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Scots pine plantations growth adaptation to climate warming in locations at the southernmost distribution limit of the species

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Abstract

Under the current climate change conjuncture, understanding the forest plantations capacity of acclimation to warming and increased drought stress is crucial for forest managers. To get some understanding of their adaptability, plantations of similar provenance but located in climatically contrasting sites can be compared. Here we study the growth dynamics and their relationship with climate and drought in two Scots pine (*Pinus sylvestris* L.) plantations located in the center (*Sierra de Guadarrama*, wetter site) and south (*Sierra Nevada*, drier site) of Spain, the latter situated at the southernmost distribution limit of the species. Our objectives are to quantify the trends in radial growth of these plantations, to quantify the influence of climate on growth, and to project the plantations growth as a function of forecasted climate. Results reveal that the plantations from the drier site show lower, and less responsive to climate, growth and greater resilience than those from the wetter site. Furthermore, if the current climate-growth relationships continue in the future, these plantations would maintain the current limited growth rate during the 21st century. On the contrary, plantations from the wetter site show higher growth rate and more resistance to drought, and they are projected to increase growth under the warmer conditions forecasted for the 21st century. Our study shows that plantations in drier sites may have a great capacity to acclimate to local climate conditions and would not be negatively impacted by the projected climate warming.

Keywords: dendroecology, drought stress, plantations, *Pinus sylvestris*, SPEI.

1. Introduction

Pine plantations cover wide extensions across drought-prone areas like the Mediterranean Basin, where most afforestation efforts were done during the 20th century (FAO, 2006). These plantations provide a set of services such as regulation of the water flow, protection against erosion, timber production, CO₂ uptake and storage, and conservation of biodiversity (Brockerhoff et al., 2008; Gómez-Aparicio et al., 2009; Ruiz-Peinado et al., 2017; Valbuena-Carabaña et al., 2010). However, certain characteristics of some plantations make them more vulnerable to climatic (e.g., drought) and biotic stressors (e.g., pests) such as high stand density due to a lack of management, low structural and genetic diversity, and a defective adaptation derived from an unsuitable seed origin (Alia et al., 1995; Benito Garzón et al., 2011; Gil et al., 2009). Abrupt climate extremes such as droughts may have profound consequences on the performance of maladapted forests and non-acclimated afforestations, which may lead to growth decline, dieback and mortality, and also to a loss of ecosystem integrity and function (Sánchez-Salguero et al., 2012).

Spain is one of the countries with the largest area of pine plantations in the world (FAO, 2006; Payn et al., 2015). In the mid-19th century Spanish woodlands covered approximately six million hectares, representing 12.5% of the national territory (Armenteras, 1903), an extension resulting from logging and intensive agricultural use during previous centuries (Valbuena-Carabaña et al., 2010). Nowadays woodlands cover more than sixteen million hectares (Vadell et al., 2016). In total, more than five million hectares were planted since 1877, approximately ten percent of the entire country area (Vadell et al., 2016). However, the seed origin and quality were not considered in reforestations carried out in Spain until the second half of the 20th century, and many plantations were carried out with non-local provenances (Gil et al., 2009).

Due to a shift towards warmer climate conditions, the capacity of adaptation may be reduced in homogeneous and poorly managed pine plantations (Sánchez-Salguero et al., 2012). The last 30 years constituted the warmest period at the Earth's surface since 1850 (IPCC, 2014). Ongoing climate change will increase the recurrence and severity of adverse climate extremes such as severe droughts and heat waves, especially in Southern Europe, a climate change hotspot (Jacob et al., 2014). This scenario affects specially those tree populations located at the southernmost, xeric limit of the tree species distribution area (Sánchez-Salguero et al., 2017, 2012). In relation with the climate change, several cases of growth decline and dieback have been documented in drought-prone conifer forests (Camarero et al., 2015; Macias et al., 2006; Sarris et al., 2011, 2007).

The study of sensitive forests, due to their location or origin, can help to understanding the impact that climate change is having and will have on these ecosystems throughout the 21st century. Here we study the growth dynamics and its relationship with climate in two Scots pine (*Pinus sylvestris* L.) plantations located in the center (*Sierra de Guadarrama*) and South (*Sierra Nevada*) of Spain. The latter site is located at the southernmost distribution limit of the species. Scots pine is widely distributed across Eurasia, and it has been profusely planted worldwide. In Spain it is the second tree species most used in plantations (Valbuena-Carabaña et al., 2010), creating forests with productive, ecological and/or soil protection purposes. The plantations in *Sierra de Guadarrama* were established in the second half of the 20th century, whereas most of *Sierra Nevada* plantations were established in the middle of that century. Both sites are currently protected areas. The seed source is the same in both study sites, central Spain (Mesa Garrido, 2016), a provenance (hereafter CS provenance) encompassing *Sierra de Guadarrama*. This implies that *Sierra de*

Guadarrama plantations are better adapted to local conditions, whereas *Sierra Nevada* plantations may be maladapted (Rubio-Cuadrado et al., 2018b). Consequently, we hypothesize that plantations are less adapted to local climate and to the forecasted warmer and increasingly arid climate in *Sierra Nevada* than in *Sierra de Guadarrama*. Our specific objectives are: (i) to compare the growth trends of Scots pine plantations in a wet (*Sierra de Guadarrama*) vs. a dry site (*Sierra Nevada*) with common seed source from CS provenance; (ii) to analyze the influence of climatic factors on the radial growth in these two climatically contrasting sites; (iii) to analyze the effect of droughts on radial growth in both sites; (iv) and to project their growth over the course of the 21st century. In this work we consider radial growth as a proxy of sensitivity to climate warming and drought stress.

2. Materials and methods

2.1. Study area

We compared Scots pine plantations located in *Sierra de Guadarrama* (Segovia province, central Spain) and *Sierra Nevada* (Granada province, southeastern Spain) located 400 km southwards (**Fig. 1**). Both areas are currently included in the Spanish network of National Parks. In *Sierra de Guadarrama* the climate is continental Mediterranean with average temperature of 9.9 °C and annual precipitation of 975 mm (estimated data for the study area, see **Section 2.4**). In *Sierra Nevada* the climate is Mediterranean with average temperatures of 10.1 °C and annual precipitation of 588 mm (see climate diagrams in **Fig. S1** in **Appendix A** of the Supplementary material). Soils are siliceous and acid in both sites.

Figure 1. Map of sampled locations (crossed red circles), area of provenance (yellow) and distribution of natural Scots pine forests in the Iberian Peninsula (green).

2.2. Field sampling

To acquire data representative of the environmental and structural variability of the forests (see **Table 1**) we surveyed both sites establishing a network of field plots. In *Sierra Nevada* we sampled 135 plots in 2015, distributed in four locations between coordinates $36^{\circ} 58' 15''$ – $37^{\circ} 9' 53''$ N and $3^{\circ} 2' 54''$ – $3^{\circ} 27' 34''$ W, within the 1445–2163 m a.s.l. altitudinal range. In *Sierra de Guadarrama* we sampled 41 plots in 2016 in a homogeneous area located between $40^{\circ} 47' 54''$ – $41^{\circ} 1' 50''$ N and $3^{\circ} 52' 53''$ – $4^{\circ} 7' 47''$ W, within the 1499–1810 m a.s.l. altitudinal range. Because *Sierra Nevada* population is located at the southernmost limit of the species distribution area, the sampling density in this site was higher than in *Sierra de Guadarrama*, aiming to increase the representativeness of the results.

In both sites the plots were systematically distributed on a square grid of 250 m $\times$ 250 m. In each plot, a pair of stereoscopic hemispherical images was acquired using

ForeStereo (Sánchez-González et al., 2016) to characterize the area estimating basal area (BA), tree density (N) and the mean diameter at breast height (DBH_{stand}) at the plot level. ForeStereo is a passive proximal sensing device that acquires images from the plot center and allows trees located up to 15 m to be mapped and their height and DBH estimated (Rodríguez-García et al., 2014). In addition, two cores were extracted at 1.3 m from the dominant or codominant tree closest to the plot center using a Pressler increment borer. The diameter at breast height (DBH_{cored}) of this tree was measured with a caliper. Topographical variables (altitude, slope and aspect) of each plot were obtained from a Digital Terrain Model (PNOA, Instituto Geográfico Nacional, Spain) with a spatial resolution of 25 m.

Table 1. Main characteristics of the study sites. Average values per site with their standard deviations in parentheses.

Site	<i>Sierra de Guadarrama</i>	<i>Sierra Nevada</i>
Mean altitude (m a.s.l.)	1625 (70)	1907 (106)
Aspect (°)	254 (90)	189 (106)
Slope (°)	21 (5)	18 (5)
DBH_{stand} (cm)	26.8 (5.8)	21.6 (4.0)
Basal area ($m^2 ha^{-1}$)	32.5 (10.8)	30.4 (15.2)
Density (stems ha^{-1})	587.5 (276.3)	746.5 (324.4)
Tree age at 1.3 m (years)	35 (7)	46 (13)
No. sampled trees	41	135

2.3. Dendrochronological analyses

Cores were mounted on wooden supports and carefully sanded until tree rings were clearly visible. Tree rings were visually cross-dated and measured to the nearest 0.01 mm using the semi-automatic LINTAB device with the TSAP-Win software (RINNTECH, Heidelberg, Germany). Cross-dating was further verified with the COFECHA program (Holmes, 1997).

We calculated ring-width series for each tree and these series were subsequently transformed into basal area increments (BAI) as this variable captures growth trends better than tree-ring width (Biondi and Qeadan, 2008). The BAI was calculated as follows:

$$BAI = \pi(r_t^2 - r_{t-1}^2) \quad (1)$$

where r_t and r_{t-1} are the stem radius at the end and at the beginning of a given annual ring increment. When cores did not contain the pith, the length of the missing radius was estimated for BAI calculation using a graphical method based on the convergence of rays at the pith (Rozas, 2003). The final chronologies were built by averaging individual BAI measurements (Speer, 2012). The statistical quality of each chronology was checked via Expressed Population Signal (EPS) (Wigley et al., 1984) using *dplR* package (Bunn et al., 2016) in R statistical software (R Development Core Team, 2017). When the EPS was greater than 0.85, the chronology was considered reliable and well replicated. We analyzed the BAI as a function of time and as a function of tree age. The differences in BAI between sites were analyzed through Mann-Whitney U tests.

Tree age was estimated with two approaches. When cores reached the pith, age was estimated cross-dating and counting the total number of rings. In the other cases, we first estimated the missing length to the pith following Rozas (2003), and then we estimated the number of innermost lost rings dividing the length of the missing radius by the mean growth rate of the 5 rings adjacent to the missing part of the core.

2.4. Climate data

Monthly data of precipitation and mean temperature from 58 and 99 meteorological stations covering the study area in *Sierra de Guadarrama* and *Sierra Nevada*, respectively, were interpolated at the sampling locations using spatio-temporal

Universal Kriging. The generalized product-sum model (De Iaco et al., 2002) was fitted to the space-time variogram. The altitude and the projected coordinates XY, as well as the interactions “altitude $\times$ X” and “altitude $\times$ Y” were included as auxiliary variables in the trend function. The variogram model parameters and trend function coefficients were estimated using the variance based least squares method (VLS method) (Montes and Ledo, 2010). Cross-validation was carried out to check the unbiasedness and the ratio between the estimated kriging variance and the mean of the cross validation squared residuals. To show the long-term climate trends we fitted piecewise regressions to the data using the *segmented* package in R (Muggeo, 2008).

Using the estimated meteorological data, we calculated the Standardised Precipitation Evapotranspiration Index (SPEI) on 12-month scales (Vicente-Serrano et al., 2010) to estimate the evolution of the drought intensity over time. For this, we used the Thornthwaite equation within the *SPEI* package in R (Beguería and Vicente-Serrano, 2017). The SPEI drought index considers the effect of temperatures on evapotranspiration rates and the cumulative water deficit. High and low SPEI values correspond to wet and dry conditions, respectively.

We considered the climate projections for monthly precipitation and mean temperature during the 21st century from the 0.5°-gridded Coordinated Regional Climate Downscaling Experiment (CORDEX) dataset (Jacob et al., 2014). We obtained the CORDEX climate data from the 0.5° grids with coordinates 40.5°–41.0° N and 3.5°–4.0° W for *Sierra de Guadarrama*, and 37.0°–37.5° N and 3.0°–3.5° W for *Sierra Nevada*. We considered three ‘representative concentration pathways’ (RCPs), which are climate projections for different climate scenarios (0.3–4.8 °C global warming by the year 2099) according to anthropogenic greenhouse gas emissions (Collins et al., 2013). We used data for the scenarios RCP 2.6, RCP 4.5 and RCP 8.5. The RCP 2.6 scenario

represents a situation with an increase in temperature ranging between +0.3° and +1.7 °C during the 21st century. Under the RCP 4.5 scenario temperature might increase between 0.9 and 2.6 °C, whereas under the RCP 8.5 scenario the projected temperature increment ranges between 1.4 and 4.8 °C (van Vuuren et al., 2011).

2.5. Climate- and drought-growth relationships

To determine the main climatic drivers of radial growth, Pearson correlation coefficients were calculated between each site averaged BAI chronologies and monthly average temperature and total precipitation estimated at each site. These correlations were calculated with data from periods with more than ten samples per site and EPS > 0.85, that is: 1978-2014 in *Sierra de Guadarrama*, and 1948-2014 in *Sierra Nevada*. Correlation coefficients were calculated from October of the previous year to September of the growth year considering that: (i) tree growth is affected by the previous year climate (Bogino et al., 2009; Olivar et al., 2015), and (ii) growth of Scots pines may occur from April to September (Aldea et al., 2017; Camarero et al., 2010, 1998).

Pointer year analysis was carried out considering as *negative event year* those years with a BAI decrease of at least 30%, relative to the average BAI of the 4 preceding years –relative growth change method (Schweingruber et al., 1990)–. The growth response to these unfavorable years and the ability to recover pre-disturbance growth levels after the disturbance were estimated for the tree-ring series through the resistance (R_t) and resilience (R_s) indices (Lloret et al., 2011):

$$R_t = BAI_i / BAI_{i-4} \quad (2)$$

$$R_s = BAI_{i+4} / BAI_{i-4} \quad (3)$$

where BAI_i is the BAI value of the i year. These indices were calculated with 4-year pre- ($i-4$), and post-disturbance ($i+4$) periods, based on previous studies (Rubio-Cuadrado et

al., 2018b, 2018a), using the *pointRes* package in R (van der Maaten-Theunissen et al., 2015). The differences between sites were analyzed through Mann-Whitney *U* tests.

2.6. Growth modelling

To evaluate factors influencing BAI of planted pines at each site, and to predict future trends based on climate conditions forecasted for the 21st century, we used linear mixed-effects models. BAI was the response variable and the variables considered as fixed effects included: tree diameter (DBH_{cored}), as tree growth of mature trees is mainly driven by tree size (Mencuccini et al., 2005), altitude, aspect (calculated as the cosine of the magnetic bearing; +1 and -1 correspond to north and south, respectively), slope, and climate variables highly correlated with BAI. These climate variables were evaluated at each site and location, working with a different climate variable for each of the four sampled locations in *Sierra Nevada*, in accordance with **Section 2.4**. We also introduced the average SPEI (using 12-month long scales) from April to September to account for the drought effect during the growing season. We only considered the 1999–2014 period in order to avoid the first 15 years of growth of each series in *Sierra de Guadarrama*, which presented very low BAI values corresponding to the pre-juvenile phase, and to use the same period in both sites. Only the tree was considered as a random component (1|Tree).

The form of the fitted linear mixed-effects models with random intercept and fixed slope was as follows:

$$y_{ij} = \alpha + a_j + \beta z_{ij} + \varepsilon_{ij} \quad (4)$$

where y_{ij} represents $\log(\text{BAI}+1)$ for tree i and year j , α is the general intercept, a_j is the random intercept, β is the vector of general slopes, z_{ij} is the vector of fixed effects, and ε_{ij} is the error with a first-order temporal autocorrelation structure [AR(1)].

To identify the best-supported model we constructed all possible combinations of alternative models from the full model considering fixed and random effects. As the restricted maximum likelihood method (REML) estimates an unbiased variance but does not allow models to be compared by minimizing the Akaike Information Criterion (AIC), we first fitted all possible models using the Maximum Likelihood method (ML), then selected the best model by minimizing AIC and finally fitted it again using REML (Zuur et al., 2009). The existence of multicollinearity among explanatory variables was evaluated by calculating the variance inflation factor (VIF) (Dormann et al., 2013), which was always lower than 2 indicating low collinearity among variables. The marginal R^2_m (the percentage of variance explained by the fixed effects) and the conditional R^2_c (the percentage of variance explained by the fixed and random effects) were estimated according to Nakagawa and Schielzeth (2013). The mixed models and their VIF and pseudo- R^2 values were obtained with the *nlme* (Pinheiro et al., 2018), *car* (Fox and Weisberg, 2011) and *MuMIn* (Barton, 2012) packages in R, respectively.

In order to analyze the effect of competition on growth, the slope of the linear regressions, that relates age of the trees to the BAI of each year, has also been modeled (see **Appendix B** in Supplementary material).

2.7. Projecting tree growth as a function of climate forecasts

We projected the BAI in both study sites for the 21st century using the mixed models previously obtained and fixing (as constant) the tree diameter (DBH_{cored}). The climate variables considered were the expected CORDEX values for the 21st century, according to the RCP 2.6, RCP 4.5 and RCP 8.5 emission scenarios. We obtained the average values per site, year and climate scenario, and then we calculated linear regressions for average BAI as a function of year.

3. Results:

3.1. Climate and drought trends

In both sites there has been a significant increase in temperature since the 1970s, while rainfall did not show any trend (**Fig. 2**). Although wet periods were frequent between 1950 and 1980, with positive SPEI values, the aridity has increased since 1980 in both sites, as shown by the frequency of negative SPEI values (**Fig. 3**).

Figure 2. Local climate data: a) mean annual temperature; b), total precipitation in *Sierra de Guadarrama* (filled symbols and black lines) and *Sierra Nevada* (empty symbols and grey lines) showing significant trends and changes in trends (vertical dashed lines) based on segmented regressions. Changes in temperature trends were detected in 1973 and 1974 in *Sierra Nevada* and *Sierra de Guadarrama*, respectively, whereas changes in precipitation trends were not detected. When $p < 0.05$, the significance levels of each segment or trend are indicated (black letters for *Sierra de Guadarrama* and grey letters for *Sierra Nevada*). Years with growth drops (see **Section 3.4**) are marked with grey circles.

Figure 3. Temporal variability of the monthly SPEI drought index using 12-month long scales in the two study sites. Trends based on regressions are shown and the significance level of each trend is indicated. Years with growth drops (see **Section 3.4**) are marked with grey circles.

3.2. Growth rates and trends

Planted Scots pine individuals in *Sierra de Guadarrama* showed significantly higher growth rates (BAI) than *Sierra Nevada* pines from 1990 to 2014 (**Fig. 4**). In *Sierra de Guadarrama* BAI showed a significant ($p < 0.001$) decreasing trend after the maximum growth rates at 10-30 years since plantation, while in *Sierra Nevada* growth stabilized 20 years after the plantation (non-significant trend, $p = 0.395$). The trend in *Sierra de Guadarrama* was related to the current competition level of the stand (**Table S1** in **Appendix B** of the Supplementary material). In stands with high current competition level, the slope of the regression that relates BAI to tree age for *Sierra de Guadarrama*

reached lower values (the regression fitted to mean values of the site is shown in **Fig. 4b**).

Figure 4. Growth trends (basal area increment, means $\pm$ standard errors) calculated for *Sierra de Guadarrama* (filled symbols) and *Sierra Nevada* (empty symbols) Scots pine trees. Trends are represented as a function of time (a) and tree age (b). Grey bars at the bottom of each plot indicate years when there are significant differences in growth between sites ($p < 0.05$) based on Mann-Whitney U tests. In the bottom plot, regressions are plotted with 95% confidence intervals (dashed lines) and they were calculated omitting the juvenile growth phase (first 15 years of life).

3.3. Climate-growth relationships

Basal area increment of planted Scots pines showed different relationships with climate depending on their site (**Fig. 5**). The most important climate variables in *Sierra de Guadarrama* Scots pine plantations were temperature in October of the previous year ($r = -0.342$, $p = 0.038$), temperature from February to May ($r = 0.649$, $p < 0.001$), precipitation from February to March ($r = -0.569$, $p < 0.001$) and precipitation from May to August ($r = 0.532$, $p < 0.001$). In the case of *Sierra Nevada*, the most important climate variables were temperature from previous December up to March ($r = 0.300$, $p = 0.013$), temperature from August to September of the growth year ($r = 0.298$, $p = 0.014$), and precipitation from previous October to December ($r = 0.393$, $p < 0.001$).

Figure 5. Correlation (Pearson coefficient) calculated between monthly climate data (mean temperature, black bars; total precipitation, grey bars) and radial growth (basal area increment) of Scots pine trees sampled at *Sierra de Guadarrama* and *Sierra Nevada* sites. The dashed and dotted horizontal lines show the 0.05 and 0.01 significance levels, respectively. Correlations were calculated from the prior October (months abbreviated by lowercase letters correspond to the previous year) to the current

September (months abbreviated by uppercase letters corresponding to the year of growth). Significance thresholds change between sites due to differences in the period considered and, therefore, in the number of degrees of freedom (see **Section 2.5**).

3.4. Growth response to droughts: resilience indices

The most important BAI reductions occurred in 1986, 1991, 1995, and 1996 in *Sierra de Guadarrama*, and in 1994, 1995, 1999, and 2005 in *Sierra Nevada* (**Table 2**). All these negative growth events coincided with periods of intense aridity (see **Figs. 2 and 3**), except the 1996 event, when heavy snowfalls caused abundant breakage of branches and stems in *Sierra de Guadarrama* (Montero et al., 1997). Although both sites presented the same number of *negative event years*, the relative number of growth falls in *Sierra Nevada* is lower due to the higher age of trees than in *Sierra de Guadarrama*. The growth reductions occurred during *negative event years* in *Sierra Nevada* were higher and affected more trees than in *Sierra de Guadarrama*. However, *Sierra Nevada* pines also showed higher resilience in the post-disturbance years (**Table 2**).

Table 2. Statistics related to *negative event years* (sharp growth reductions corresponding to a relative growth loss > 30%) and post-disturbance resilience indices (resistance and resilience) in the Scots pine trees sampled at *Sierra de Guadarrama* and *Sierra Nevada* sites. The last column shows the significance level (*p*) of the comparison between sites based on Mann-Whitney *U* tests.

	<i>Sierra de Guadarrama</i>	<i>Sierra Nevada</i>	<i>p</i>
Number of event years	4	4	—
Relative number of event years (%)	13.3	6.6	—
Average percentage of trees showing an event year	42.60	63.21	—
Mean resistance (<i>R_t</i>)	0.64	0.52	< 0.0001
Mean resilience (<i>R_s</i>)	0.81	0.85	0.044

3.5. Growth modelling

According to the selected models, the most important factors affecting BAI in both sites were tree size (DBH_{cored}), temperature of the previous winter and of current spring, and SPEI (**Table 3**). In *Sierra Nevada*, the altitude has also a significant influence. Fixed factors explained more growth variability in the *Sierra de Guadarrama* model (59.1%) than in *Sierra Nevada* (46.6%) model. The tree factor, which encompasses the differences in genotype, phenotype, soil and microclimate, explained 17.1% and 28.4% of the total growth variability in *Sierra de Guadarrama* and *Sierra Nevada* sites, respectively.

Table 3. Statistics of the linear mixed-effects models fitted to basal area increment of planted Scots pine trees sampled at *Sierra de Guadarrama* and *Sierra Nevada* sites. Values are coefficient estimates and standard errors (SE) are shown in parentheses. T is the mean temperature of the months considered and SPEI is the mean SPEI value from April to September. The last two lines show the marginal (R^2_m) and conditional (R^2_c) R^2 values which show the percentage of BAI variance explained by the fixed effects and by the fixed plus random effects, respectively. Significance level: *** $p < 0.001$.

Model		BAI in <i>Sierra de Guadarrama</i>	BAI in <i>Sierra Nevada</i>
		Linear mixed-effects model coefficients (SE)	
Fixed effects	Intercept	2.587 (0.057) ***	2.094 (0.04) ***
	DBH_{cored}	0.485 (0.057) ***	0.410 (0.04) ***
	Altitude	—	0.190 (0.04) ***
	SPEI	-0.028 (0.007) ***	0.165 (0.007) ***
	T from February to May	0.062 (0.008) ***	—
	T from previous December to current March	—	0.077 (0.009) ***
Variance explained	R^2_m	0.591	0.466
	R^2_c	0.762	0.750

3.6. Projecting tree growth as a function of climate forecasts

In *Sierra de Guadarrama* the time-BAI regressions showed R^2 values of 0.003 ($p = 0.615$), 0.233 ($p < 0.001$) and 0.483 ($p < 0.001$) for the RCP 2.6, RCP 4.5 and RCP 8.5

climate scenarios, respectively (**Fig. 6**). Focusing on the RCP 2.6 scenario, growth would remain stable according to our projections. However, in the other two scenarios, which assume higher temperature increments, the growth of pines would increase throughout the 21st century. Models in *Sierra Nevada* showed R^2 values of 0.044 ($p = 0.054$), 0.023 ($p = 0.168$) and 0.018 ($p = 0.213$) for the RCP 2.6, RCP 4.5 and RCP 8.5 scenarios, respectively. In *Sierra Nevada* none of the projections have a significant trend, predicting all scenarios steady growth rates.

Figure 6. Projection of basal area increment over the 21st century for three climate scenarios (RCP 2.6, RCP 4.5 and RCP 8.5) in *Sierra de Guadarrama* and *Sierra Nevada* sites. Simple linear regressions, with their 95% confidence intervals (dashed lines), were fitted for each scenario.

4. Discussion

4.1. Growth trends

Scots pine plantations located in *Sierra de Guadarrama* and *Sierra Nevada* sites have similar competition characteristics, with basal area equal to 32.5 and 30.4 m² ha⁻¹ respectively (**Table 1**). However, the different climatic conditions, in particular the higher precipitation in *Sierra de Guadarrama* site (**Fig. 2** and **S1** in **Appendix A** of the Supplementary material), enable maintaining higher radial-growth rates (**Fig. 4**). During the initial years of growth, BAI follows a logistic function (**Fig. 4b**), but later, when trees mature, BAI increases or maintains a constant level, and then declines when trees become stressed (Duchesne et al., 2003; Pedersen, 1998). Due to this influence of age on growth, and since in both study sites forests sampled were planted at different times, the relationship between age and BAI (**Fig. 4b**) is more relevant than the temporal changes of BAI (**Fig. 4a**) to study and compare growth trends. *Sierra Nevada* plantations showed a stable growth, in contrast with the growth decline observed in *Sierra de Guadarrama* plantations. According to previous studies (Sánchez-Salguero et al., 2012; Sarris et al., 2011, 2007) this growth decline could be due to an increase in drought in the last decades (**Figs. 2** and **3**). However, the aridification trend was also observed in *Sierra Nevada*, where no growth decline has shown. Therefore, the growth decrease in *Sierra de Guadarrama* is more likely due to other factors such as increased tree-to-tree competition (Madrigal-González and Zavala, 2014; Sánchez-Salguero et al., 2015b). According to the results of **Table S1** (see **Appendix B** of the Supplementary material) a higher current stand competition influences negatively the slope of the growth trend in *Sierra de Guadarrama*. Although we do not know how competition has changed over time, we can assume that, in general, in those plots where competition is higher at the present time, it was also higher in the near past.

4.2. Growth responses to climate

Growth in *Sierra Nevada* was more strongly related to the temperature and precipitation prior to the start of the vegetative period than with other climate variables (**Fig. 5**). This kind of relationship is typical in dry Mediterranean climate conditions (Camarero et al., 2013; Sánchez-Salguero et al., 2015a), where growth depends on the recharge of soil water during the dormancy period, and the vegetative period begins earlier than in continental and cooler sites. Indeed, the spring growth onset in *Sierra Nevada* would occur in mid to late April (Guada et al., 2016), whilst in *Sierra de Guadarrama* it would begin in early May (Fernández-de-Uña et al., 2013). In *Sierra de Guadarrama* plantations, by contrast, BAI was related with the prior winter and the current spring and summer climate, possibly because here the growth peak occurs later, between late May and June (Fernández-de-Uña et al., 2013), than in *Sierra Nevada*, where it takes place in early to mid-May (Guada et al., 2016). The negative correlation observed between BAI and winter precipitation in *Sierra de Guadarrama* plantations is probably related to cool, cloudy conditions leading to a decrease in photosynthesis rates and carbon uptake (Hari et al., 1981; Young et al., 2012). Contrary to what was expected, we found that Scots pine in *Sierra de Guadarrama* was more sensitive to climate, with more significant relationships than in the drier *Sierra Nevada* site. A mixed climate signal of Scots pine forests from central Spain mountains has already been described, with higher responsiveness to dry and cold conditions downwards and upwards, respectively, and mixed responses at intermediate altitudes (Sánchez-Salguero et al., 2015a). All sampled trees were dominant or codominant; thus, it could be expected that the competition from surrounding vegetation has not obscured the climatic signal on radial growth. Therefore, the weaker climatic signal in *Sierra Nevada* could indicate that the planted pines have reduced their growth and their climate response as an

adaptation or acclimation to more arid conditions in this site, whereas in *Sierra de Guadarrama*, planted pines can reach their growth potential in favorable years. In fact, the growth of Scots pines of natural-origin in *Sierra Nevada* have similar weak correlations with climate than close plantations (Rubio-Cuadrado et al., 2018b). This limiting effect of climate in *Sierra Nevada*, joint to the increase in competition, may also be related with the growth stagnation of this site, whereas in *Sierra de Guadarrama* competition hinders growth potential, decreasing the BAI after the initial developmental stages.

4.3 Growth reactions to severe droughts

All years detected with growth drops (**Table 2**) occurred after the increase of aridity, which started in the 1980s (**Fig. 3**). Growth resistance during drought was lower and post-drought growth resilience was higher in *Sierra Nevada*, which is the drier site. According to previous studies, the growth resistance and/or resilience can be directly related to aridity (Gazol et al., 2018; Sohn et al., 2016), possibly due to changes in carbon allocation (e.g., higher root to shoot ratios) in trees adapted to drier conditions (Maguire and Kobe, 2015), although these relationships are not uniform and may be influenced by competition, age, size or topography (Rubio-Cuadrado et al., 2018b; Sohn et al., 2016). The growth stagnation in *Sierra Nevada* plantations did not seem to be smoothing the effect of drought events on growth when compared with the behavior of plantations located in their area of provenance (*Sierra de Guadarrama*), since resistance of plantations is also lower, but resilience is similar to pines of natural origin in *Sierra Nevada* (Rubio-Cuadrado et al., 2018b).

4.4 Growth projections for the 21st century

When modelling growth, most of the tree growth variability was explained by tree size ($\text{DBH}_{\text{cored}}$), similar to previous reports (Monserud and Sterba, 1996). Effectively, according to our models, tree size was the most important factor and it was directly related to BAI, while climate variables had less influence (lower coefficients in the models) and their relationships with growth were diverse (**Table 3**). In the case of the RCP 2.6 emissions scenario in *Sierra de Guadarrama*, and in the three emissions scenarios in *Sierra Nevada*, our results predict stable growth trends for the 21st century (**Fig. 6**). However, for the RCP 4.5 and RCP 8.5 emissions scenarios in *Sierra de Guadarrama*, the models predict a growth increase possibly due to an increase of growth rates and a lengthening of the growing season.

Contrary to what we expected and to what the species distribution models predict (Benito Garzón et al., 2011; García-López and Allué, 2010), growth in *Sierra Nevada* plantations has so far not been affected by the climate warming and aridification after the 1970s. Although the growth rate of these plantations was lower than in *Sierra de Guadarrama* plantations, the growth trend has remained constant in *Sierra Nevada*, without negative effects of the temperature increment, which could have amplified the evaporative demand and increased drought stress. Our models are based on current climate-growth relationships, which can be modified as climate and stand structure change, and they do not take into account the evolution of competition related to stand maturation and temporal instability of climate-growth relationships. Therefore, if these relationships do not significantly change and factors not considered (e.g., competition) maintain their current influence, the growth of the Scots pine plantations in *Sierra Nevada* would not be affected by the forecasted climate warming, whereas their northern counterparts in *Sierra de Guadarrama* would improve their growth. In any

case, the lower growth of trees in *Sierra Nevada* could indicate a less efficient hydraulic system or site/climate conditions limiting growth. Thus, although the presented model does not forecast growth reductions, it is possible that increased drought stress could raise the risk of decline or mortality events.

5. Conclusions

Analyzing growth rates and trends of Scots pine plantations in two sites under different climate conditions has demonstrated that plantations in the drier site (*Sierra Nevada*), located at the species' southernmost distribution limit, showed a stable and lower growth than plantations in *Sierra de Guadarrama*, located in wetter sites. In addition, if the current climate-growth relationships hold, *Sierra Nevada* plantations will maintain the current limited growth over the 21st century. Furthermore, *Sierra Nevada* plantations have been less responsive to climate, and have shown higher resilience after droughts. On the contrary, growth of *Sierra de Guadarrama* plantations shows higher drought resistance, and it is projected to increase under the warmest emission scenarios considered for the 21st century. The different reactions of the two Scots pine plantations to climate warming reflect their different site conditions. The northern population benefits from warmer climate, whereas in the southern site climate warming will not increase growth, and we cannot discard more drought stress occurring in the future. Plantations show a great capacity to acclimate to local climate conditions.

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7. References

- Aldea, J., Bravo, F., Bravo-Oviedo, A., Ruiz-Peinado, R., Rodríguez, F., del Río, M., 2017. Thinning enhances the species-specific radial increment response to drought in Mediterranean pine-oak stands. *Agric. For. Meteorol.* 237–238, 371–383.
<https://doi.org/10.1016/J.AGRFORMET.2017.02.009>
- Alia, R., Gil, L., Pardos, J.A., 1995. Performance of 43 *Pinus pinaster* Ait. provenances on 5 locations in central Spain. *Silvae Genet.* 44, 75–81.
- Armenteras, A.A., 1903. Árboles y Montes. Curiosidades artísticas e históricas. Imprenta Ricardo Rojas, Madrid. Spain.
- Barton, K., 2012. MuMin package: multi-model inference. Model selection and model averaging based on information criteria (AICc and alike). <https://cran.r-project.org/package=MuMIn>.
- Beguiría, S., Vicente-Serrano, S.M., 2017. Calculation of the Standardised Precipitation-Evapotranspiration Index. <http://sac.csic.es/spei>.
- Benito Garzón, M., Alía, R., Robson, T.M., Zavala, M.A., 2011. Intra-specific variability and plasticity influence potential tree species distributions under climate change. *Glob. Ecol. Biogeogr.* 20, 766–778. <https://doi.org/10.1111/j.1466-8238.2010.00646.x>
- Biondi, F., Qeadan, F., 2008. A theory-driven approach to tree-ring standardization: defining the biological trend from expected basal area increment. *Tree-Ring Res.* 64, 81–96. <https://doi.org/10.3959/2008-6.1>

- Bogino, S., Fernández Nieto, M., Bravo, F., 2009. Climate effect on radial growth of *Pinus sylvestris* at its southern and western distribution limits. *Silva Fenn.* 43, 609–623. <https://doi.org/10.14214/sf.183>
- Brockhoff, E.G., Jactel, H., Parrotta, J.A., Quine, C.P., Sayer, J., 2008. Plantation forests and biodiversity: Oxymoron or opportunity? *Biodivers. Conserv.* 17, 925–951. <https://doi.org/10.1007/s10531-008-9380-x>
- Bunn, A., Korpela, M., Biondi, F., Campelo, F., Mérian, P., Qeadan, F., Zang, C., 2016. dplR: Dendrochronology Program Library in R. R package version 1.6.4. [WWW Document]. URL <https://cran.r-project.org/package=dplR>
- Camarero, J.J., Gazol, A., Sangüesa-Barreda, G., Oliva, J., Vicente-Serrano, S.M., 2015. To die or not to die: early warnings of tree dieback in response to a severe drought. *J. Ecol.* 103, 44–57. <https://doi.org/10.1111/1365-2745.12295>
- Camarero, J.J., Guerrero-Campo, J., Gutierrez, E., 1998. Tree-ring growth and structure of *Pinus uncinata* and *Pinus sylvestris* in the Central Spanish Pyrenees. *Arct. Alp. Res.* 30, 1. <https://doi.org/10.2307/1551739>
- Camarero, J.J., Manzanedo, R.D., Sanchez-Salguero, R., Navarro-Cerrillo, R.M., 2013. Growth response to climate and drought change along an aridity gradient in the southernmost *Pinus nigra* relict forests. *Ann. For. Sci.* 70, 769–780. <https://doi.org/10.1007/s13595-013-0321-9>
- Camarero, J.J., Olano, J.M., Parras, A., 2010. Plastic bimodal xylogenesis in conifers from continental Mediterranean climates. *New Phytol.* 185, 471–480. <https://doi.org/10.1111/j.1469-8137.2009.03073.x>
- Collins, M., Knutti, R., Arblaster, J., Dufresne, J.L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J., Wehner, M., 2013. Long-term climate change: projections,

commitments and irreversibility, in: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

De Iaco, S., Myers, D.E., Posa, D., 2002. Nonseparable space-time covariance models: some parametric families. *Math. Geol.* 34, 23–42.
<https://doi.org/10.1023/A:1014075310344>

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., McClean, C., Osborne, P.E., Reineking, B., Schröder, B., Skidmore, A.K., Zurell, D., Lautenbach, S., 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography (Cop.)*. 36, 27–46.
<https://doi.org/10.1111/j.1600-0587.2012.07348.x>

Duchesne, L., Ouimet, R., Morneau, C., 2003. Assessment of sugar maple health based on basal area growth pattern. *Can. J. For. Res.* 33, 2074–2080.
<https://doi.org/10.1139/x03-141>

FAO, 2006. Global planted forests thematic study. Results and analysis (No. 38), Planted Forests and Trees. Food and Agriculture Organization of the United Nations, Rome, Italy.

Fernández-de-Uña, L., Fonti, P., Aranda, I., Cañellas, I., Gea-Izquierdo, G., 2013. Impact of drought on the intra-annual growth of *Pinus sylvestris* L. *Open For. Sci. J.* 6, 43–45. <https://doi.org/10.2174/1874398601306010043>

Fox, J., Weisberg, S., 2011. An R companion to applied regression, Second. ed. SAGE

Publications, Inc, Thousand Oaks, USA.

- García-López, J.M., Allué, C., 2010. Effects of climate change on the distribution of *Pinus sylvestris* L. stands in Spain. A phytoclimatic approach to defining management alternatives. *For. Syst.* 19, 329. <https://doi.org/10.5424/fs/2010193-8694>
- Gazol, A., Camarero, J.J., Vicente-Serrano, S.M., Sánchez-Salguero, R., Gutiérrez, E., de Luis, M., Sangüesa-Barreda, G., Novak, K., Rozas, V., Tíscar, P.A., Linares, J.C., Martín-Hernández, N., Martínez del Castillo, E., Ribas, M., García-González, I., Silla, F., Camisón, A., Génova, M., Olano, J.M., Longares, L.A., Hevia, A., Tomás-Burguera, M., Galván, J.D., 2018. Forest resilience to drought varies across biomes. *Glob. Chang. Biol.* 24, 2143–2158. <https://doi.org/10.1111/gcb.14082>
- Gil, L., López, R., García-Mateos, Á., González-Doncel, I., 2009. Seed provenance and fire-related reproductive traits of *Pinus pinaster* in central Spain. *Int. J. Wildl. Fire* 18, 1003–1009. <https://doi.org/10.1071/WF08101>
- Gómez-Aparicio, L., Zavala, M.A., Bonet, F.J., Zamora, R., 2009. Are pine plantations valid tools for restoring Mediterranean forests? An assessment along abiotic and biotic gradients. *Ecol. Appl.* 19, 2124–41. <https://doi.org/10.1890/08-1656.1>
- Guada, G., Camarero, J.J., Sánchez-Salguero, R., Cerrillo, R.M.N., 2016. Limited growth recovery after drought-induced forest dieback in very defoliated trees of two pine species. *Front. Plant Sci.* 7, 418. <https://doi.org/10.3389/fpls.2016.00418>
- Hari, P., Hallman, E., Salminen, R., Vapaavuori, E., 1981. Evaluation of factors controlling net photosynthetic rate in Scots pine seedlings under field conditions without water stress. *Oecologia* 48, 186–189. <https://doi.org/10.1007/BF00347962>
- Holmes, R.L., 1997. The dendrochronology program library, in: Grissino-Mayer, H.D., Holmes, R.L., Fritts, H.C. (Eds.), *The International Tree-Ring Data Bank Program*

Library Ver. 2.1 User's Manual. Laboratory of Tree-Ring Research, University of Arizona, Tucson, USA, pp. 40–71.

IPCC, 2014. Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., Yiou, P., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Reg. Environ. Chang.* 14, 563–578. <https://doi.org/10.1007/s10113-013-0499-2>

Lloret, F., Keeling, E.G., Sala, A., 2011. Components of tree resilience: effects of successive low-growth episodes in old ponderosa pine forests. *Oikos* 120, 1909–1920. <https://doi.org/10.1111/j.1600-0706.2011.19372.x>

Macias, M., Andreu, L., Bosch, O., Camarero, J.J., Gutiérrez, E., 2006. Increasing aridity is enhancing silver fir *Abies alba* Mill.) water stress in its south-western distribution limit. *Clim. Change* 79, 289–313. <https://doi.org/10.1007/s10584-006-9071-0>

Madrigal-González, J., Zavala, M.A., 2014. Competition and tree age modulated last century pine growth responses to high frequency of dry years in a water limited forest ecosystem. *Agric. For. Meteorol.* 192–193, 18–26. <https://doi.org/10.1016/J.AGRFORMET.2014.02.011>

- Maguire, A.J., Kobe, R.K., 2015. Drought and shade deplete nonstructural carbohydrate reserves in seedlings of five temperate tree species. *Ecol. Evol.* 5, 5711–5721.
<https://doi.org/10.1002/ece3.1819>
- Mencuccini, M., Martínez-Vilalta, J., Vanderklein, D., Hamid, H.A., Korakaki, E., Lee, S., Michiels, B., 2005. Size-mediated ageing reduces vigour in trees. *Ecol. Lett.* 8, 1183–1190. <https://doi.org/10.1111/j.1461-0248.2005.00819.x>
- Mesa Garrido, M.Á., 2016. Geografía y política forestal: Análisis general de la gestión de los montes en la provincia de Granada: Siglos XVIII-XX. Dissertation, Universidad de Granada, Granada, Spain.
- Monserud, R.A., Sterba, H., 1996. A basal area increment model for individual trees growing in even- and uneven-aged forest stands in Austria. *For. Ecol. Manage.* 80, 57–80. [https://doi.org/10.1016/0378-1127\(95\)03638-5](https://doi.org/10.1016/0378-1127(95)03638-5)
- Montero, G., del Río, M., Ortega, C., 1997. Efectos de la selvicultura en la reducción de los daños por la nieve en masas de *Pinus sylvestris* del Sistema Central. *Montes* 47, 5–10.
- Montes, F., Ledo, A., 2010. Incorporating environmental and geographical information in forest data analysis: a new fitting approach for universal kriging. *Can. J. For. Res.* 40, 1852–1861. <https://doi.org/10.1139/X10-131>
- Muggeo, V.M.R., 2008. Segmented: an R package to fit regression models with broken-line relationships. *R News* 8, 20–25.
- Nakagawa, S., Schielzeth, H., 2013. A general and simple method for obtaining R^2 from generalized linear mixed-effects models. *Methods Ecol. Evol.* 4, 133–142.
<https://doi.org/10.1111/j.2041-210x.2012.00261.x>
- Olivar, J., Bogino, S., Spiecker, H., Bravo, F., 2015. Changes in climate-growth relationships and IADF formation over time of pine species (*Pinus halepensis*, *P.*

- pinaster* and *P. sylvestris*) in Mediterranean environments. *For. Syst.* 24, e-010.
<https://doi.org/10.5424/fs/2015241-05885>
- Payn, T., Carnus, J.M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, S., Orazio, C., Rodriguez, L., Silva, L.N., Wingfield, M.J., 2015. Changes in planted forests and future global implications. *For. Ecol. Manage.* 352, 57–67.
<https://doi.org/10.1016/j.foreco.2015.06.021>
- Pedersen, B.S., 1998. The role of stress in the mortality of Midwestern oaks as indicated by growth prior to death. *Ecology* 79, 79–93. [https://doi.org/10.1890/0012-9658\(1998\)079\[0079:TROSIT\]2.0.CO;2](https://doi.org/10.1890/0012-9658(1998)079[0079:TROSIT]2.0.CO;2)
- Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., R Core Team, 2018. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-131. <https://cran.r-project.org/package=nlme>.
- R Development Core Team, 2017. R: a language and environment for statistical computing. <http://www.R-project.org/>.
- Rodríguez-García, C., Montes, F., Ruiz, F., Cañellas, I., Pita, P., 2014. Stem mapping and estimating standing volume from stereoscopic hemispherical images. *Eur. J. For. Res.* 133, 895–904. <https://doi.org/10.1007/s10342-014-0806-6>
- Rozas, V., 2003. Tree age estimates in *Fagus sylvatica* and *Quercus robur*: testing previous and improved methods. *Plant Ecol.* 167, 193–212.
<https://doi.org/10.1023/A:1023969822044>
- Rubio-Cuadrado, Á., Bravo-Oviedo, A., Mutke, S., del Río, M., 2018a. Climate effects on growth differ according to height and diameter along the stem in *Pinus pinaster* Ait. *iForest - Biogeosciences For.* 11, 237–242. <https://doi.org/10.3832/for2318-011>
- Rubio-Cuadrado, Á., Camarero, J.J., Aspizua, R., Sánchez-González, M., Gil, L.,

- Montes, F., 2018b. Abiotic factors modulate post-drought growth resilience of Scots pine plantations and rear-edge Scots pine and oak forests. *Dendrochronologia* 51, 54–65. <https://doi.org/10.1016/j.dendro.2018.08.001>
- Ruiz-Peinado, R., Bravo-Oviedo, A., López-Senespleda, E., Bravo, F., del Río, M., 2017. Forest management and carbon sequestration in the Mediterranean region: A review. *For. Syst.* 26, eR04S. <https://doi.org/10.5424/fs/2017262-11205>
- Sánchez-González, M., Cabrera, M., Herrera, P.J., Vallejo, R., Cañellas, I., Montes, F., 2016. Basal area and diameter distribution estimation using stereoscopic hemispherical images. *Photogramm. Eng. Remote Sens.* 82, 605–616. [https://doi.org/10.1016/S0099-1112\(16\)30098-2](https://doi.org/10.1016/S0099-1112(16)30098-2)
- Sánchez-Salguero, R., Camarero, J.J., Carrer, M., Gutiérrez, E., Alla, A.Q., Andreu-Hayles, L., Hevia, A., Koutavas, A., Martínez-Sancho, E., Nola, P., Papadopoulos, A., Pasho, E., Toromani, E., Carreira, J.A., Linares, J.C., 2017. Climate extremes and predicted warming threaten Mediterranean Holocene firs forests refugia. *Proc. Natl. Acad. Sci.* 114, E10142–E10150. <https://doi.org/10.1073/pnas.1708109114>
- Sánchez-Salguero, R., Camarero, J.J., Hevia, A., Madrigal-González, J., Linares, J.C., Ballesteros-Canovas, J.A., Sánchez-Miranda, A., Alfaro-Sánchez, R., Sangüesa-Barreda, G., Galván, J.D., Gutiérrez, E., Génova, M., Rigling, A., 2015a. What drives growth of Scots pine in continental Mediterranean climates: Drought, low temperatures or both? *Agric. For. Meteorol.* 206, 151–162. <https://doi.org/10.1016/j.agrformet.2015.03.004>
- Sánchez-Salguero, R., Linares, J.C., Camarero, J.J., Madrigal-González, J., Hevia, A., Sánchez-Miranda, Á., Ballesteros-Cánovas, J.A., Alfaro-Sánchez, R., García-Cervigón, A.I., Bigler, C., Rigling, A., 2015b. Disentangling the effects of competition and climate on individual tree growth: A retrospective and dynamic

- approach in Scots pine. *For. Ecol. Manage.* 358, 12–25.
<https://doi.org/10.1016/J.FORECO.2015.08.034>
- Sánchez-Salguero, R., Navarro-Cerrillo, R.M., Camarero, J.J., Fernández-Cancio, Á., 2012. Selective drought-induced decline of pine species in southeastern Spain. *Clim. Change* 113, 767–785. <https://doi.org/10.1007/s10584-011-0372-6>
- Sarris, D., Christodoulakis, D., Körner, C., 2011. Impact of recent climatic change on growth of low elevation eastern Mediterranean forest trees. *Clim. Change* 106, 203–223. <https://doi.org/10.1007/s10584-010-9901-y>
- Sarris, D., Christodoulakis, D., Körner, C., 2007. Recent decline in precipitation and tree growth in the eastern Mediterranean. *Glob. Chang. Biol.* 13, 1187–1200.
<https://doi.org/10.1111/j.1365-2486.2007.01348.x>
- Schweingruber, F.H., Eckstein, D., Serre-Bachet, F., Bräker, O.U., 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. *Dendrochronologia* 8, 9–38.
- Sohn, J.A., Saha, S., Bauhus, J., 2016. Potential of forest thinning to mitigate drought stress: A meta-analysis. *For. Ecol. Manage.* 380, 261–273.
<https://doi.org/10.1016/j.foreco.2016.07.046>
- Speer, J.H., 2012. *Fundamentals of tree ring research*. The University of Arizona Press, Tucson, USA.
- Vadell, E., de-Miguel, S., Pemán, J., 2016. Large-scale reforestation and afforestation policy in Spain: A historical review of its underlying ecological, socioeconomic and political dynamics. *Land use policy* 55, 37–48.
<https://doi.org/10.1016/J.LANDUSEPOL.2016.03.017>
- Valbuena-Carabaña, M., de Heredia, U.L., Fuentes-Utrilla, P., González-Doncel, I., Gil, L., 2010. Historical and recent changes in the Spanish forests: A socio-economic

process. *Rev. Palaeobot. Palynol.* 162, 492–506.

<https://doi.org/10.1016/J.REVPALBO.2009.11.003>

van der Maaten-Theunissen, M., van der Maaten, E., Bouriaud, O., 2015. pointRes: An R package to analyze pointer years and components of resilience.

Dendrochronologia 35, 34–38. <https://doi.org/10.1016/J.DENDRO.2015.05.006>

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. *Clim. Change* 109, 5–31. <https://doi.org/10.1007/s10584-011-0148-z>

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. *J. Clim.* 23, 1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>

Wigley, T.M.L., Briffa, K.R., Jones, P.D., Wigley, T.M.L., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *J. Clim. Appl. Meteorol.* 23, 201–213. [https://doi.org/10.1175/1520-0450\(1984\)023<0201:OTAVOC>2.0.CO;2](https://doi.org/10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2)

Young, G.H.F., McCarroll, D., Loader, N.J., Gagen, M.H., Kirchhefer, A.J., Demmler, J.C., 2012. Changes in atmospheric circulation and the Arctic Oscillation preserved within a millennial length reconstruction of summer cloud cover from northern Fennoscandia. *Clim. Dyn.* 39, 495–507. [https://doi.org/10.1007/s00382-011-1246-](https://doi.org/10.1007/s00382-011-1246-3)

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Zuur, A.F., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., 2009. Mixed effects models and extensions in ecology with R, *Statistics for Biology and Health*.

Springer New York, New York, USA. <https://doi.org/10.1007/978-0-387-87458-6>