Article

The Impact of Climate and Adaptative Forest Management on the Intra-Annual Growth of *Pinus halepensis* Based on Long-Term Dendrometer Recordings

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Abstract: Future climate predictions for the Mediterranean area include prolonged droughts and an increase in the frequency of extreme events. Silvicultural modification of stand density can buffer the response of tree growth to changes in climate by enhancing soil water availability. We analyzed the stem growth dynamics of *Pinus halepensis*, including the days of the year when 25%, 50% and 75% of the intra-annual basal growth was achieved, considering two different social statuses (suppressed and dominant) under four different thinning intensities (15%, 30% and 45% removal of the basal area) for 8 years, based on biweekly band dendrometer recordings. The moment the trees reached 25% of the intra-annual basal growth was significantly influenced by the amount of precipitation accumulated during the previous winter. On the other hand, the moment the trees reached 75% of the intra-annual basal growth was significantly influenced by water availability in a shorter term, which also affected the length of the growing period. Modification of competition through thinning showed a significantly positive impact on growth, causing a delayed attainment of 50% of the intra-annual basal growth. These results imply valuable information about forest dynamics that will support forest managers' decisions dealing with low water-availability in forests.

Keywords: thinning; stand density; Aleppo pine; drought stress; aridity; dominant; suppressed

1. Introduction

In recent years, the water stress caused by severe and prolonged droughts has been inducing tree-growth decline, forest die-off and tree mortality on a global scale [1]. The Mediterranean region's forest productivity is expected to decrease as well. Hence, in the Mediterranean climate, the most limiting resource for plant growth is water. In future, this essential parameter is predicted to become increasingly critical in the Mediterranean Basin, since climate-change models predict higher air temperatures and lower precipitation. Longer and more frequent drought periods are supposed to occur with greater irregularity and an appreciable impact on the most arid areas [2,3].

Thinning stands to lower densities, making more water available for the remaining trees, is one of the most important measures of forest managers to mitigate the influence of drought on tree growth [4]. It has been proved that modification of stand density by thinning can buffer the response of tree growth and vigor to drought by enhancing soil water availability for the remaining individuals [5]. Nonetheless, previous studies have shown that thinning may cause additional stress in already dry sites, increasing solar radiation, leading to higher air and soil temperatures [6]. In addition, trees of different sizes

and crown classes compete in a different manner for water, light and other resources [7–9]. Consequently, radial growth responses to climate vary substantially according to social status and local tree density under water limitation [10]. In particular, it is helpful to know the growth responses to drought of trees in different crown classes [11].

Aleppo pine (*Pinus halepensis* Mill.) is the most widespread pine species in the Mediterranean region and can grow under extensively varied climatic conditions [12,13]. The mean annual temperature range of its natural distribution area is 12–16 °C, and its annual precipitation range is 300–700 mm [14]. The area covered by this species has increased due to plantation carried out during the 20th century and spontaneous colonization of abandoned land. As many forests are dominated by this species, a better understanding of how the growth at different time scales is constrained by the climate is required [15]. The Spanish *P. halepensis* forests occupy 1,770,530 ha [16], of which around 800,000 ha are natural forests, constituting almost 7% of the total forested area in Spain [17].

Most studies on the relationships between secondary growth (the growth that results from cell division in the cambia or lateral meristems that causes the stems and roots to thicken) and climate are based on annual radial stem growth increment, which is an important variable that allows tree growth and climate variability to be connected on local to continental scales [18]. However, dendrometers allow us to obtain short-term data on growth dynamics that are needed to analyze growth responses in relation to climatic variability in short time scales. The availability of this information may be helpful for evaluating the range of plasticity of a species under varying environmental conditions as a first step for predicting its responses to future climatic scenarios [19].

In this paper, we analyze the stem growth dynamics of *P. halepensis* of two different social status (dominant and suppressed trees) under different thinning intensities for eight years, based on two-week band dendrometer recordings. The following question is answered: are there differences in the intra-annual growth profile of trees considering water availability, competition and social status?

2. Materials and Methods

2.1. Study Site

The study site was located in a 65-year-old *Pinus halepensis* plantation in the north Spanish Meseta (Figure 1). Within the plantation, there were some *Pinus pinea* individuals that were not included in the study. The area is characterized by a continental Mediterranean climate, with low winter temperatures and frequent summer droughts. Over the last 20 years, the mean annual temperature was 10.7 °C (minimum 6.4 °C, maximum 11.7 °C) and the average annual precipitation was 363 mm (minimum 218 mm, maximum 598 mm).
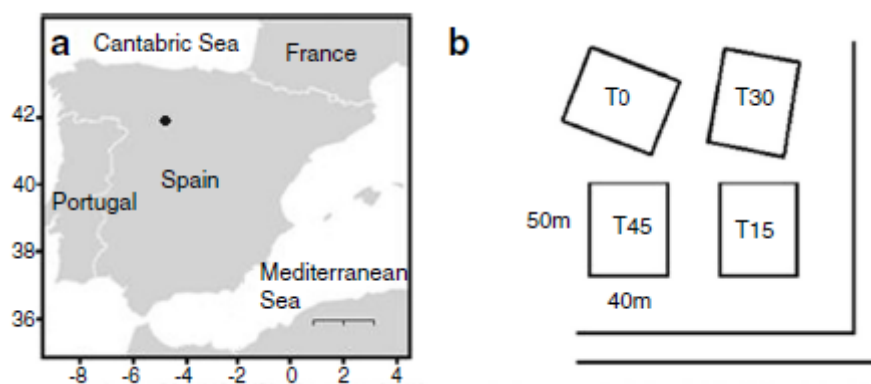
Figure 1. Location (**a**) and design (**b**) of the experimental plot in Spain. T0-Control; T15-15% removal of the basal area; T30-30% removal of the basal area; T45—45% removal of the basal area. The basal area reduction was performed as a thinning from below.

Thinning treatments were conducted prior to the studied period (autumn 2010) in an area of similar stand basal area and stand structure within the forest (Table 1). Four

experimental plots of 40 m × 50 m were established, and four thinning intensities were realized: 0%, 15 %, 30 % and 45 % reduction in the basal area of the unthinned control plot (T0). The unthinned stand was considered the control. The basal area reduction was performed as a thinning from below. Due to the experimental design, no replication of thinning treatments existed. In the statistical approach, we therefore forewent the use of "thinning intensity" to explain intra-annual growth patterns. However, we considered the trees' competitive situation, which partly reflected different thinning intensities (Figure 2a).

Table 1. Stand characteristics.

Stand	Reduction in BA [1] (%)	Ho [2] (m)	Initial BA [1] (m²ha⁻¹)	Final BA [1] (m²ha⁻¹)	Initial Mean DBH [3] (cm)	Final Mean DBH [3] (cm)	Longitude [4]	Latitude [4]
T0	0	10.6	22.6 (0.1)	22.6 (0.1)	18.6 (6.4)	18.6 (6.4)	35°32′22″	46°36′342″
T15	15	10.1	27.6 (0.1)	23.5 (0.1)	18.2 (6.1)	18.9 (6.1)	35°31′89″	46°36′384″
T30	30	9.4	20.0 (0.1)	14.0 (0.1)	17.1 (5.8)	18.5 (5.8)	35°31′41″	46°36′347″
T45	45	9.1	20.5 (0.1)	11.2 (0.1)	17.6 (6.1)	21.2 (6.2)	35°31′56″	46°36′281″

[1] Stand basal area; mean value and standard deviation in brackets; [2] mean height of the 100 trees with bigger diameter; [3] quadratic mean diameter at breast height. Mean value and standard deviation in brackets. [4] EPSG:25830-ETRS89/UTM zone 30N.
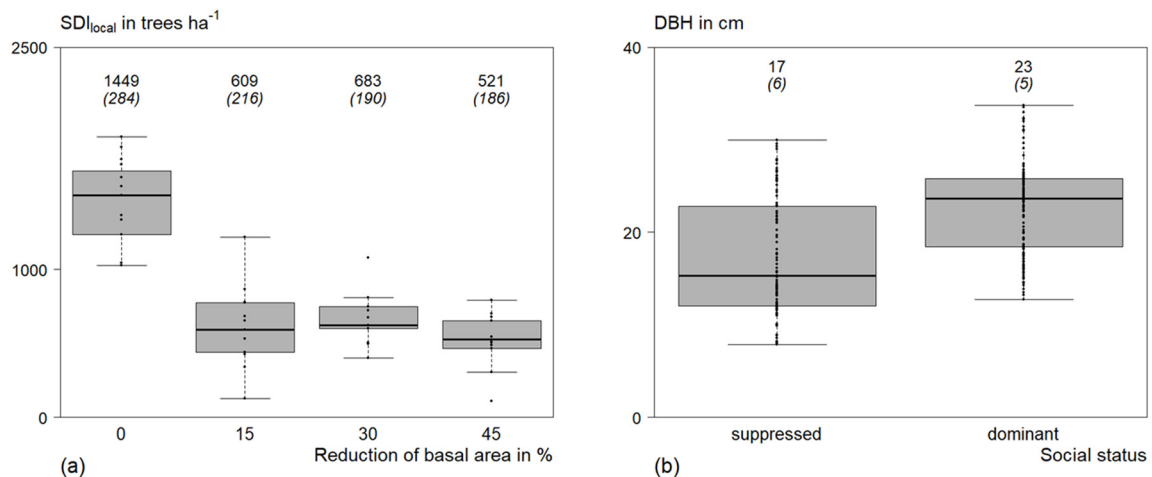

Figure 2. (**a**) The relationship between competition and thinning regime. (**b**) The relationship between DBH and social status. Mean value and standard deviation (italic and in brackets) are given.

2.2. Measurements

In 2011, we installed 48 stainless-steel band dendrometers (Dendrometer Increment Sensor DB20 EMS Brno) around the stem at breast height in 12 randomly selected trees per stand: 6 dominant trees and 6 suppressed (Figure 2b). Dominant trees are defined as those individuals that stand above all other trees in their proximity and receive full light from above, while suppressed trees are defined as those individuals that grow below the tree canopy [20]. Dominant trees diameter ranged from 20 to 25 cm and suppressed trees diameter ranged from 10 to 15 cm. Before installing the dendrometers, we removed the dead outermost tissue of the bark with a rasp. This allowed us to diminish swelling and shrinkage of the bark as a part of the increment dynamics. Dendrometer readings were taken to the nearest 0.01 mm. In order to reduce diurnal bias, because daytime transpiration causes stem shrinkage, readings were taken in the morning to [21]. According to [22], we did not consider the measurements obtained during the first three months after installation as these were within the adjustment phase of the band dendrometers.

Dendrometer data were recorded biweekly over an 8-year period. Due to jumps and unexpected spikes, we discarded some annual series by visual inspection (Table 2). The annual readings took place throughout the year, but mainly during the growth period (Figure 3). The competitive situation of individual trees was described according to [23] by

the local stand density index (SDI$_{local}$). They defined the competition situation by means of a modified local version of the original stand density index SDI [24]. Daily bioclimatic variables (temperature and precipitation) were measured at the closest meteorological station (data provided by InfoRiego). On their basis, the De Martonne aridity index [25] (applied, for instance, by [26]) was calculated. The index was calculated for the time between 1st March and 30th November. Winter precipitation of a particular year ranged from the beginning of December in the previous year until the end of February in the year of interest.

Table 2. Measurements information and parameters included in the models.

Year	n	Omitted Time-Series (%)	SDI$_{local}$ [1] (trees ha^{-1})	De Martonne Index [2] (mm $^\circ$C^{-1})	Winter Precipitation [3] (mm)
2011	41	14.6	834 (455)	5.9	96
2012	30	37.5	803 (460)	8.2	28
2013	37	22.9	896 (485)	18.3	109
2014	34	29.2	882 (485)	11.1	177
2015	31	35.4	794 (441)	9.7	55
2016	40	16.7	794 (436)	11.2	127
2017	14	70.8	711 (239)	5.5	63
2018	15	68.8	736 (249)	20.2	99

[1] The competition index SDI$_{local}$ was calculated once in 2011 and assumed to be constant for all following years. Mean value and standard deviation in brackets. [2] Defined between 1st March and 30th November. [3] Defined between 1st December in previous year and 28th (29th) February in the year of interest.

2.3. Data Preparation

We chose the basal area (Figure 3b) instead of the diameter (Figure 3a) to represent the different tree sizes. In addition, the basal area growth of a year was normalized by the total basal area growth of that year to get the annual relative basal area growth *RelBA* (Figure 3c); multiplying by 100, the unit of the annual relative basal area growth was percent (%).

For further analysis, we calculated the day of the year (DOY)—based on the individual, idealized intra-annual growth pattern—when 25%, 50% and 75% of the *RelBA* was achieved. The non-parametric technique was closest to the measured data. Interpolation was used, since days where 25%, 50% or 75% of growth were reached did not coincide with days of single readings. The nearest surveys before and after were found, and the temporal distance weighted mean between the two surveys was calculated to get the appropriate DOY.

2.4. Statistical Analysis

Linear mixed models were used to determine whether intra-annual growth, i.e., *RelBA25*, *RelBA50* and *RelBA75*, was affected by social status, competitive situation, winter rainfall and weather condition of the growth period. The basic formula encompassing all possible explanatory variables was as follows (exemplarily shown for *RelBA25*):

$$RelBA25 = a_0 + a_1 \times \textit{Social status} + a_2 \times \textit{SDI}_{local} + a_3 \times \textit{De Martonne index} + a_4 \times \textit{Winter precipitation} + b_i + b_{ij} + \varepsilon_{ij}$$

We considered random effects to match the error structure of the data. Parameters b_i and b_{ij} were nested random effects at plot and tree-in-plot levels [27,28], i.e., trees that came from the same plot (b_i), and several time series were recorded from the same tree (b_{ij}). Although the random effects covered lots of the nested data structure, the presence of autocorrelation was still possible [29]. Consequently, final models included an auto-regressive correlation structure ("corAR1") for fully modeling the time dependency [27]. The error term ε_{ij} and the random effects were normally distributed, with an expected value of zero and constant variance.

We generated all 16 possible combinations from four explanatory variables. The Akaike Information Criterion (AIC) was used as an adaptation criterion for the selection of the best model [30]. Based on the AIC values with a delta of smaller than 4, we calculated

Akaike weights to add a multi-model inference and to reflect model-selection uncertainty more precisely [31]. The processing was performed within the programming environment of R [32] and the R packages tidyverse [33], mgcv [34] and MuMIn [35].
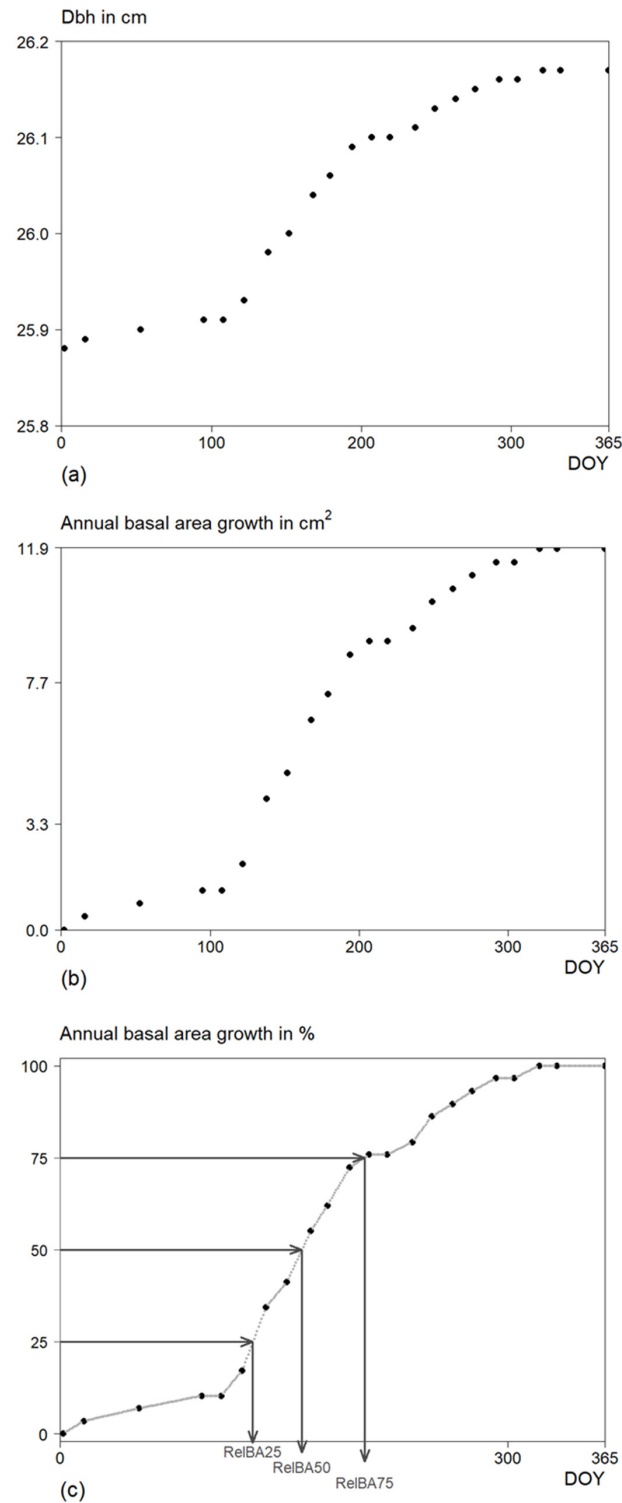

Figure 3. (**a**) The intra-annual course of the diameter (dbh) and (**b**) of the basal area of an example tree. On average, 19.7 diameters per year and tree were recorded. (**c**) Based on an interpolation, the day of the year (DOY) was extracted on which the relative basal area growth achieved 25%, 50% and 75% of the total annual growth.

3. Results

Figure 4 shows the original data of 242 time series plotted against the day of the year (DOY).

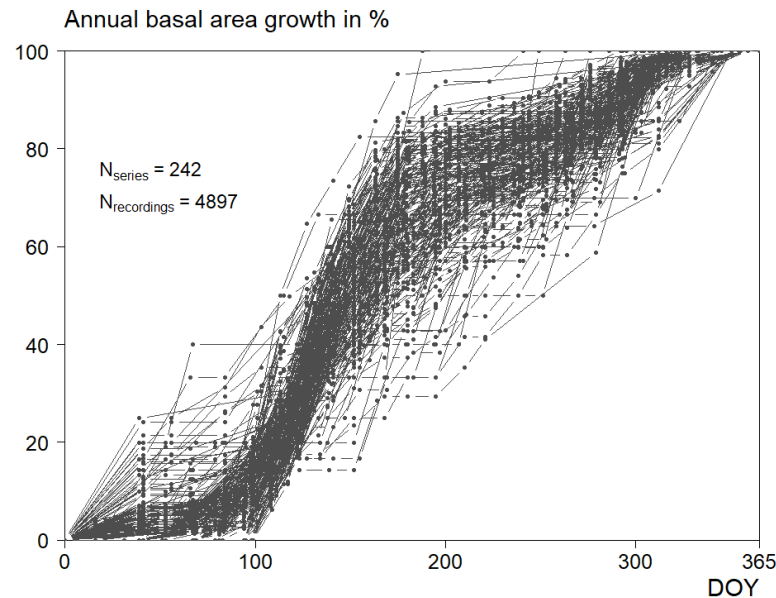**Annual basal area growth in %**

Figure 4. The intra-annual basal area growth pattern of all 242 time series.

On average, 25% of the total annual basal area growth was achieved on 25th April (*DOY* = 115), 50% on 1st June (*DOY* = 152) and 75% on 28th August (*DOY* = 213). Variation increased from 15 days for *RelBA25* to 37 days for *RelBA75* (Figure 5).
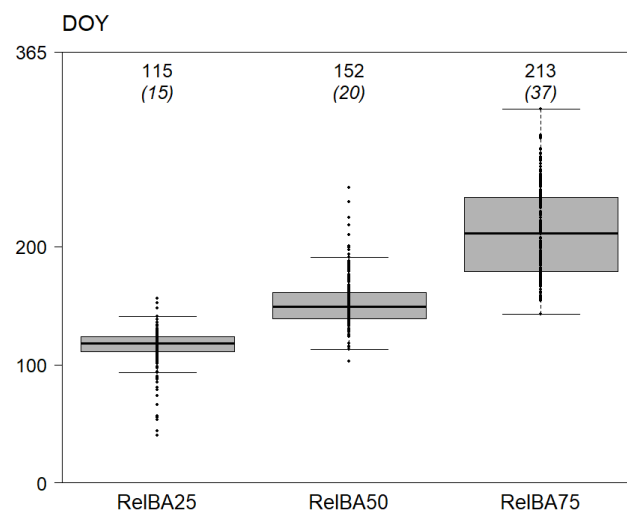

Figure 5. The distribution of the three different dependent variables used in this study: the days of the year (DOY) when 25%, 50% and 75% of the total annual basal area growth were reached. Mean value and standard deviation (italic and in brackets) are given.

There was no significant influence of rainfall in the previous winter on the intra-annual basal growth. An increase in the De Martonne index caused a significant earlier attainment of *RelBA75*. An increase of 1 mm $°C^{-1}$ led to an earlier attainment of 2.1 days. The impact of SDI_{local} was significant on *RelBA50* and *RelBA75*. High competition (an increase of 100 trees of a standardized dbh of 25 cm per ha) caused a delayed attainment of 1.3 days on *RelBA50* and 2.1 days on *RelBA75*. Neglecting the nested structure of the data and looking at single dependencies between intra-annual growth and tree characteristics, competitiveness and

weather conditions, linear regression analysis did not reveal any influence of the social status (Table 3).

Table 3. The results of 12 linear regression analyses between the three dependent (RelBA25, RelBA50, RelBA75) and the four independent variables (social status, SDI_{local}, De Martonne index, winter precipitation). Numbers in brackets next to the regression coefficients represent the standard error. Significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$, $p < 0.1$.

		RelBA25 (Day of Year)	RelBA50 (Day of Year)	RelBA75 (Day of Year)
	offset (suppressed)	114 (2)	153 (2)	208 (4)
Social status	dominant	2.3 (2.0)	−1.3 (2.6)	8.4 (4.8)
	p-value	0.249	0.629	0.0792
	offset	115 (2)	142 (3)	196 (5)
SDI_{local}	slope	5.7×10^{-4}	1.3×10^{-2}	2.1×10^{-2}
(ha^{-1})		(2.3×10^{-3})	(2.8×10^{-3})	(5.2×10^{-3})
	p-value	0.804	***	***
	offset	111 (3)	155 (3)	236 (6)
De Martonne index	slope	4.1×10^{-1}	-2.4×10^{-1}	−2.1
(mm °C^{-1})		(2.2×10^{-1})	(2.8×10^{-1})	(0.5)
	p-value	0.057	0.402	***
	offset	119 (2)	156 (3)	225 (6)
Winter precipitation	slope	-3.6×10^{-2}	-3.7×10^{-2}	-1.2×10^{-1}
(mm)		(2.2×10^{-2})	(2.9×10^{-2})	(5.3×10^{-2})
	p-value	0.110	0.209	0.021
	n	242	242	242

In the more general approach, the best model describing *RelBA25* included the winter rainfall of the previous year. *RelBA25* came 5.1 days earlier, with 100 mm more winter precipitation. Less arid conditions in the growth period, i.e., higher De Martonne index, led to a later attainment of *RelBA25* and an earlier attainment of *RelBA75*. Trees' competition was also important. SDI_{local} was part of the best model describing *RelBA50*. An increase of 100 trees of a standardized dbh of 25 cm per ha caused a significant delay of 1.3 days on the *RelBA50*. The social status was never part of the best model (Table 4).

Table 4. Mixed-model statistics; effect of SocStat, SDIlocal, DeMart and PrecWint on intra-annual basal area growth. Numbers in brackets next to the regression coefficients represent the standard error. Significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$, $p < 0.1$.

			RelBA25 [Day of Year]	RelBA50 [Day of Year]	RelBA75 [Day of Year]
		a_0	114 (3)	146 (4)	229 (11)
Social status	suppressed	a_1	-	-	-
	dominant				7.9 (4.2)
SDIlocal (ha^{-1})		a_2	-	1.3×10^{-2} *** (2.8×10^{-3})	1.1×10^{-3} (8.3×10^{-3})
De Martonne index (mm °C^{-1})		a_3	6.1×10^{-1} ** (2.2×10^{-1})		-2.0 *** (4.8×10^{-1})
Winter precipitation (mm)		a_4	-5.1×10^{-2} * (2.3×10^{-2})	-4.4×10^{-2} (2.8×10^{-2})	
		b_i (σ)	5.7×10^{-4}	9.1×10^{-4}	13.4
		b_{ij} (σ)	9.3×10^{-4}	1.4×10^{-3}	4.1×10^{-3}
		ε_{ij} (σ)	1.5×10^1	1.9×10^1	3.3×10^1
		φ	0.06	−0.02	−0.05
		RMSE	15.1	19.0	32.9
		AIC weights	0.385	0.248	0.300
		n$_{series}$	242	242	242
		n$_{tree}$	46	46	46

4. Discussion

4.1. The Influence of Weather Conditions on Growth

Higher winter precipitation produced an earlier reach of 25% of the intra-annual basal growth. These results add information to studies conducted on the same stands [5] and agree with previous studies of *P. halepensis* [36,37], which stated that carry-over effects from the former growing season can substantially influence tree growth, especially in areas with severe climatic conditions, as is the case in the study area. Reserves from the previous growing season can affect wood allocation in the following year [38]. Such lag effects are probably introduced by enhanced nutrient storage and a variety of climate and biological processes, such as a later termination of the growing season [39].

Under a Mediterranean climate, growth is expected to be essentially limited by water availability [40], and previous studies have analyzed the effect of water stress on the ratio of transpiration to evapotranspiration [41]. The aridity index applied proved that the growth is influenced by weather conditions in a different way at the earlier and the latter stages of the growth period, also affecting its length. A high De Martonne index, meaning low aridity, produced a delay on the reach of 25% of the intra-annual basal growth, and an earlier reach of 75% of the intra-annual basal growth, resulting in a significantly shortened length of the growth period. This result adds information to studies performed at the same stands that defined soil moisture as the most important climatic driver of tree growth [5].

4.2. Can Thinning Mitigate Drought Stress?

The reduction in the competition that originated as a result of thinning improved the annual growth of the remaining trees, which corresponds with many other reports [5,10,42–44]. Secondary tree growth has been proved to respond differently to climatic variations depending on tree density [10]. Nonetheless, few new studies have analyzed the thinning effects on climate-growth sensitivity, especially in forests that are sensitive to drought, where the combined effects of competition and drought are not completely understood [5,44–46].

Competition influenced the time when trees reach 50% of their total annual growth. In stands with higher thinning intensity, trees reached 50% of their total annual growth 1.3 days later than in the stands with lower thinning intensity. Competition for resources among trees has been broadly acknowledged as a key aspect of forest dynamics, affecting ecological functions and biogeochemical cycling. Forest-management measurements have even been recommended to reduce vulnerability to drought in the context of climate change [42]. In semiarid ecosystems, higher density has been suggested to buffer or mitigate the adverse effects of high competition for water during extreme climatic events [47,48], especially in older stands, which become more susceptible to drought when thinned [49]. Forest managers might therefore consider the characteristics of their forest before reducing tree density through thinning, since it modulates tree-growth performance, the influence of climate on microclimatic conditions and mortality [4,46].

Some studies have previously pointed out the extension of the growing season after thinning. The authors of [10,42] suggest that a reduction in competition through thinning prolonged the growing seasons in *Fagus sylvatica* L. and *Abies pinsapo* Boiss. The main factors stimulating this process are more radiation and/or higher air and soil temperature generated after thinning [44].

4.3. The Impact of Social Status on Intra-Annual Growth Pattern

The social status of the trees had no influence on the moment they reached 25%, 50% and 75% of their total annual growth. These results complement the results found in previous studies on the same stands [5], which concluded that the growth rates of dominant trees (larger DBH) were significantly higher than the growth rates of suppressed trees (smaller DBH). The demands on water and nutrient supplies, hydraulic resistance and photosynthetic rates are physiological processes associated with tree size [50] and, as a result, growth-related environmental signals are expected to be size-dependent [51]. In general, suppressed trees have more restricted access to soil water reserves than dominant

trees because of their shallower and less developed root systems, especially in semi-arid environments and in high-density stands [5]. In consequence, their growth rates fluctuate depending on short-term water reserves concentrated in surface soil layers, while dominant trees with more developed root systems have better access to deeper water reserves, showing more homogeneous growth rates [52]. Previous studies suggest that competition affects tree growth by reducing the growth period in suppressed trees [53,54]. Our results indicate that this continuous access to water reserves of dominant trees has a significant impact on their total annual growth in comparison to suppressed trees but has no impact regarding the length of their growth period, which is more dependent on the weather conditions during the growth period.

4.4. Perspectives

It has been suggested that the resistance of individual trees to drought stress is improved by thinning, since the reduction in stand density decreases the competition for resources [47,55,56]. However, it should not be concluded that open stands are universally desirable. Forest managers should maintain an adequate stand density in order to mitigate the effect of climatic extremes, considering other ecosystem parameters such as tree age, regeneration or soil protection [47]. In addition, the results show that the promotion of more diverse stands mixing species with complementary temporal and spatial patterns of water uptake will increase resilience to further growth declines.

5. Conclusions

Water availability was confirmed as the main driver of tree growth in Mediterranean environments. Previous winter precipitation as a water reserve highly affected the growth at the earlier stages of the growth period, while aridity affecting the growth at the latest stages of the growth period also influenced its length. The reduction in the competition through thinning significantly improved the growth of the remaining trees, especially at the middle stages of the growth period. The social status of the trees had no influence on the moment they reached the different benchmarks of their total annual growth. Forest management through thinning confirmed its value for improving the effects of water limitations on individual tree growth. These results may help managers understand how the modification of stand density will differentially affect the growth responses of *Pinus halepensis* to climate.

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