pi) = \log\left(\frac{\pi}{1-\pi}\right) = \mu + w_i + \alpha x_{ijkl} + b_l + s_{lk} + \varepsilon_{ijkl} \qquad (2)$$

All the model parameters have been defined previously; except *x* which represents vectors of covariates (corresponding to different levels depending on the covariate), *α* which represents vectors of the unknown but estimable parameters. We included as covariates the stand age and some rainfall variables (data series from the nearest weather station of the State Meteorological Agency (AEMET, 2012)): i) sum of May and June, and October and November precipitation 3 years before maturation (*Pmj* and *Pon* respectively). *Pmj* is related to formation of buds and *Pon* to the differentiation of buds into flower and growth buds. ii) summer precipitation after flowering and conditions the survival of flowers (*Ps*). iii) the sum of winter-spring months precipitation before maturation (*Pws*), which influences on cone weight. In addition, we incorporated diameter at breast height dbh as covariate since diameter is positively correlated with cone production (Krannitz and Duralia, 2004; Calama *et al*., 2008, Calama *et al*., 2011).

Moreover, the model can also be interpreted as the log of odds back to the probability such that:

$$\pi_{ijlk} = \frac{e^{\mu + w_i + \alpha x_{ijkl} + b_l + s_{lk} + \varepsilon_{ijkl}}}{1 + e^{\mu + w_i + \alpha x_{ijkl} + b_l + s_{lk} + \varepsilon_{ijkl}}} \quad (3)$$

For any given value of $\mu + w_i + \alpha x_{ijkl} + b_l + s_{lk} + \varepsilon_{ijkl}$, π_{ijkl} values (probability of finding a cone in a tree *k* with treatment *i*, in the block *l* and the year *j*) are always between 0 and 1. Therefore, we only get sensible realizations (Zuur *et al*., 2009).

Analysis was conducted using SAS 9.2 Proc GLIMMIX (SAS, 2009). In order to avoid over-parameterization an iterative sequential procedure was proposed to define the appropriate model for each response variable. Firstly, the simplest structure with only the treatment as fixed effect and without random effects was compared with more complicated models with random structures. Inclusion of random effects and selection of covariance matrix followed the same procedures described for growth models. Once the preliminary random structure was selected and the within-subject covariance matrix was chosen the inclusion of covariates was evaluated in terms of the log-likelihood ratio test, applied after pseudo maximum likelihood estimation. When the structure had been defined, the model was fitted following residual likelihood. The disadventage of pseudo-likelihood is the absence of a true log likelihood, which complicates model comparsisons and model selection based on information criteria (Schabenbeger, 2007). The GLIMMIX Procedure implements two integral approximation techniques to marginal likelihood: Laplace´s method and quadrature approximation which do not allow R-side random effects (SAS, 2009) and, therefore, they do not tolerate repeated measures.

Once the probability that a tree produces no cone was modelled, the effect of thinning treatments on cone production was evaluated using non-zero weight cone values. Weight values, even when not considering zero events, do not follow a normal distribution, so a logarithmic transformation was employed. The proposed mixed model was:

$$\log\left(C_{ijkl}\right) = \mu + w_i + \alpha x_{ijkl} + b_l + s_{lk} + \varepsilon_{ijkl} \qquad (4)$$

where C_{ijkl} is the weight of cone production for a tree *k* with treatment *i*, in the block *l* and the year *j*. All the parameters have been defined above. The methodology for model building was the same as used for the probability logistic model but using true likelihood. Analysis was carried out using Proc MIXED (SAS, 2009).

Results

Thinning effects on growth

In the case of tree diameter increment, treatment, time and the interaction treatment x time were statistically significant (p-value<0.0001 for all of them), indicating that trees with different thinning treatments had different diameter growth rates over time. Further analysis indicated that tree diameter growth was greater in thinned plots than in control plots in the second, fourth and fifth growth intervals but we did not find significant differences between moderate and heavy thinning (Figure 2). The tree diameter increments were decreasing since thinning development (2004) to the last inventory (2012) except in the fourth period (2010-2011) when the highest increments were found. Moreover, the diameter at the beginning of each period was also significant (p-value=0.0045). It had a weak negative influence (estimation coefficient=-0.00331) on tree diameter growth, ie. increments were larger when tree diameters were thin. The values of tree diameter increment were higher in released stands than those trees located in unthinned stands. Concerning the random effect, the block, was significant in terms of the log-likelihood ratio test. The best structure for within-subject covariance was the unstructured (UN) matrix indicating the existence of a common pattern associated with the tree effect, but no clear trends of correlation among tree observations (Littell *et al*., 1996).

In the case of tree height increment, treatment and time were also found to be statistically significant (p-value=0.0260 and p-value<0.0001 respectively). However, interaction treatment x year was not significant (p-value = 0.1505), indicating that effect of thinning is constant in time. Significant differences only appeared between heavy thinning and control treatment (Figure 3). Block effect also improved the model in terms of the log-likelihood ratio test. The Huyhn-Feldt structure for the variance-covariance matrix (HF) reached the lowest AIC value.

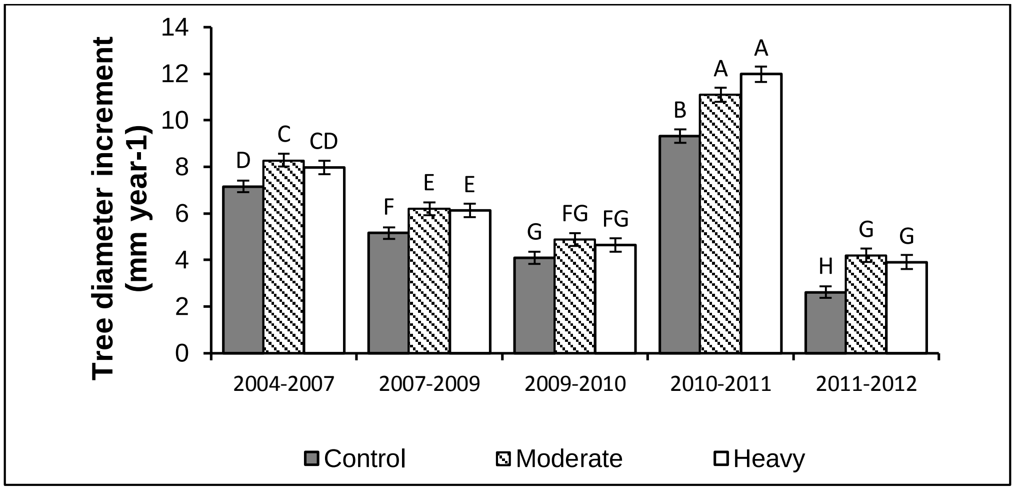

Figure 2. Average and standard error of tree diameter increment according to Type III test for fixed effects. Treatments marked with same letter are not significantly different (p-value >0.05).

As regards plot variables, thinning treatment and time had significant effects on basal area and quadratic mean diameter (p-value>0.0001 for both effects) but the interaction treatment x year did not (p-value=0.8286 and p-value=0.2514, respectively). The effect of thinning in both variables is inverse, thinning significantly decreased the basal area while increasing the quadratic mean diameter (Figure 3). In both variables the block random effect was included and the unstructured (UN) matrix was selected as the best covariance structure.

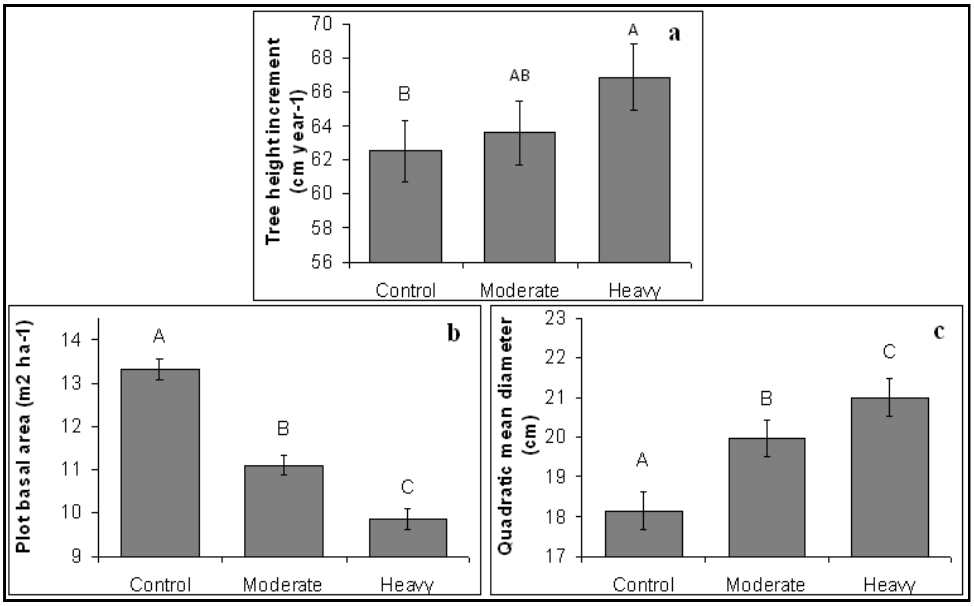

Figure 3. Average and standard error of tree and stand attributes significantly and time constant affected by thinning according to Type III test for fixed effects. Treatments marked with same letter are not significantly different (p-value>0.05) according to Tukey´s test.

The remaining variables analyzed were not statistically influenced (p-value>0.05) by the treatment or treatment x time and results are not shown.

Thinning effects on cone production

The cone production, once extrapolated taking into account 30 sampled trees per plot were proportionally selected throughout the diametric distribution, the average production of control, moderate and heavy plots was 34.4 kg ha^{-1} $year^{-1}$, 50.8 kg ha^{-1} $year^{-1}$ and 43.4 kg ha^{-1} $year^{-1}$ respectively since 2005-2012. Regarding modeling data, from 2007 to 2012 the control plots produced 14.9 kg ha^{-1} $year^{-1}$, the plots with moderate thinning 39.3 kg ha^{-1} $year^{-1}$ and the plots with heavy thinning 32.8 kg ha^{-1} $year^{-1}$. Fig. 4 shows the average cone production per plot and years according to the tree treatments. It can be seen that there was great variability among the years. Both the number and weight of cones oscillated with minima in 2007 and 2012, and peaks 2005, 2006 and 2009 (Fig. 4). The weight per cone behaved similarly; it ranged from 0.198 to 0.255 kg per cone. From 2005 to 2012, 76.22 % of the observations were null, i.e., at least one cone was found in only 23.78 % of the measurements at least a cone were found. Furthermore, more than 70% of the trees produced at least one cone during the period 2005-2012.

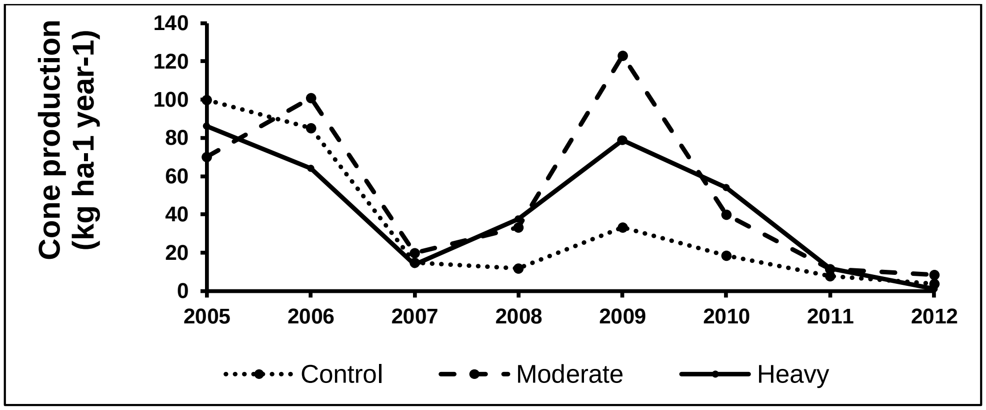

Figure 4. Average cone production per hectare according to treatment after extrapolation of 30 selected trees per plot cone production.

Concerning the probability of finding at least one cone in a given tree, the final chosen model contained just the treatment as fixed effect. In terms of pseudo-likelihood, none of the covariates analyzed improved the model (Table 2) and, therefore, they were not included in the final model. The ratio of the generalized chi-square statistic and its degrees of freedom was 0.90, indicating that the variability in this data has been properly modelled and that there was not residual overdispersion (Schabenberger, 2007). The best covariance structure was CS pointing out a constant correlation among tree observations. The treatment effect was significant for the probability of finding cones in a tree (p-value <0.0001). No significant differences between heavy and moderate thinning were found (p-value = 0.9939). In both cases, the probability of finding at least one cone in a tree is about 23%. This probability is reduced by half in the control treatment, with significant differences between thinned plots and control plots appearing (p-value < 0.0001 for both contrasts) (Table 3).

Table 2. Estimates of the fixed effects parameters and covariance components for cone production variables (only shown for significant effects p-value<0.05). p-values are referred to Type III test for fixed effects.

Source	Probability	Source	Log of weight cones
Fixed parameters			
Intercept	-2.2391	Intercept	2.0327
Heavy	1.0287	Heavy	0.1382
Moderate	1.0474	Moderate	0.1342
Control	0	Control	0
		Ps (summer precipitation)	0.002050
		dbh	0.001577
Covariance component			
Tree – CS	0.02231	Block	0.007337
		Tree – CS	0.06578
p-value treatment	<0.0001	p-value treatment	0.0084
		p-value *Ps*	0.0040
		p-value *dbh*	0.0010

Table 3. Probability mean and its confidence limits and least squares mean estimate on logit scale and its 95% confidence limits. Different letters indicate significant differences (p-value<0.05) according to Tukey´s test.

Treatment	Probability scale			Logit scale		
	Mean	Lower mean	Upper mean	Estimate	Lower	Upper
Heavy	0.2296 (A)	0.1890	0.2761	-1.2104	-1.45680	-0.9640
Moderate	0.2330 (A)	0.1916	0.2801	-1.1917	-1.43960	-0.9438
Control	0.0963 (B)	0.0698	0.1315	-2.2391	-2.5904	-1.8877

There was a significant effect of treatment (p-value=0.0488) on the logarithm of non-zero weight cone values. The most productive treatments were heavy and moderate thinning. However, Tukey´s test did not reveal significant differences between both thinning treatments (p-value=0.9933). Heavy thinning was different from control treatment (p-value=0.0114). Also, significant differences appeared between moderate thinning and control (p-value=0.0131). Ps, summer precipitation after flowering, was the only rainfall covariable that showed statistically significant influence (p-value=0.0040) on cone production (Table 2). Finally, diameter at breast height, dbh, also appeared as significant (p-value=0.0010). Both co-variables showed a positive influence on stone pine cone production.

Discussion

Thinning effects on growth

In this study, two thinning treatments (moderate and heavy) and one control one were applied in a 20-year-old *Pinus pinea* stand. As expected, thinning favored diameter growth. Similar results were found for other pine stands between 20 and 30 years old. Cooley (1970) and Pukkala *et al*. (1998) already found differences in diameter growth 5 years after first thinning. Guller (2007) found a significant relationship between thinning intensity and diameter increment. Peltola *et al*. (2007) reported higher growths in thinned stands 12 years after first thinning. However, we found significant differences among unthinned plots and thinned plots but there did not appear any difference between thinning regimes. This might be a consequence of the soft difference between both thinning goal densities. A heavier thinning could show larger tree diameter increments. In younger stands than ours, the effect of pre-commercial thinning already produced diameter growth increments in stone pine (Gordo *et al*., 2009). We suggest that the cause of the appearance of the largest tree diameter increments six years after thinning development (during 2010-2011) is the great rainfalls registered in 2010.

The diameter at the beginning of the period was significant, in that the smallest trees had the greatest diameter growth. The Calama and Montero (2005) growth model for stone pine included diameter at breast height as a negative effect on tree diameter increment. Pukkala *et al*. (1998) also found that thin trees showed larger diameter growth. Peltola *et al*. (2007) reported that regardless of thinning intensity, the small and medium sized trees grew more in relative terms in response to the thinning than the largest trees. However, they found that the largest trees grew more in absolute terms.

Our results show that heavily thinned plots had lower values of basal area than the non-thinned plots, even cumulative basal area, i.e. current basal area plus basal area removed in the thinning, is lower in thinned plots. Hasenauer *et al*. (1997) studied the effect of thinning on basal area in young plantations of loblolly pine (*Pinus taeda* L.) finding that at least 12 years after the thinning the basal area of control plots exceeds those of thinned plots.

In Mediterranean forests, competition appears, characterized by a severe summer drought during the period of high temperatures, due to competing for water and nutrient resources. Even in the case of low density of stone pine stands, as supramediterranean pine species, competition also exists from seedling state both in naturally and artificially regenerated stands (Tang *et al*., 1994). Therefore, development of silvicultural treatments in order to reduce density in each site index and stand age is primordial to optimize wood and cone production.

Thinning effects on cone production

In this study we analyzed crop weight per tree which is function of both the number of cones per tree and their weight. The number of cones is counting data and its statistical problems have been described above. The use of the probability of finding a cone in a tree allowed to complement the effect of thinnings on crop weight. To this end we used logistic regression. Logistic regression techniques have been used in the field of forestry to predict mortality (Bravo-Oviedo *et al*., 2006; Adame *et al*., 2010), ingrowth (Adame *et al*., 2010), and to predict fruit and cone production (Calama *et al*., 2011). We found that thinning favored the probability of finding at least one cone in a given tree, being more than the double in thinned than in control plots.

The fact that bud formation takes place 3 years before maturation and the thinning treatment was carried out in 2004, implies that cones harvested in 2006 and 2005 came from buds formed before the thinning treatment. Therefore, the harvest of 2007 is the first one to be considered under thinning effects. Until 2007 the differences between treatments were weak and since 2007 control plots showed lower production. This was more evident in bumper crop years, where the difference between thinned and control plots was larger. Overall, the greatest cone production appeared in thinned plots, reaching more the twice the production in thinned stands than control stands. Reukema (1961) found a similar result. He reported that thinned stands of young Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) produced much more seed than unthinned stands in good years, but thinning does not stimulate seed production in poor seed years. At the end of our study period, trees located in thinned plots produced almost two times the number of cones and they reached double of the cone production in weight. In a 20 year old *P. resinosa* plantation on a good site, Cooley (1970) reported the number of mature cones per tree was increased two years after thinning. Our results are also in concordance with Karlsson (2000), who studied seed production of mature Scots pine stands after release cutting. His results showed that released trees produce much more cones than the unreleased. Thinning treatment allows crowns to be exposed to more light and the availability of water and mineral nutrients is higher (Karlsson, 2000; Krannitz and Duralia, 2004) because of less inter-tree competition. Actually, Gonçalves and Pommerening (2012) found an inhibition of cone production between trees close in space and stimulation at larger distances. However, we did not find important differences between two thinning regimes. We suggest a small difference between heavy and moderate intensities and, therefore, the development of heavier thinnings to promote larger crops per tree. Moreover, more trials are needed to find out when first thinning should be carried out in each site index.

Although we did not find differences in cone production between moderate and heavy treatments, the harvest effectiveness is higher in heavily thinned plots since production is located in less trees and, in this way, both manual and mechanized harvesting reach greater yields.

When we carried out the statistical analysis by performing mixed model with the log of cone weight production being the dependent variable differences between treatments appeared with the significant difference between thinned treatments and control plots. Log transformation was already used by other authors (Mutke *et al*., 2005; Calama and Montero, 2007) to study stone pine cone production. However, instead of removing null weight values to perform statistical analysis, they applied the log transformation of the cone weight plus 1 to delete zero values since they were studying older stands than ours which were more productive and null values were shorter.

Regarding the effect of climatic variables on log of cone weight production, the only variable that appeared as significant was the *Ps*, summer precipitation after flowering, related to flower survival and, therefore, number of cones. The other rainfall variables (*Pmj*, *Pon* and *Pws*) are related to bud survival and cones fattening. In older stands, Calama *et al*. (2011) found all of rainfall variables considered in our study to be statistically significant. Mutke *et al*. (2005) studied meteorological effects on cone production in mature stands of stone pine. They found that cone production was significantly affected by winter/spring rainfall before primordia formation (3 years before cone maturation), rainfall in October 3 years before cone maturation, the rainfall of winter/spring before pollination and the annual rainfall before cone ripening. Null influence of these precipitation variables can be explained by short data series and the fact that pines are young and they did not reach normal and regular cone productions. We suggest that the stands were quite young and root-competition between trees was weak.

Despite of our short data series, we consider it is enough to compare the effect of the thinnings over the whole study period (not over individual years) since we did not want to identify those factors characterizing masting, or describe pattern of annual production which has already been studied (e.g. Calama *et al*., 2011).

Finally, we found a positive effect of diameter at breast height with cone production. This is in concordance with other authors (Krannitz and Duralia, 2004; Calama *et al*., 2008; Calama *et al*., 2011). Therefore, thinning treatments, on the one hand, reduced the density decreasing inter-tree competition and favoring cone production and, on the other hand, increase diameter growths and, hence, promote larger crops.

Conclusions

We observed a positive effect of the density reduction on the growth of young stone regenerated artificially pine stands. Also, cone production increased by employing early thinning treatments. However, we did not find significant differences between moderate and heavy thinning both on tree diameter growth and cone production and, despite of our short data series, our results suggest to carry out heavier thinnings to favour individual tree cone production. Wider knowledge about starting thinning age in each site index is necessary.

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