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Thinning has a positive effect on growth dynamics and growth–climate relationships in Aleppo pine (*Pinus halepensis*) trees of different crown classes

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Abstract

• **Context** Modification of stand density by thinning may buffer the response of tree growth and vigor to changes in climate by enhancing soil water availability.
• **Aims** We tested the impact of thinning intensity on cambial growth of Aleppo pine (*Pinus halepensis* L.) under semi-arid, Mediterranean conditions.
• **Methods** A multiple thinning experiment was established on an Aleppo pine plantation in Spain. We analysed the stem growth dynamics of two different crown classes under four different thinning intensities (15 %, 30 %, and 45 % removal

of the basal area) for 2 years, based on biweekly band dendrometer recordings. Local relative extractable soil water was derived from the use of a water balance model Biljou© (available at <https://appgeodb.nancy.inra.fr/biljou/>) and used as an explanatory variable.

• **Results** Radial growth was mainly controlled by soil water availability during the growing season, and differed by crown class. The growth rates of dominant trees were significantly higher than the growth rates of suppressed trees. Removal of 30 % and 45 % of the initial basal area produced a growth release in both dominant and suppressed trees that did not occur under less intense thinning treatments.

• **Conclusions** Soil water availability was the main driver of radial growth during the growing season. Forest management confirmed its value for ameliorating the effects of water limitations on individual tree growth. These results may help managers understand how altering stand density will differentially affect diameter growth responses of Aleppo pine to short-term climatic fluctuations, promoting forests that are resilient to future climatic conditions.

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Contribution of the co-authors Jorge OLIVAR: writing the paper, data analysis, field measurements.

Stella BOGINO: supervising the work

Cyrille RATHGEBER: supervising the work

Vivien BONNESOEUR: data analysis.

Felipe BRAVO: supervising the work, designing the experiment.

The study was carried out at the University of Valladolid.

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Keywords Forest management · Stand density · Dendrometer · Dominant · Suppressed

1 Introductions

In coastal Mediterranean areas, with mild winters and dry summers, cold-season growth dormancy may not occur and, consequently, cambial activity is probably continuous (de Luis et al. 2007). However, in inland areas with continental Mediterranean climate, plants endure double climatic stress, caused by low winter temperatures and summer drought (Mitrakos 1980). As a result, optimal growth conditions are split into two mild periods with higher rainfall (spring and autumn), which suggest a bimodal pattern of cambial activity

(Camarero et al. 2010). Pine stands are the most extensive coniferous forests in the Mediterranean zone, and Aleppo pine (*Pinus halepensis* Mill.) is one of the dominant tree species in the Western Mediterranean Basin and the most ecologically important species in semi-arid woodlands (Néeman and Trabaud 2000). Growth rates of *P. halepensis* may be expected to follow the bimodal pattern described above for trees growing in a continental Mediterranean climate, with maximum values in spring and autumn when precipitation is high and temperatures are mild.

In the Mediterranean climate, water is considered to be the most limiting resource for plant growth (Specht 1981). Nevertheless, trees of different sizes and crown classes compete differently for light, water, and other resources within a stand (Peet and Christensen 1987; Orwig and Abrams 1997). Radial growth responses to climate vary considerably according to local tree density and crown class in areas where water is limiting (Linares et al. 2009). Therefore, contrasting growth responses to climate among trees in different crown classes might be particularly relevant for understanding the dynamics of forests dominated by species that are highly sensitive to drought stress (Adams and Kolb 2004).

Climate change models project a decrease in annual mean precipitation and rising air temperatures over the Mediterranean Basin for the twenty-first century, leading to an increase in evapotranspiration (Parry et al. 2007). If water is a limiting resource, as it is predicted to be, one of the most important measures that forest managers have to moderate the influence of climate on tree growth within stands is to thin to residual stand densities that make more water available for the remaining trees (Martín-Benito et al. 2010).

Although forest managers rely heavily on the use of silvicultural treatments that manipulate stand structure and stand dynamics to modify responses to climate change, few studies have directly assessed the effects of stand structure or canopy position on climate–growth relationships (Carnwath et al. 2012). The effect of different silvicultural treatments and stand densities on tree growth response to climate is likely to be a key aspect for influencing forest preservation, particularly in the driest sites (Gea-Izquierdo et al. 2009). The influence of tree density on tree response to climate and drought is not a straightforward issue, since different approaches (e.g., eco-physiological, dendroecological, growth modelling) might give different insights (Misson et al. 2003; Moreno and Cubera 2008).

Short-term data on growth dynamics are required to understand growth responses in relation to climatic variability at short time scales. Dendrometers are a valuable tool for these studies, since they provide short-term measurements of radial fluctuations in relation to climate without disturbing the cambium. Here, we analysed the stem growth dynamics of *P. halepensis* of two different crown classes under four different thinning intensities for 2 years, based on biweekly band

dendrometer recordings. We expected that short-term variations in climatic factors and water availability were reflected in the entire growth profile. The following hypotheses were tested: (i) soil water content is the main climatic driver of intra-annual variation in growth of *P. halepensis* at our site, representing semi-arid Mediterranean environments, (ii) suppressed trees are more affected by water stress than dominant trees, and (iii) the reduction of stand density through thinning stimulates diameter growth responses that offset declines expected under more severe water limitation.

2 Materials and methods

2.1 Species and study site

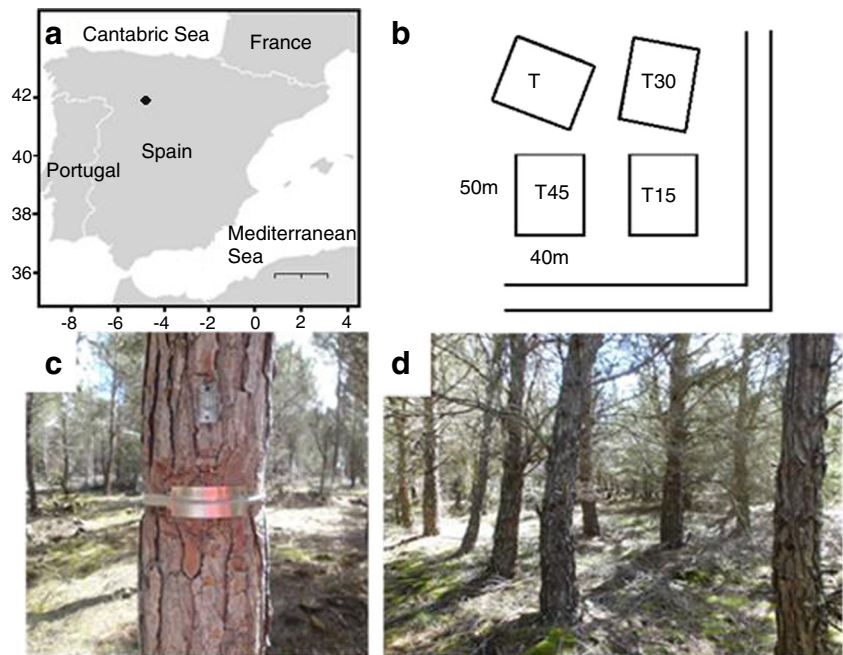
P. halepensis is one of the most studied Mediterranean trees. Forests dominated by this species provide a valuable system to explore how growth measured at different time scales is constrained by climate (Pasho et al. 2012) and it is considered well-adapted to withstand drought by reducing growth as water availability decreases (Rathgeber et al. 2005; de Luis et al. 2007; Camarero et al. 2010; Pasho et al. 2012). The study site is located in a 60-year-old *P. halepensis* plantation in the north of the Spanish Meseta (Fig. 1). The area is characterized by a continental Mediterranean climate, with low winter temperatures and summer droughts. Mean annual temperature was 11.3 °C and average annual precipitation was 418 mm over the last 30 years. The climatic conditions in 2011 and 2012 were among the driest in the late 20th century in Spain. Total annual rainfall was 245 and 244 mm respectively (40 % lower than the average).

2.2 Thinning treatments

Thinning treatments were conducted in autumn 2010 in three stands of similar basal area and stand structure (Table 1). The stand sizes were 40 m × 50 m. Three thinning intensities were considered: 15 % reduction of the basal area (T15), 30 % reduction of the basal area (T30), and 45 % reduction of the basal area (T45), using an unthinned stand as control (T0) (Fig. 2). The reduction of the basal area was based on initial basal area of each stand.

The upper growing stock limit for *P. halepensis* is determined by the criteria of avoiding density-related mortality, which appears when the stand density index (SDI) is over the 60 % of maximum SDI found for each species (Dean and Baldwin 1993). The lower limit establishes the level at which adequate site occupancy is maintained, and can be set at 35 % of maximum SDI for the species (Long 1985). Keeping the stand between these two limits guarantees adequate density for the stand, avoiding density-related mortality that can provide biomass in case of a forest fire. The thinning treatments

Fig. 1 **a** Study area of *Pinus halepensis* in Spain. **b** Large-scale map of the thinning experiment. **c** Band dendrometer (Dendrometer Increment Sensor DB20 EMS Brno). **d** T0 unthinned stand



conducted on pine species in this area usually follow a 30 % reduction of the total basal area, and the marginal thinning intensity (MTI), defined as maximum intensity that can be maintained without loss of volume production (Kula 1988), might be close to a 45 % removal of the total basal area.

2.3 Dendrometer measurements

To estimate the changes in stem increment, 48 stainless-steel band dendrometers (Dendrometer Increment Sensor DB20 EMS Brno) were mounted around the stem at 1.3 m height in 12 randomly chosen trees per treatment: six dominant trees (trees with crowns receiving full light from above and partly from the side) and six suppressed (trees with crowns receiving no direct light either from above or from the sides) in each plot. In most cases, the diameter of dominant trees ranged from 20 to 25 cm and suppressed trees from 10 to 15 cm. However, some suppressed or dominant trees were selected

outside of these respective ranges if their relative position in relation to its neighbours gave them the dominant or suppressed status.

Dead outermost tissue of the bark was smoothly and evenly removed with a rasp before attaching the dendrometer. Removing the bark allowed us to reduce swelling and shrinkage from the bark as a component of the increment dynamics. Dendrometer readings to the nearest 0.01 mm were recorded biweekly over a 2-year period. Readings were done in the morning to reduce diurnal bias because daytime transpiration causes stem shrinkage (Zweifel et al. 2001). Following Keeland and Sharitz (1993), measurements obtained in the first 3 months after installation were discarded for being within the adjustment period of the band dendrometers.

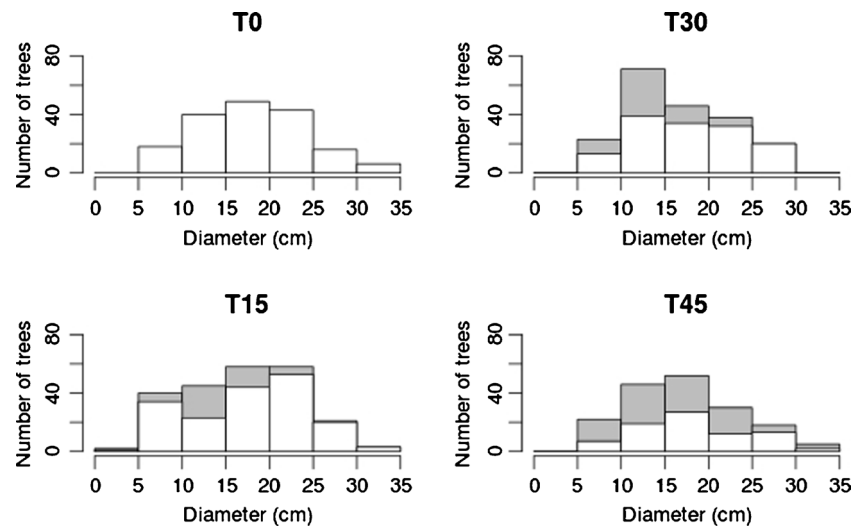
2.4 Statistical analyses

Daily climatic data were measured at the closest meteorological station (data provided by Inforriego and the Spanish Meteorological Agency AEMET). Soil water availability to the trees, which can be characterized by relative extractable water (hereafter abbreviated as REW), was included in the analysis. REW is the daily available water standardized by maximum available water. Water stress is assumed to occur when REW drops below a threshold of 0.4, under which transpiration is gradually reduced due to stomatal closure (Granier et al. 1999). REW was calculated by the daily water balance model Biljou© (<https://appgeodb.nancy.inra.fr/biljou/>) (Granier et al. 1999). This model requires daily potential evapotranspiration and rainfall as input climatic data. Potential evapotranspiration (hereafter abbreviated as PET) was calculated

Table 1 Stand parameters of the four plots. BA Basal area; DBH Diameter at breast height; H_0 Dominant height (mean height of the hundred largest trees per hectare); LAI Leaf area index (projected needle area per unit ground area)

Stand	Thinning intensity	H_0 (m)	Initial BA (m ² /ha)	Final BA (m ² /ha)	Initial mean DBH (cm)	Final mean DBH (cm)	Initial LAI	Final LAI
T0	0 %	10.6	22.6	22.6	18.6	18.6	1.90	1.90
T15	15 %	10.1	27.6	23.5	18.2	18.9	2.19	1.90
T30	30 %	9.4	20.0	14.0	17.1	18.5	1.97	1.45
T45	45 %	9.1	20.5	11.2	17.6	21.2	1.80	1.00

Fig. 2 Thinning treatments. Grey extracted trees. *T0* unthinned stand, *T15* 15 % reduction of the total basal area, *T30* 30 % reduction of the total basal area, *T45* 45 % reduction of the total basal area



with the Penman potential evapotranspiration equation (Granier et al. 1999). Required site and stand parameters are maximum extractable soil water and leaf area index (LAI). Soil properties were measured at the site and considered homogeneous at the four plots (Table 2). LAI controls stand transpiration, forest floor evapotranspiration, and rainfall interception (Granier et al. 1999). LAI was calculated according to López-Serrano et al. (2000):

$$L_t = 0.0536 * D^{2.05}$$

where L_t is the leaf area of individual tree (m^2) and D is the DBH (cm^2); $R^2=85.53$ % (Table 1). The short time between thinning and the start of diameter growth monitoring allows us to avoid the changes in DBH–crown allometrics expected after thinning. The bioclimatic variables (temperature, precipitation, PET, and REW) were averaged (or accumulated in the case of precipitation) over the 5, 15, and 30 days prior to each diameter measurement, in order to determine which climatic variables were the main constraints for growth and at which temporal scales they act. These weather intervals were selected on the assumption that growth responded to weather or climatic variables that prevailed just prior to each growth period.

Table 2 Soil characteristics of the study area included in the model Biljou© (<https://appgeodb.nancy.inra.fr/biljou/>) (Granier et al. 1999)

Variables	Horizon 1	Horizon 2
Dept (cm)	0–30	30–200
Water reserve (mm)	36	48
Roots (%)	75	25
Stones (%)	1	80
Humidity (pF 4.2)	0.0158	0.0158
Apparent density	1.46	1.46

We fitted a linear mixed-effect model using the lme function with R-Package nlme (Laird and Ware 1982). The model was fitted by maximizing the restricted log-likelihood:

$$Gr_{ij} = intercept + \alpha_1 * Clim_{ij} + \sum \alpha_{2ik} * T_k + \alpha_3 * S_i + \alpha_4 * (Clim_{ji} * S_i) + \sum \alpha_{5ik} * S_i * T_i + \mu_i + \varepsilon_{ijk}$$

$$\mu_i \sim N(0, \sigma^2_{Tree})$$

$$\varepsilon_{ij} \sim N(0, \sigma^2_x | Clim_{ij} |^{2\delta})$$

where i indicates the i th tree, j indicates the j th 2-week period, k indicates the thinning intensity, Gr the radial growth, and $Clim$ the mean (or accumulated) values of the bioclimatic variables (temperature, precipitation, potential evapotranspiration and relative extractable water); T is an indicator variable for the thinning intensities:

if $T_1 = 0, T_2 = 0, T_3 = 0$; then thinning intensity is 0%
 if $T_1 = 1, T_2 = 0, T_3 = 0$ then thinning intensity is 15%
 if $T_1 = 0, T_2 = 1, T_3 = 0$ then thinning intensity is 30%
 if $T_1 = 0, T_2 = 0, T_3 = 1$ then thinning intensity is 45%

S is an indicator variable for the status of the tree ($S=0$ for suppressed trees and $S=1$ for dominant trees), μ_i is a tree random effect, and the variance of the residuals is modeled as σ^2 , multiplied by the power of absolute value of the absolute value of covariate $Clim$. The parameter δ is estimated by the model (see Zuur et al. 2009).

The period used for growth and climate analysis corresponded only with the main period of stem growth (Deslauriers et al. 2007). Based on our records, the period between 20 November 2011 and 15 April 2012 was excluded from the analysis. Statistical analyses were performed using R software (R Development Core Team 2011). Initial stand density was similar between sites. However, there were some differences due to microsite effects prevailing in

Table 3 Comparison of the linear mixed-effect model for the different bioclimatic variables (mean or cumulative value for the previous 5, 15 and 30 days)

Variable	Delay (days)	AIC	RMSE
ETP	5	4,565	0.016
	15	4,539	0.015
	30	4,463	0.014
T	5	4,226	0.014
	15	4,155	0.013
	30	4,009	0.012
PP	5	4,165	0.013
	15	4,196	0.014
	30	4,165	0.013
REW	5	3,745	0.011
	15	3,734	0.011
	30	3,978	0.011

AIC Akaike information criterion; *RMSE* root mean square error; *ETP* evapotranspiration; *T* mean temperature; *PP* cumulative precipitation; *REW* relative extractable water (daily available water standardized by maximum available water)

Mediterranean environments. To test the similarity of past radial growth, increment cores were extracted from 15 trees belonging to the four plots. We fitted a linear model using past growth as a response variable, and a mixed model including the plot random effect. The relative goodness of fit of the

models was assessed using the Akaike information criterion (AIC). Since AIC value (4399) did not change when the plot random effect was included, we concluded that there are no significant differences in previous growth between plots.

Climate sensitivity is defined as the degree of growth response to climate variability. Because our growth data are intra-annual, coefficient of variation (hereafter abbreviated as CV), which shows the extent of variability in relation to the mean, was calculated in order to assess the climate sensitivity of the radial increment series. CV was calculated for the radial growth during the 2-week growth periods on each tree, and aggregated for trees within status, plots and years.

3 Results

The results of the linear mixed-effect model applied for each variable (temperature, precipitation, PET, and REW) confirmed that REW was the main bioclimatic variable that influenced tree radial growth at the studied stands. Mean REW of the previous 15 days showed the lowest AIC values (Table 3). The comparison between mean REW of the previous 15 days and radial increment of the four plots can be observed in Fig. 3. It can be observed how thinning intensity increases REW and radial growth.

We fitted the model with mean REW of the previous 15 days (Table 4) as the climatic variable. Results showed

Fig. 3 Relative extractable water (daily available water standardized by maximum available water) and radial increment of *Pinus halepensis* at the four plots. T45: black solid line, T30: grey solid line, T15: black dashed line, T0: black dashed line for REW and grey dashed line for radial increment. Water stress is assumed to occur when REW drops below a threshold of 0.4 (Granier et al. 1999). Grey areas show periods not considered for the analysis

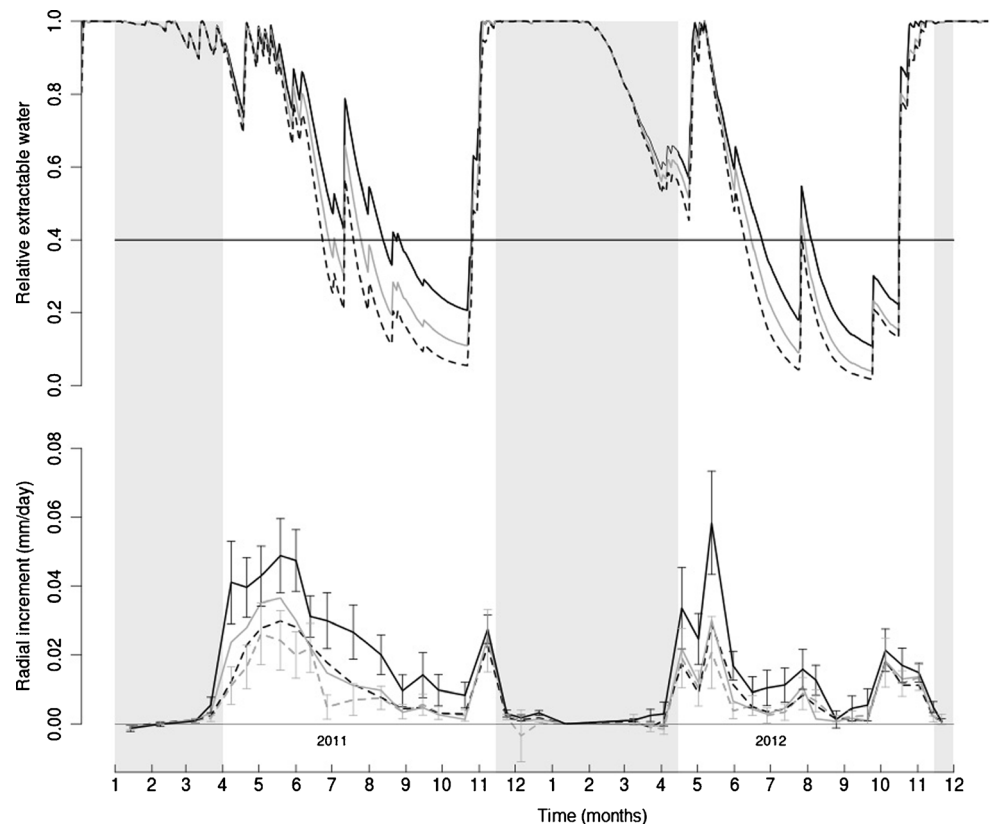


Table 4 Results of the linear mixed-effect model for REW15. Relative extractable water (REW) is the daily available water standardized by maximum available water

Parameter	Value	Std. error	P-value
Intercept	-0.0004	0.0017	0.834
Dominant	0.0049	0.0025	0.055
REW	0.0081	0.0018	<0.0001
T15	-0.0014	0.0025	0.587
T30	-0.0006	0.0026	0.793
T45	-0.0032	0.0026	0.223
Dominant * REW	0.0233	0.0018	<0.0001
T15 * REW	0.0055	0.0023	0.017
T30 * REW	0.0093	0.0024	<0.0001
T45 * REW	0.0248	0.0026	<0.0001
Dominant * T15	0.0005	0.0036	0.896
Dominant * T30	-0.0042	0.0036	0.253
Dominant * T45	-0.0014	0.0036	0.708
σ^2_{Tree}	0.0042		

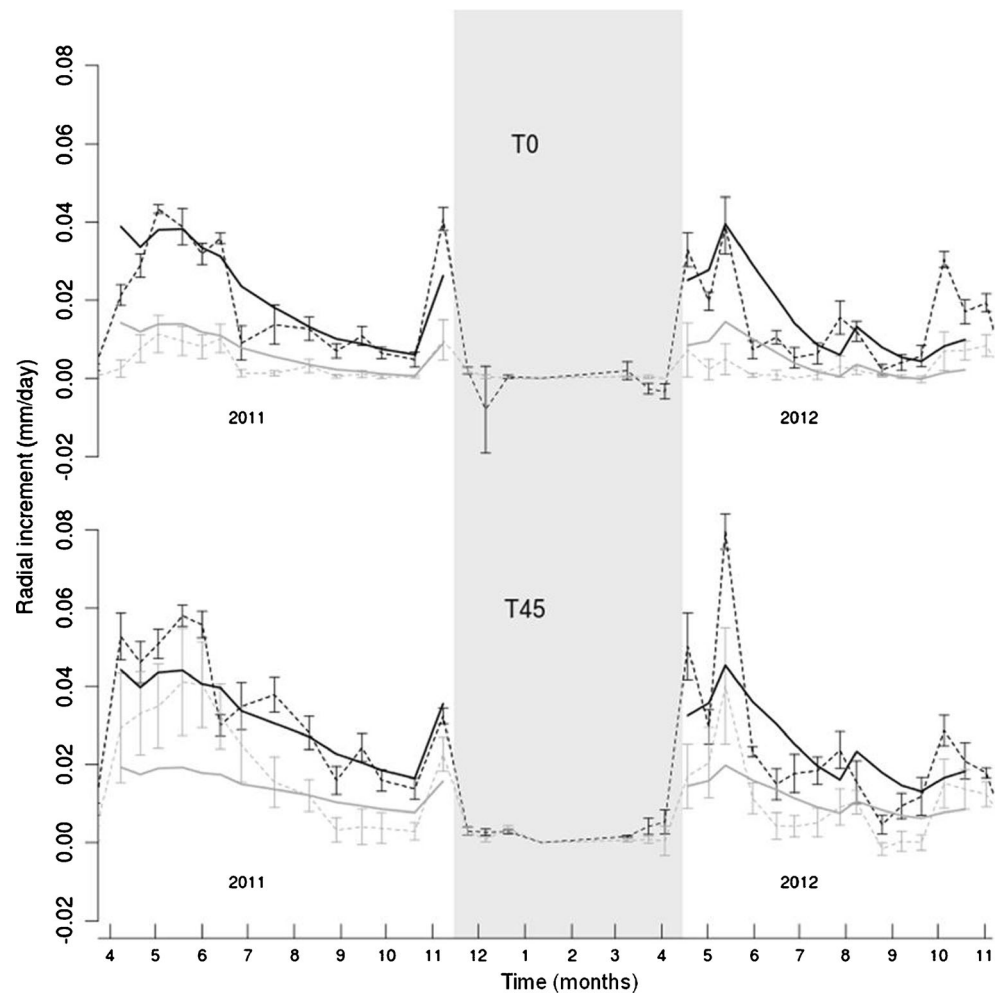
T0 unthinned stand; T15 15 % reduction of the total basal area; T30 30 % reduction of the total basal area; T45 45 % reduction of the total basal area

that dominant trees and trees in T30 and T45 had significantly higher growth rates. The comparison between real growth and predicted values of the model for T0 and T45 are shown in Fig. 4. Model predictions are more accurate for dominant than suppressed trees and for T45 than T0.

Growth patterns of the four stands are described in Fig. 5. The growth dynamics of *P. halepensis* showed a bimodal growth pattern, with two major growth phases in spring and autumn and low rates in late summer and beginning of autumn. The spring maximum increment rate was higher than the autumn maximum increment rate, except for T0 in 2011.

In order to understand how thinning affects the climate–growth relationship, Fig. 6 represents mean radial growth \pm standard deviation predicted by the model for dominant and suppressed trees with low and high soil water availability (REW=0.2 and 0.8 respectively). Soil water availability increases growth rates in all thinning intensities, and the T45 treatment produces a higher radial growth increase than the rest of the thinning treatments for the same REW value.

Fig. 4 Real growth (dashed lines) and growth predictions from the model (solid lines). Black dominant trees; grey suppressed trees. T0: unthinned stand. T45: 45 % reduction of the total basal area. Grey areas show periods not considered for the analysis



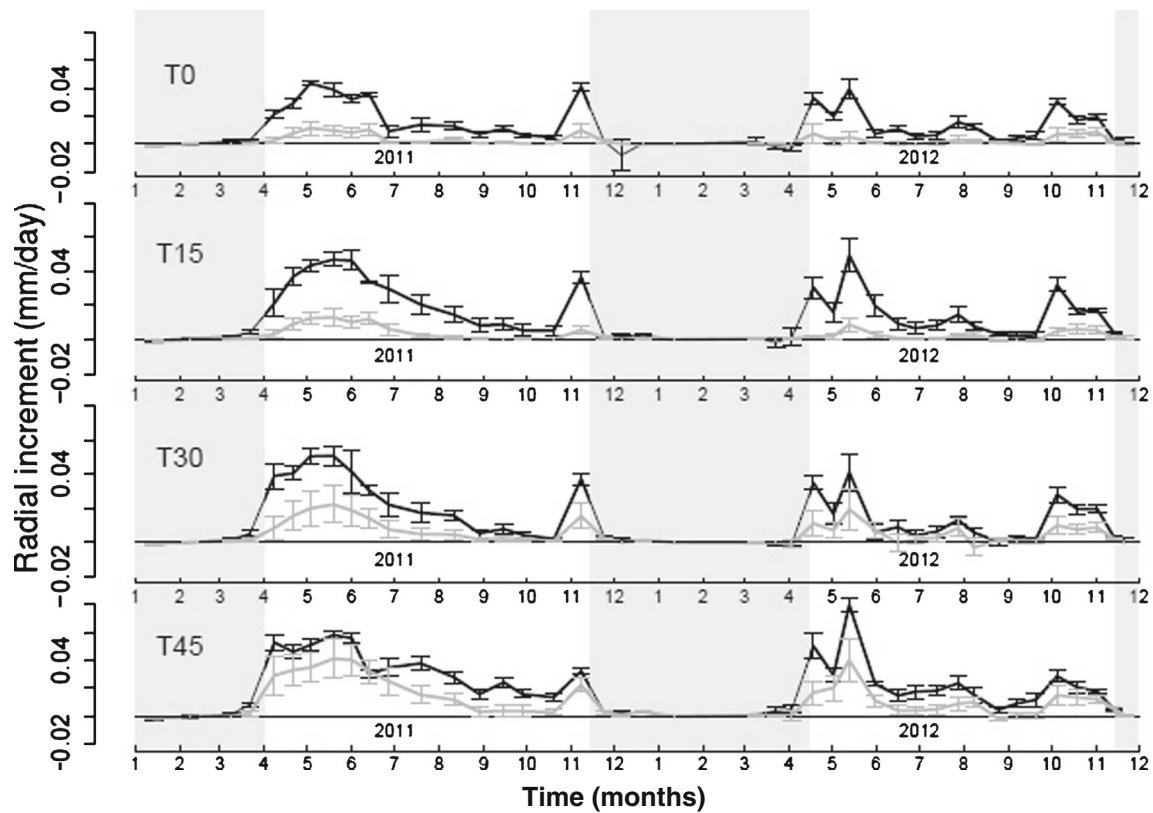
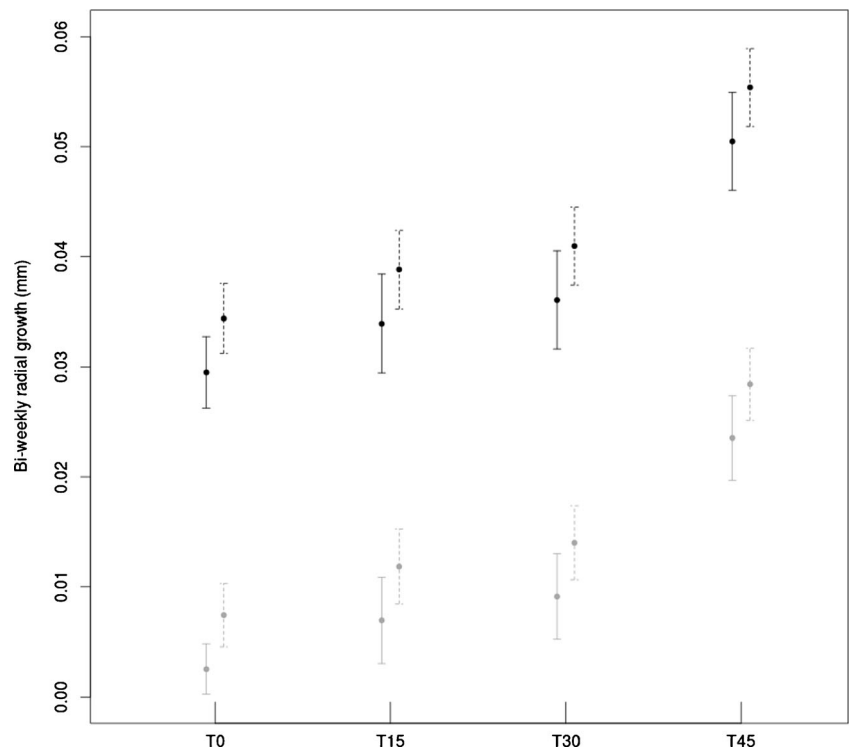


Fig. 5 Growth dynamics of *Pinus halepensis* at the study site. Black line dominant trees; grey line suppressed trees. Grey areas show periods not considered for the analysis

The analysis of the variance of the growth data (Fig. 7) showed that suppressed trees had higher CV values than

dominant trees. T45 showed the lowest CV values in both crown classes during the 2 years of study.

Fig. 6 Climate–growth correlations by thinning intensity and canopy class (mean \pm standard deviation). T0: unthinned stand, T15: 15 % reduction of the total basal area, T30: 30 % reduction of the total basal area, and T45: 45 % reduction of the total basal area. Black dominant trees; grey suppressed trees



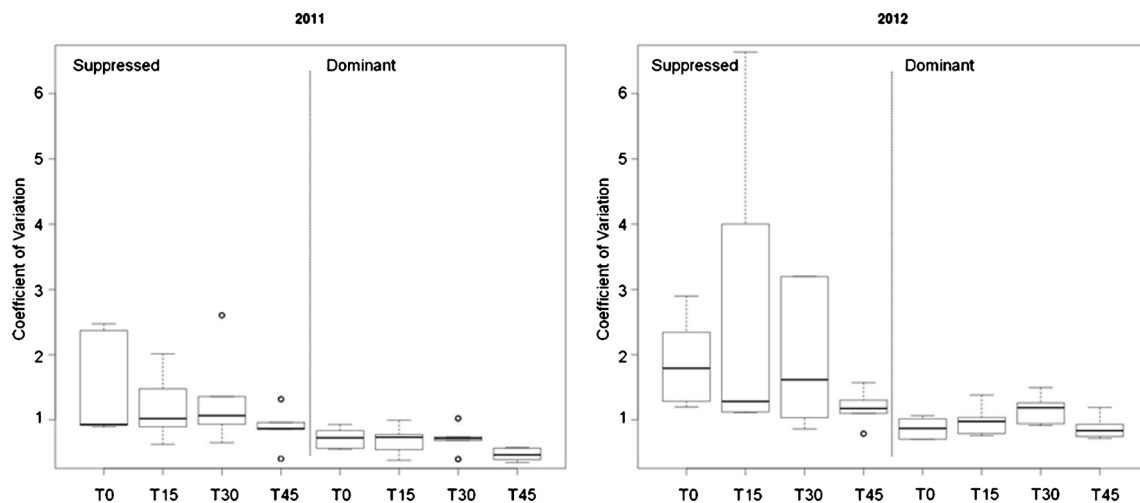


Fig. 7 Coefficient of variation of the growth data of *Pinus halepensis* at the four plots: unthinned stand (*T0*), 15 % reduction of the total basal area (*T15*), 30 % reduction of the total basal area (*T30*), and 45 % reduction of the total basal area (*T45*)

4 Discussion

Dendrometers have been criticized when used to record cambial activity with a high temporal resolution, because of the reversible stem shrinking and swelling (de Luis et al. 2007). These criticisms are, to some extent, justified when dendrometers are used to identify cambial growth onset and ending or differentiate growth from stem water content variation in slow-growing species (Deslauriers et al. 2007). However, several studies have been published in recent years describing stem growth phenology and/or assessing growth–climate relationships (Bouriaud et al. 2005; de Luis et al. 2007; Gea-Izquierdo et al. 2009; Linares et al. 2009; Camarero et al. 2010; Gutiérrez et al. 2011). In our study, removing the bark and the fixing interval of the day during which stem radius variation was measured allowed us to improve precision by eliminating effects of bark irregularities and subtle sloughing, and to reduce swelling and shrinkage as a component of the increment dynamics (Zweifel et al. 2001).

REW is the main bioclimatic variable which influences tree radial growth at the studied stands. These results add information to previous inter-annual studies on the same stands (Olivar et al. 2012) that defined monthly rainfall as the main climatic driver of tree growth. The utilisation of soil moisture rather than rainfall is less susceptible to confounding between the effects of water and temperature in the growth response function. Furthermore, soil moisture has more biological meaning than precipitation because it better reflects water availability for trees. These points are particularly relevant for studies performed in Mediterranean regions (Rathgeber et al. 2005).

In the Mediterranean area with a continuous water deficit, at least for *P. halepensis*, wood formation reflects environment conditions for most of the year, and a precipitation event is generally followed by an increase in growth within a week

after the event (Attolini et al. 1990). Water availability is expected to be the major limiting factor for growth under a Mediterranean climate, and its influence decreases with altitude in the Mediterranean region, with temperature showing the opposite trend (Cherubini et al. 2003). There is a general idea that radial growth is primarily dependent on the short-term water availability, which affects the actual tree water status and xylogenesis (Eilmann et al. 2009). In the studied stands, the influence of REW on dominant trees was significantly higher than on suppressed trees. In drought-stressed environments, suppressed trees usually have shallower and less developed root systems than dominant trees, and less moisture is available to them (Van Lear and Kapeluck 1995). Therefore, the amount of available water for suppressed trees is limited to the short-term water reserves concentrated in surface soil layers; while dominant trees, with more developed root systems, can access deeper soil water reserves accumulated over a long period of time (Camarero et al. 2010), inducing higher vulnerability of suppressed trees to water stress.

The growth dynamics of *P. halepensis* had two major growth phases during the growing season, one in spring and another in autumn, interrupted by a period with low or no cambial activity during late summer as a result of drought and high temperatures (Cherubini et al. 2003). This pattern of xylem production is responsible for the frequent formation of intra-annual density fluctuations observed in this species (Olivar et al. 2012). Stem growth started in mid-March in 2001 and April in 2012, when temperatures were high enough for vegetative growth, and stopped growing at the end of November in both years, when temperatures were too low. The radial growth pattern of *P. halepensis* was asymmetrical, with most of the annual growth occurring in spring. The maximum growth rate in spring was the highest of the year except for *T0* in 2011, where the autumn maximum growth

rate was higher. Growth patterns of *P. halepensis* showed high-plasticity in response to climatic conditions during the growing season, which may be an advantage in areas with a Mediterranean climate where the annual rainfall pattern is variable (Gutiérrez et al. 2011). *P. halepensis* has been characterized as a sensitive Mediterranean species based on the strong response of growth dynamics to changes in climatic conditions (Lev-Yadun 2000). It has also been suggested that the cambium is able to remain active throughout the whole year if climate conditions are favourable (Lipshitz et al. 1984).

Growth rates prior to thinning proved to be not significantly different among the experimental units, suggesting that the thinning intensities were sufficient to cause differences in diameter growth rates. Specifically, we can conclude that T30 and T45 thinning treatments were able to induce a growth release on both crown classes that did not occur under less intense thinning treatments. Thinning is less effective on dry sites if it is not intense enough, because inter-tree competition for water is stronger and drier sites cannot support stands of sufficiently high density to warrant thinning (Cotillas et al. 2009; Linares et al. 2009; Moreno and Cubera 2008). Thus, a high residual stand density that is not sufficiently reduced by thinning, coupled with the more limiting climatic conditions, should have obscured the advantages of thinning on less intense thinning treatments (Misson et al. 2003).

Growth variability was higher in suppressed than in dominant trees. T45 showed the lowest CV values in both crown classes, which means higher homogeneity of the growth data. Tree growth responses to climate are highly context-dependent (Carnwath et al. 2012). However, these results are in agreement with the idea that in semi-arid environments, suppressed trees usually have more limited access to soil water reserves than dominant trees, due to their shallower and less developed root systems, especially in high density stands. Therefore, their growth rates fluctuate depending on short-term water reserves concentrated in surface soil layers, while dominant trees with more developed root systems and suppressed trees in thinned stands and therefore better access to water show more homogeneous growth rates.

The reduction of stand density through thinning has been suggested to improve the resistance of individual trees to drought stress and the extent of this differential response changes within the same species along climatic gradients (Misson et al. 2003; Moreno and Cubera 2008; Gea-Izquierdo et al. 2009). However, open stands should not be concluded to be universally desirable (Gea-Izquierdo et al. 2009). Forest managers should retain adequate stand density to mitigate the effect of climatic extremes, taking other ecosystem parameters such as regeneration or soil protection into account. Less dense and more diverse stands could be promoted by mixing species with different drought resistance to avoid or limit further growth declines in plantations.

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