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Declining trends in long-term *Pinus pinea* L. growth forecasts in Southwestern Spain

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ABSTRACT

Warmer and drier climate is among the main factors of the declining processes reported and expected for the future in the Mediterranean forest ecosystems. *Pinus pinea* is one the main Mediterranean conifers and its largest populations are in SW Spain, providing multifunctional services. The sensitivity of this species to drought is known, but the potentiality of its productivity to decline in SW Spain has not been yet assessed. We modeled *P. pinea* growth with climate covariates and a large set of tree ring chronologies from the beginning of the 20th century to the 2010s. Then we forecast annual increments over the period 2030–2100 using regionalized estimates of a global change model in three scenarios of greenhouse gas concentration. The climatic conditions between winter and mid spring were the most significant for the model. The climate predictions indicated an increase of potential water stress, and our forecasts described downturn trends of the annual growth, more accentuated in the scenario with the highest emissions and temperatures. These are the first long-term forecasts of growth of *P. pinea* in SW Spain. Our model cannot be directly applied at higher latitudes, where previous studies have shown differences in climate-growth relationships, but provides a benchmark for research and forestry of the potential climate-driven decrease of productivity of the *P. pinea* populations in the Southern Iberian Peninsula.

1. Introduction

Sustained global warming has been observed in the recent past and is expected for the near future, with heatwaves and droughts becoming more frequent, and human activities, mainly through emissions of greenhouse gases, are unequivocally implicated in this process (IPCC, 2023).

Changes related to global warming in the Mediterranean forest ecosystems have been already occurring and are expected in the future (Lindner and Calama, 2013). Western Mediterranean forests will undergo potential stress under stable CO_2 emissions by the mid-century (2040–2070) and are highly vulnerable under scenarios of increasing emissions and higher temperatures by the end of the century (Hidalgo-Triana et al., 2023). Moreover, in Mediterranean forests, the higher atmospheric concentration of CO_2 will most probably not counterbalance the impact of warming through enhanced net primary productivity, unless trees exhibit extreme (unlikely) carbon fertilization mechanisms (Gea-Izquierdo et al., 2017).

Pinus pinea L. is an emblematic conifer of the Mediterranean landscape. It is present throughout southern Europe and the eastern and southern Mediterranean coasts. It is an autochthonous species in the Iberian Peninsula (Martínez and Montero, 2004), where its area is 474, 000 ha (including pure and mixed stands), i.e 3.5 % of the total Spanish forest cover and more than the 70 % of the total distribution area of the species in the Mediterranean region (Montero et al., 2004). In Spain, the distribution range of *P. pinea* has been influenced by human activities and most of its stands have been originated from reforestation and afforestation carried out during the 20th century (Montero et al., 2004). The largest Spanish *P. pinea* forest systems are in southwestern Spain, especially in the province of Huelva, where it is present in almost 80, 000 ha (16.5 % of the national area). *P. pinea* forests in Huelva are multifunctional systems, which provide 20 % of the national production of *P. pinea* timber and 12 % of the national production of edible pine nuts (Porras and Bueno, 2003).

The response to climate of *P. pinea* trees living in forests has been assessed in different areas of the Mediterranean basin and exhibit some

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variability related to site-specific adaptation or plasticity (see Mechergui et al., 2021). Studies in the Southwestern Iberian Peninsula showed a strong relationship between *P. pinea* tree growth and the meteorological conditions of the moister and milder months of the year (November--February) indicating that water availability is the main limiting factor and that tree growth is reduced or even stopped in summer (Natalini et al., 2015, 2016a; Gonçalves et al., 2023). These findings suggest that more severe and frequent droughts and/or longer and drier dry seasons may limit *P. pinea* forest productivity in Southern Spain as at higher latitudes (Pardos et al., 2015; Calama et al., 2019). However, there is a lack of estimations of whether and how this could happen in the SW Spain, where a loss of forest productivity would entail a loss of multifunctionality (Peñuelas et al., 2017; Morán-Ordóñez et al., 2021; also see the review by Nocentini et al., 2022).

In this study we modeled stem growth in *P. pinea* stands in SW Spain using climate covariates as predictors, and we forecast growth over the coming decades under different climate change scenarios. Our objective was to give an estimation of the likely trends of forest productivity as a baseline for adaptive management of forests and environment. Our hypothesis was that growth should exhibit some declining trend at least in the driest predicted climate scenarios.

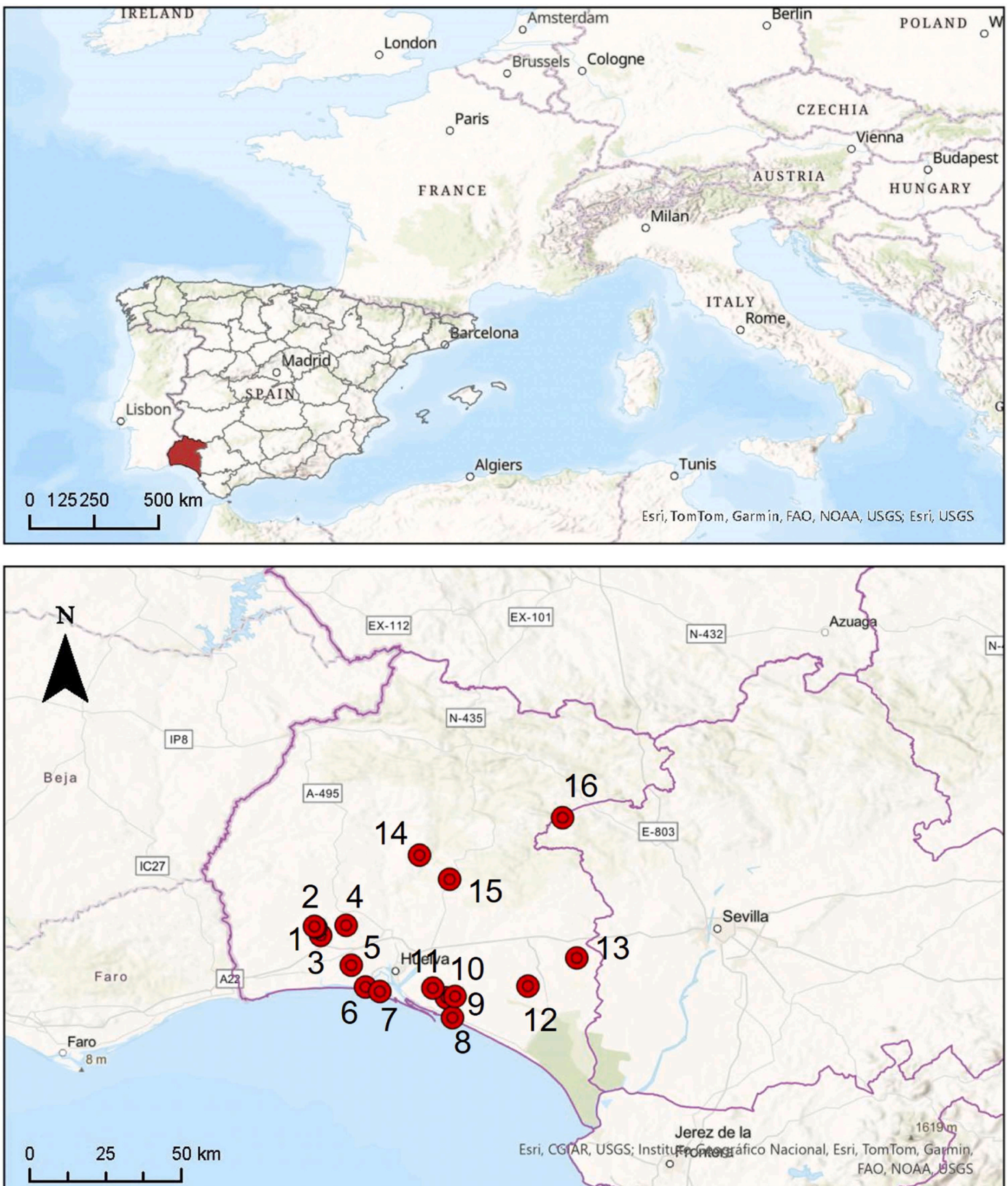

Fig. 1. Location of the study region (red area, upper map) and the 16 study sites (red dots, lower map).

2. Material and methods

2.1. Study sites

The data were collected from 16 *P. pinea* stands in the province of Huelva, SW Spain (Fig. 1, Table 1). The maximum distance between stands is 76 km. The stands are monospecific and present a regular structure. Between sites, the mean diameter at breast height varies between 25 cm and 70 cm, the mean tree height varies between 10 m and 20 m, and the mean stand density is 190 trees/ha with a standard deviation of 40. The terrains are predominantly flat (mean slope 5 %, standard deviation 9 % and mode 0 %).

The climate of the study region in Mediterranean, with a mean annual temperature varying between 16.5 and 18.9 ℃, a mean annual precipitation between 523 and 750 mm and a dry period (i.e. monthly summed rainfall lower than monthly mean temperature × 2, following Bagnouls-Gaussen's definition of xerothermic index) lasting for 4–6 months between May/June and September/October (Table 2, Fig. 4). There is a positive gradient of precipitation from the coastal zone to the interior zone (higher precipitation in study sites 14–16) and an slight increment of the mean annual temperature and mean of the maximum temperatures of the hottest month in the sites with less oceanic influence (excepting site 16, with a higher altitude).

Soils vary between dystric regosols and arenosols in the dunes areas that are situated besides the see (sites 7, 8), eutric planosols in the flat areas near the coast showing hydromorphic properties (sites 1–6, 11–13), albic arenosols in sites 9–10, where deep sandy sediments are present, and eutric cambisols (sites 14–16), situated on gently undulating terrains over acid rocks (Table 2).

2.2. Tree ring data

We used a data set of 352 annual tree ring width series, including published and unpublished data (Table 1, Fig. 2, Fig. 3). We started with a bigger data set, but we discarded the series that were uncomplete (the innermost ring was far from the stem pith) because they could not be used with confidence to estimate the age of the tree. The series that showed great and sudden growth increases due to past silvicultural operations were also discarded to ease the expression of the climatic signal.

There were two samples per tree, and the individual tree chronologies were the means of the paired series. Sample preparation, ring width measurement and dating followed the commonly used methods in dendrochronology (a detailed description can be found in Natalini, 2017). With cross-dating we detected missing rings, i.e. rings that were partially or not formed.

To appraise the common climatic signal of the tree ring chronologies, we computed pairwise correlations and ran a principal component analysis to check the proportion of variance on the first component (Natalini et al., 2015). We carried out bivariate analyses to study the relationships between BAI, diameters at breast height (DBH) and age.

From the ring width series we computed the basal are increments (BAI), that we adopted as an index of forest productivity and as response variable in growth modelling. The BAI remove the trend of decreasing ring width with increasing stem size over time (Biondi and Qeadan, 2008). Moreover, the BAI reflects the real biomass growth and is thus suitable to study long-term changes of forest productivity. As per tree allometry, when the stereometric body grows, the BAI becomes the driver of growth while the radial increments decrease and do not reflect the volume and biomass growth (Pretzsch, 2020). For that, BAI is often used to study growth trends and climate-growth relationships (e.g. Piovesan et al., 2008; Gea-Izquierdo et al., 2017; Andivia et al., 2018; Colangelo et al., 2021). The dendrochronological data treatment was done with dplR (version 1.7.4, release date 2022-06-23; Bunn, 2008).

Table 1
Number of sampled trees, coordinates, altitudes and statistics (range, mean and standard deviation) of individual tree basal area increment (BAI) series, ring width series and age. "Publication" refers to published and unpublished data (for published data, the reference is provided).

Site	# trees	Lat.	Long.	Elev. (m a.s.l.)	BAI (mm^2)				Ring widths (mm)				Age				Publication
					min.	max.	mean	s.d.	min.	max.	mean	s.d.	min.	max.	mean	s.d.	
1	12	37.39	− 7.19	413	0	3252.75	780.64	466.38	0	12.63	1.86	1.42	67	73	70.00	2.16	unpublished
2	2	37.39	− 7.19	100	305.33	5826.74	2288.95	1302.79	0.48	14.16	3.26	2.28	65	68	66.50	2.12	Natalini et al. (2015)
3	16	37.36	− 7.17	302	0	5213.67	781.78	696.96	0	15.05	1.79	1.87	49	102	68.92	13.71	unpublished
4	26	37.39	− 7.10	136	0	3911.86	421.08	509.21	0	15.38	1.45	1.75	31	110	54.05	17.02	unpublished
5	5	37.27	− 7.08	72	0	1512.66	409.50	284.08	0	9.92	1.03	1.09	71	144	123.8	30.33	unpublished
6	10	37.21	− 7.04	20	0	4951.12	813.05	809.82	0	11.98	1.97	1.79	36	100	56.88	24.01	Natalini et al. (2015)
7	8	37.2	− 7.00	20	0	1290.15	335.13	195.03	0	6.40	1.07	0.93	43	111	75.60	32.32	Natalini et al. (2015)
8	16	37.12	− 6.78	20	0	5491.40	764.25	615.20	0	14.87	1.75	1.74	52	91	73.14	13.55	unpublished
9	4	37.18	− 6.77	55	0	2414.44	366.46	401.07	0	8.40	1.15	0.92	74	81	78.25	3.10	unpublished
10	31	37.18	− 6.80	161	0	6786.93	755.79	719.85	0	14.34	1.66	1.67	48	158	82.24	32.02	unpublished
11	4	37.21	− 6.84	30	0	6512.23	1521.48	1061.83	0	10.99	2.17	1.75	61	175	92.25	55.23	Natalini et al. (2015)
12	10	37.21	− 6.56	75	0	6732.06	995.28	869.39	0	8.62	2.06	1.47	50	107	67.50	18.74	unpublished
13	9	37.30	− 6.41	348	0	4276.10	850.51	689.33	0	11.46	1.99	1.58	40	86	63.86	19.89	unpublished
14	12	37.60	− 6.88	185	0	4249.09	567.85	453.74	0	9.83	1.66	1.4	40	79	59.75	14.45	unpublished
15	8	37.53	− 6.79	260	0	5809.75	1071.86	618.59	0	8.75	1.64	1.21	83	135	114.62	17.13	Natalini et al. (2016a)
16	3	37.71	− 6.45	494	8.97	3451.45	1069.67	703.32	0.38	14.62	2.91	2.27	31	45	39.67	7.57	unpublished

Table 2
Climate and soil characteristics of the study sites. P: mean annual precipitation (mm), MAT: mean annual temperature (°C), MMT: mean of the maximum temperatures of the hottest month (°C), mmT: mean of the minimum temperatures of the coldest month (°C), Dry period: number of months in which monthly precipitation is lower than twice the monthly mean temperature (months). Climate data from the Spanish Meteorological Agency (AEMET). Reference Soil Group according to FAO classification (IUSS Working Group WRB, 2015).

Site	P	MAT	MMT	mmT	Dry period	Reference soil group
1	523	18.0	33.6	6.7	4.9	Eutric Planosols/Gleyic Luvisols
2						
3						
4						
5	563	17.7	31.0	6.5	5.9	
6						
7						Dystric Regosols/Arenosols
8	523	16.9	30.8	5.8	4.7	
9						Albic Arenosols/Cambisols (humic)
10						
11						Eutric Planosols/Gleyic Luvisols
12	564	16.7	33.7	2.9	4.7	
13	579	18.9	35.7	6.8	5.0	
14	727	18.3	35.6	5.7	4.2	Eutric Cambisols
15						
16	750	16.5	32.4	6.0	4.0	

2.3. Climate data

To model and forecast the influence of climate on tree growth we used the Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010) as climatic variable. The SPEI is derived from meteorological data on a monthly basis and can be computed at different time scales, i.e. it is possible to incorporate the influence of past values in the computation enabling the index to reflect the memory of the system under study: for instance, a value of 6 implies that data from the current month and of the previous five months are taken into account for computing the SPEI value of the current month. To compute the SPEI we used the SPEI package (version 1.8.1 release date 2023-03-02; Beguería and Vicente-Serrano, 2023).

We computed the historical series and expected projections of SPEI with two data sets of minimum temperatures, maximum temperatures and precipitation: meteorological station records and regionalized estimates of the global model BCC-CSM1.1 (Wu et al., 2013). The meteorological station was "Huelva" (37.26 N, 6.95 W, 17 m a.s.l.) of the Spanish Meteorological Agency (AEMET); we retrieved the data compiled by the European Climate Assessment Dataset project (ECA&D, see Klok and Klein Tank, 2009) through the Climate Explorer of the Royal Netherlands Meteorological Institute at https://climexp.knmi.nl/. The regionalized estimates for Southwestern Spain are elaborated by the AEMET (https://www.aemet.es/es/serviciosclimaticos/cambio_climat/datos_diarios, Amblar et al., 2017) for different Representative Concentration Pathways (RCP, see IPCC, 2014). For this study, we selected the RCP 4.5, the RCP 6.0 and the RCP 8.5. The RCP 4.5 is an intermediate scenario in which CO_2 emissions peak around 2040 and then decline; in the RCP 6.0 is an intermediate scenario with emissions increasing until around 2080 and then decline; the RCP 8.5 is the worst scenario with emissions rising throughout the 21st century.

The climate scenarios describe warmer and drier conditions in the three RCP scenarios over the period 2030–2100: the mean annual temperature is expected to increase 1.7, 1.9 and 2.4 Celsius degrees in the RCP 4.5, 6.0 and 8.5 respectively, while the xerothermic index indicates a longer dry period, with an earlier start and a later end compared to those observed until 2020 (Fig. 4). The computed SPEI series for the historical period (1920–2020) and for the three forecasts (period 2030–2100) are displayed in Fig. 5.

2.4. Growth modelling and forecasting

To model the tree growth we followed this procedure:

1) First, we analyzed the Pearson correlations between the series of individual tree BAI and the SPEI series (one per month from January to October) at 1-, 3- and 6-month scales. We computed the correlations using the raw BAI series as well as standardized BAI series, i.e. detrended with a cubic smoothing spline (frequency response of 50 % at a wavelength of 30 years) and then prewhitened with an autoregressive model, following reference dendroclimatological methods (Cook and Kairiukstis, 1990). Based on our previous studies in the region, the used spline is the most suitable to extract the climatic signal, and the 1-, 3- and 6-month scales of the SPEI incorporate the data of the most relevant period in which the highest growth response to climate should be expected (Natalini et al., 2016a, 2016c).
2) Then we selected the SPEI series of the month and time scale that showed the highest significant correlations and tested them as covariates in mixed-effect linear models with one random factor (tree). We tested the SPEI series separately, i.e. one SPEI series per model, because the correlations among the SPEI series were high. The models were fitted over the whole historical data.

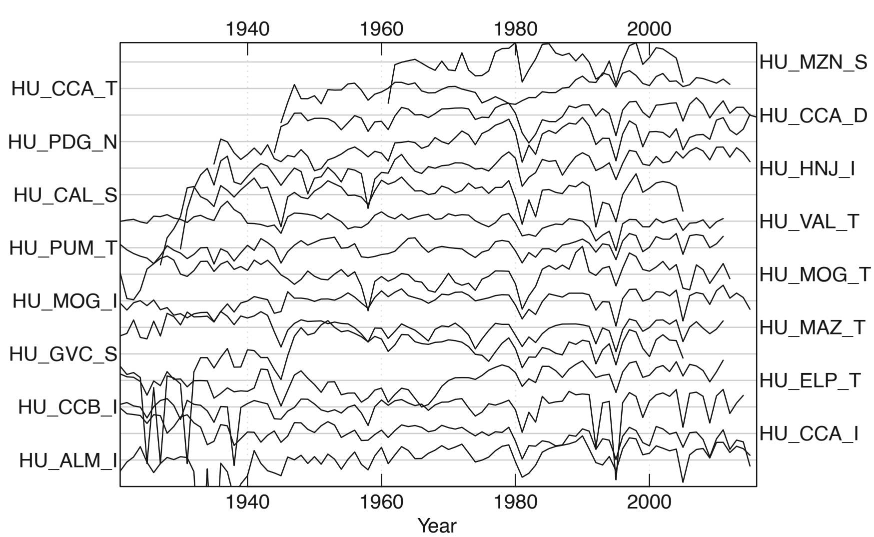

Fig. 2. Mean BAI series of each study site.

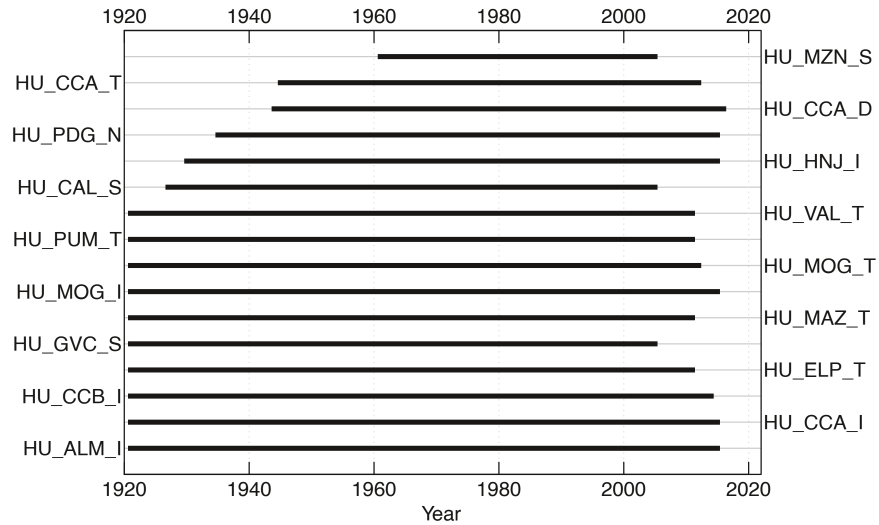

Fig. 3. Segment plot showing the time span covered by the mean basal area increment (BAI) series of each study site.

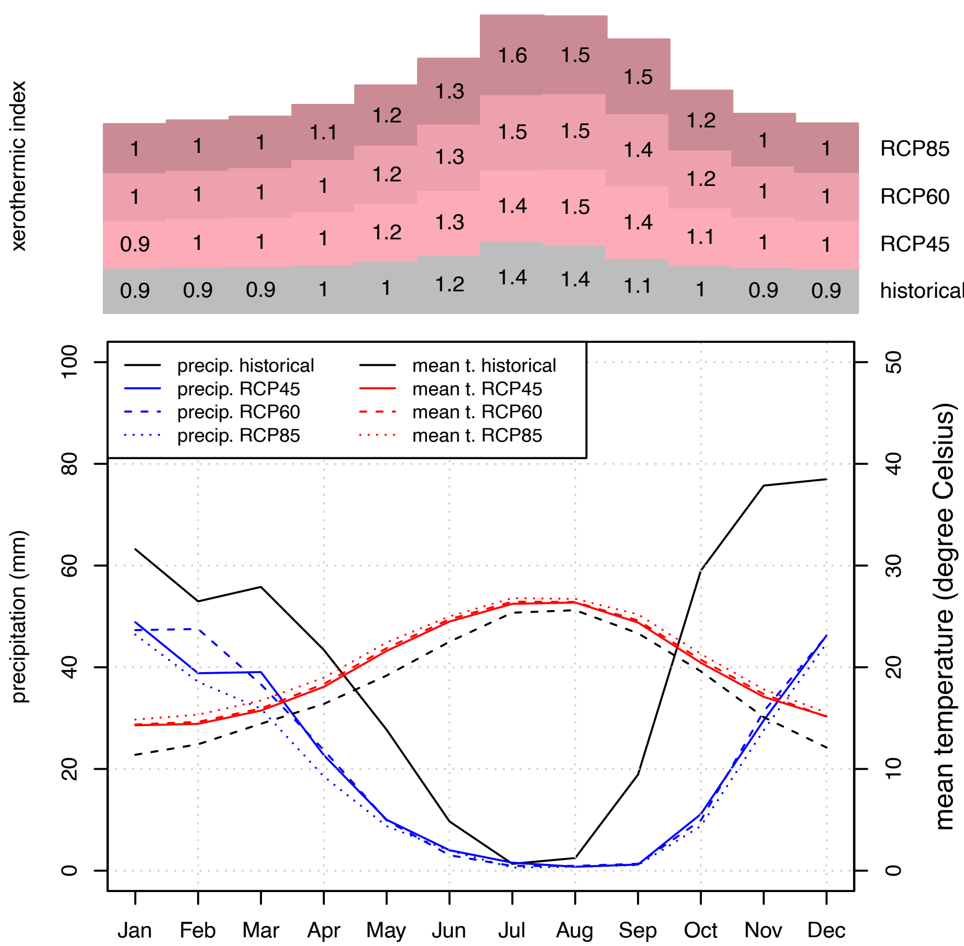

Fig. 4. Top: monthly xerothermic index calculated as a ratio between mean temperature (x2) and precipitation (based on Bagnouls-Gaussen's definition) with historical records of Huelva and forecasted climate estimates of the three RCP scenarios. Bottom: climograph showing the mean monthly temperature and the monthly precipitation of the historical records of the meteorological station Huelva (period 1920–2020) and of the forecasted climate in RCP 4.5, RCP 6.0 and RCP 8.5 scenarios (period 2023–2100).

3) We repeated the step 2, but this time setting two nested random factors (trees within sites).
4) From the steps 2 and 3 we selected the best model, based on the coefficient of determination (R squared), the root mean square error (RMSE), the Akaike information criterion (AIC) and chi-squared tests of the residuals.
5) To validate the predictive performance of the model selected in the step 4, from the historical data we extracted a validation subset

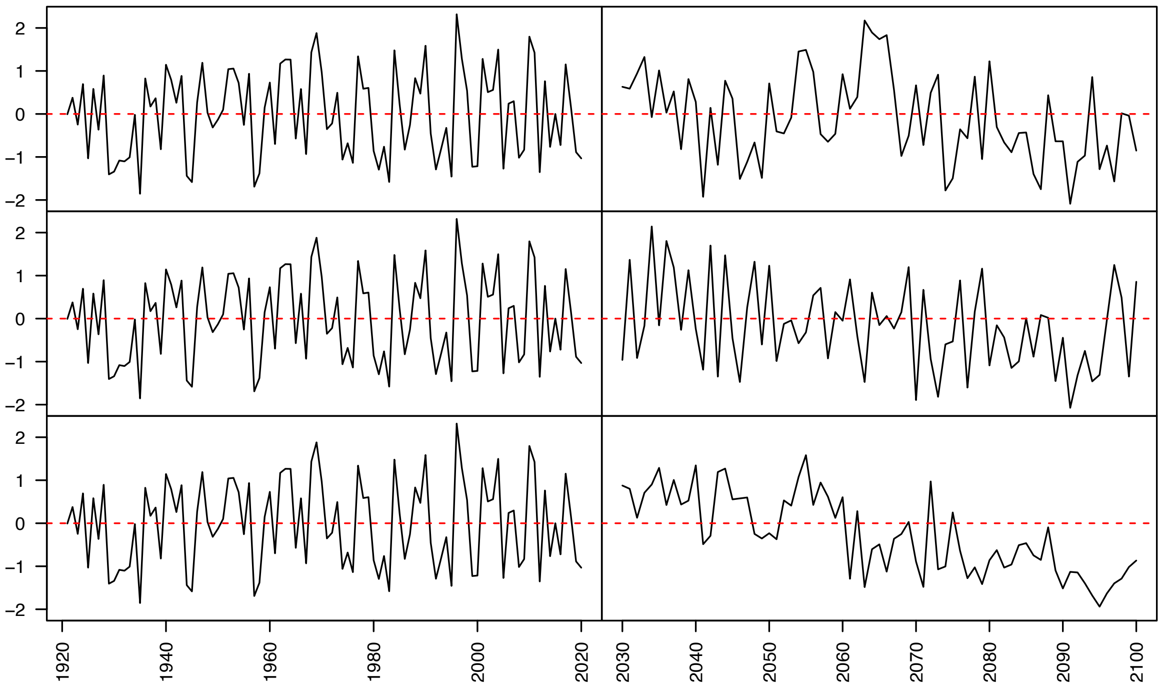

Fig. 5. 6-month March SPEI computed with historical records of the meteorological station Huelva (left) and computed with the forecasted climate estimates of the RCP 4,5 (top, right), RCP 6.0 (center, right) and RCP 8.5 (bottom, right) scenarios.

containing the last 10 years of each tree; we trained the model with the remaining data and checked the predictions with the validation subset with the R squared.

In all the models we included a binary variable as fixed effect to account for missing rings, i.e. when BAI was zero (due to missing rings on both samples of a tree) or tiny (due to missing ring on one of the two samples) the value of this variable was "1", elsewhere was "0". Moreover, we added a first-order autocorrelation structure (AR1) within each BAI series to account for the dependency of each annual BAI on the BAI of the previous year. The models were fitted with the packages lme4 (version 1.1-34, release date 2023-07-04; Bates et al., 2015) and nlme (version 1.1-162, release date 2023-01-31; Pinheiro and Bates, 2000).

We eventually used the validated model to generate BAI forecasts over 70 years (2030–2100) in the three RCP scenarios using forecasted values of the SPEI that had been selected as the best climate covariate in the model. We did not forecast missing rings, i.e. the binary variable was let constant zero. The mean BAI of each forecast scenario was compared with the mean historical observed BAI with a t test and computing relative percentage differences. To analyze differences in growth trends among the three forecast scenarios, we fitted a regression line through the series of the overall mean annual BAIs, and tested differences between regression constants and slopes. To discover downturns in the growth trends and compare them among scenarios, we performed a segmented linear regression of the overall mean annual BAI series using the package "segmented" (Muggeo, 2008).

3. Results

Statistics of the ring width series, BAI series and tree ages are presented in Table 1. The mean correlation among the ring width series was 0.35 and the first principal component explained the 47 % of the variance (Fig. 6).

Age and DBH showed a direct relationship, i.e. the older the tree the wider the diameter (Fig. 7), while age did not show any clear relationship with BAI (Fig. 8).

The mean correlation among the 3-month and 6-month SPEI series

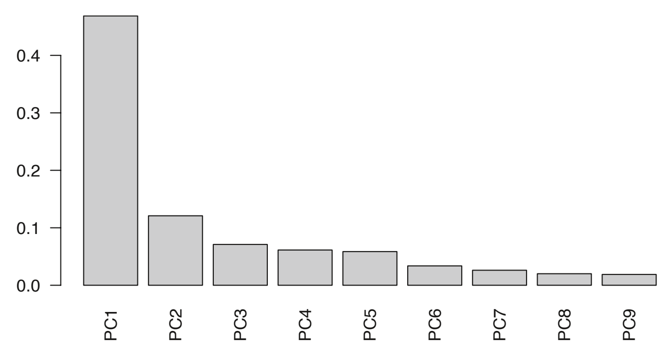

Fig. 6. Percentage of variance explained by the first 9 principal components of a principal component analysis run with the ring width dataset.

was 0.54. The 6-month SPEI series from January to May showed the highest correlations with the BAI series (Fig. 9) and were tested in the models.

The best model included the two nested random factors, the 6-month March SPEI, the binary variable for missing rings and a first-order autocorrelation term (Tables 3 and 4). Setting two nested random factors significantly improved the model, compared to the model with one random factor (chi-squared test p value < 0.01). The coefficient of determination of the model was 0.741 on training and 0.740 on validation. The structures of the residuals over the train and validation sets are displayed in Fig. 10 and Fig. 11 respectively.

The predicted BAIs over the period 2023–2100 in the three RCP scenarios are showed in Fig. 12. Compared to the overall mean BAI of the historical period, the overall mean BAI over the forecast period was 5 % lower, 6 % lower and 8 % lower in the RCP 4.5, 6.0 and 8.5 respectively. The differences of the means (historical vs. each RCP forecast) was statistically significant with a 95 % confidence. The intercepts of the regression lines fitted to the forecast mean BAI series were similar ($0.10 > p$ value > 0.05), but the slope (always negative) was significantly steeper in the RCP 8.5 compared to the other two scenarios (p value < 0.05). The segmented regression analysis suggested that there

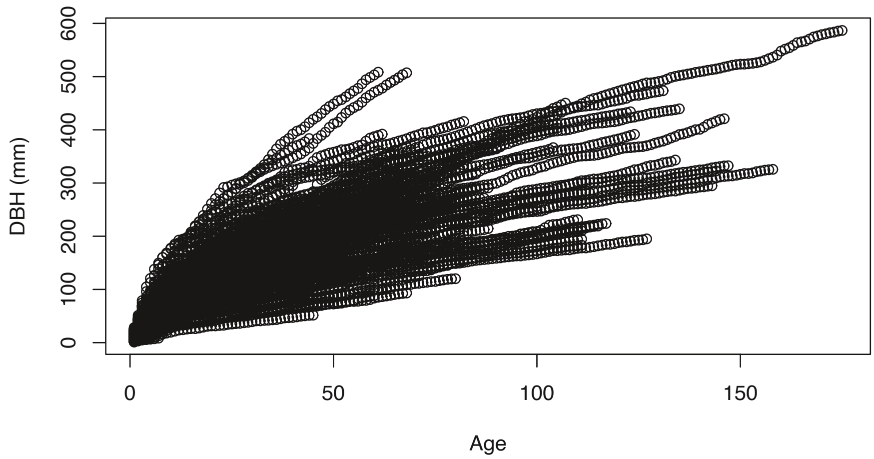

Fig. 7. Scatter plot of age and diameter at breast height.

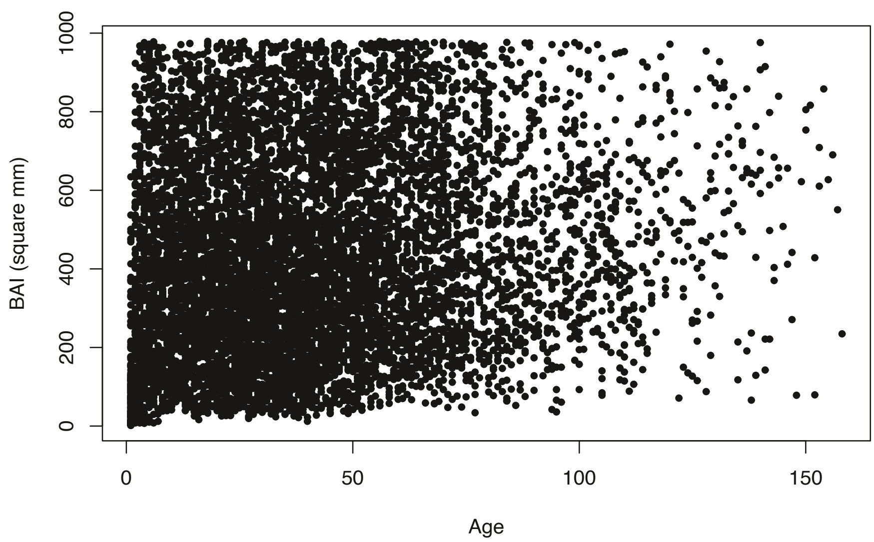

Fig. 8. Scatter plot of age and basal area increments.

will be a downturn around 2065 in the RCP 4.5 scenario, but more than two decades earlier in the other two scenarios (around 2036 in RCP 6.0 and around 2044 in RCP 8.5).

4. Discussion

The growth of *Pinus pinea* in our study sites showed a strong relationship with the climatic conditions of winter and spring, and this is consistent with the results found in other Mediterranean areas (see Mechergui et al., 2021). The strength of the climatic signal in our chronologies was also confirmed by the principal component analysis and the correlation among sites (Natalini et al., 2015). What differentiates the Southwestern Iberian Peninsula from higher latitudes is that the correlations are weak or insignificant from June to September, a finding that we had found in previous studies in this region (Natalini et al., 2016a) and it is confirmed now with a much bigger data set. To interpret these findings, we have to consider the climatic patterns in SW Spain: precipitations are concentrated in winter and are always negligible in summer, so tree growth mainly depends on the water availability deriving from winter, and stops or is reduced during the hot and dry summers. These considerations are important when thinking about the external validity of our model, that means: climate-growth relationships of some species are, to some extent, site-specific (see e.g. De Luis et al., 2013; Di Filippo et al., 2021), and a model developed for a region is not generally applicable in another region. Micro-site conditions influence tree growth, generating differences in the ring series of trees from nearby locations, and this partly explains why the correlation among our tree ring series is not high (although higher than that reported in other studies on *P. pinea*, e.g. Nabais et al., 2014). However, although micro-site differences can be relevant for dendroclimatology, the large-scale climate generally overrides small-scale conditions (Hartl et al., 2021). While our study sites present some environmental differences (see Table 2), the principal component analysis confirmed the strong, common climatic signal in our chronologies (Natalini et al., 2015), as the variance explained by the first component was much higher than the amount explained by the second component. Moreover, our modelling procedure with nested random effects accounts for micro-site effects while setting apart the climatic influence of larger scale.

The series of the SPEI computed with the 3-month and 6-month scales were highly correlated, while tree growth was weakly correlated with the 1-month SPEI, so we could not include more than one significant SPEI variable in our model. However, the variance explained by the model was high, and this also indicates that the growth of *P. pinea* in SW Spain strongly depends on climate and in a relatively narrow interval, i.e. mild months in spring preceded by rainy winters. These

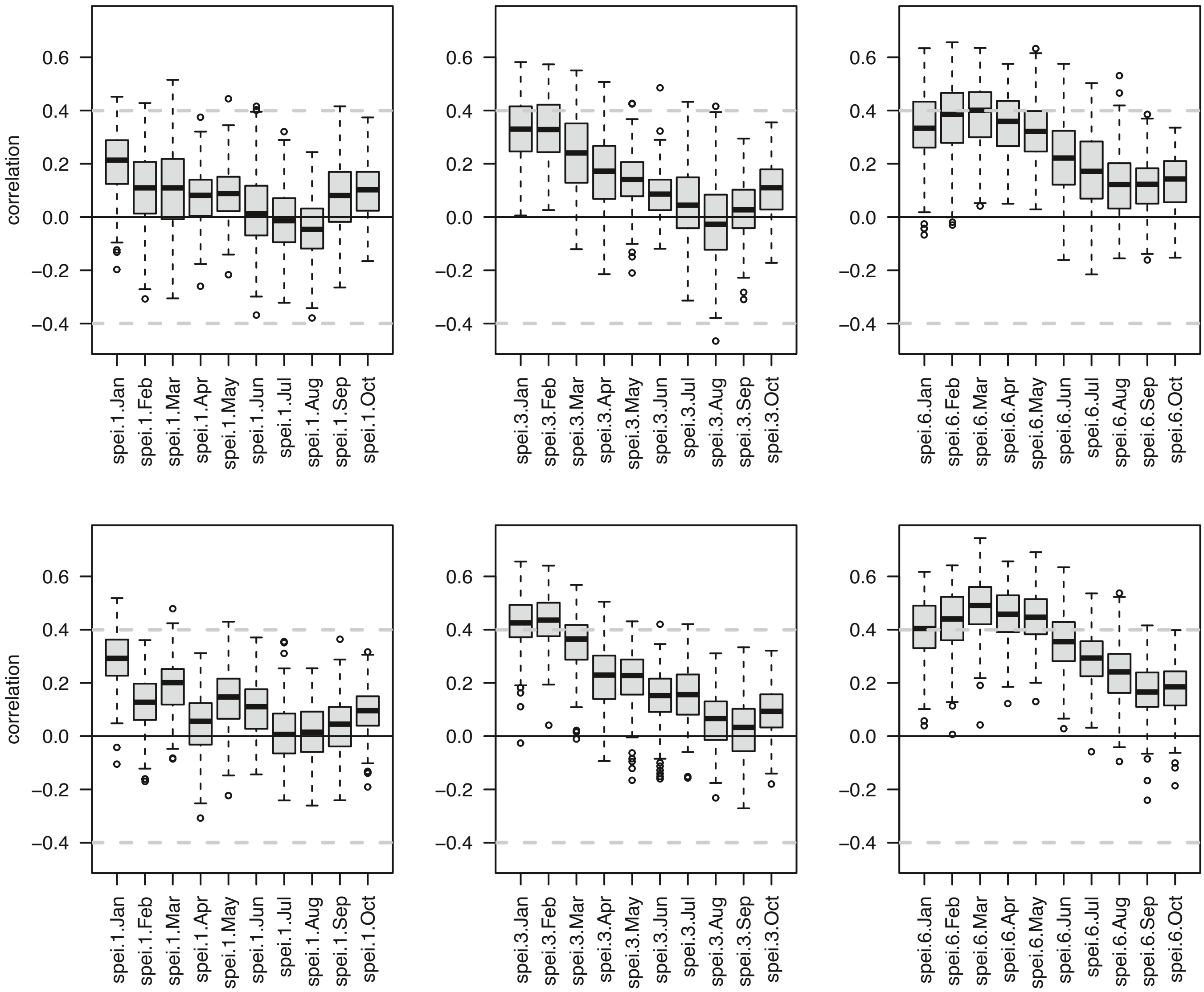

Fig. 9. Correlations between the BAI series (raw BAI in the top graphs and standardized prewhitened BAI in the bottom graphs) and the SPEI series at different time scales (1-month, 3-month and 6-month SPEI). Each box plot describes the distribution of the correlation coefficients computed between the corresponding monthly SPEI series and all the BAI series. The dashed horizontal lines indicate the critical level p= 0.05 corrected with the Bonferroni rule.

Table 3
Root mean squared error (RMSE, in squared millimeters), coefficient of determination (R^2) and Akaike information criterion (AIC) of the models fitted with the 6-month SPEI series from January to May and with one (tree) and two (site/tree) nested random factors. The table is ordered by the AIC (ascending order).

	RMSE (tree)	RMSE (site/ tree)	R^2 tree	R^2 (site/ tree)	AIC (tree)	AIC (site/ tree)
March	1.85123	1.85127	0.742	0.742	23,004	22,972
February	1.85887	1.85891	0.739	0.739	23,159	23,127
April	1.86617	1.86623	0.735	0.735	23,305	23,272
January	1.87427	1.87433	0.732	0.732	23,466	23,433
May	1.87658	1.87663	0.731	0.731	23,510	23,478

Table 4
Estimates and 95 % confidence intervals of the model finally selected and used to forecast.

		Lower	Estimates	Upper
Fixed effects:	Intercept	6.030	6.266	6.503
	spei.6.Mar	0.197	0.205	0.213
	missing.ring	− 4.930	− 4.867	− 4.804
Random Effects:	Level: site sd(intercept)	0.267	0.437	0.713
	Level: tree within site sd(intercept)	0.469	0.530	0.599
Autocorrelation structure:	Phi	0.587	0.603	0.620

findings are linked to the trends of the growth forecasts. We predicted a growth decline in the driest scenario (RCP 8.5), as we hypothesized; but we also predicted some growth reduction (although with smaller magnitude) in the intermediate scenarios RCP 4.5 and RCP 6.0. We must consider that soils in the study sites are mostly coarse-grained, so trees will be exposed to more frequent water shortage in the considered climate change scenarios. Indeed, productivity decline seems the most likely process in the coming decades, because it is also suggested by other studies, especially when the considered species is at or close to the most xeric limit of its distribution range. For instance, the results by Calama et al. (2019) point out significant decreases in timber and cone production under severe climate change scenarios. Similarly, growth decline has been predicted for other species in higher latitudes as well

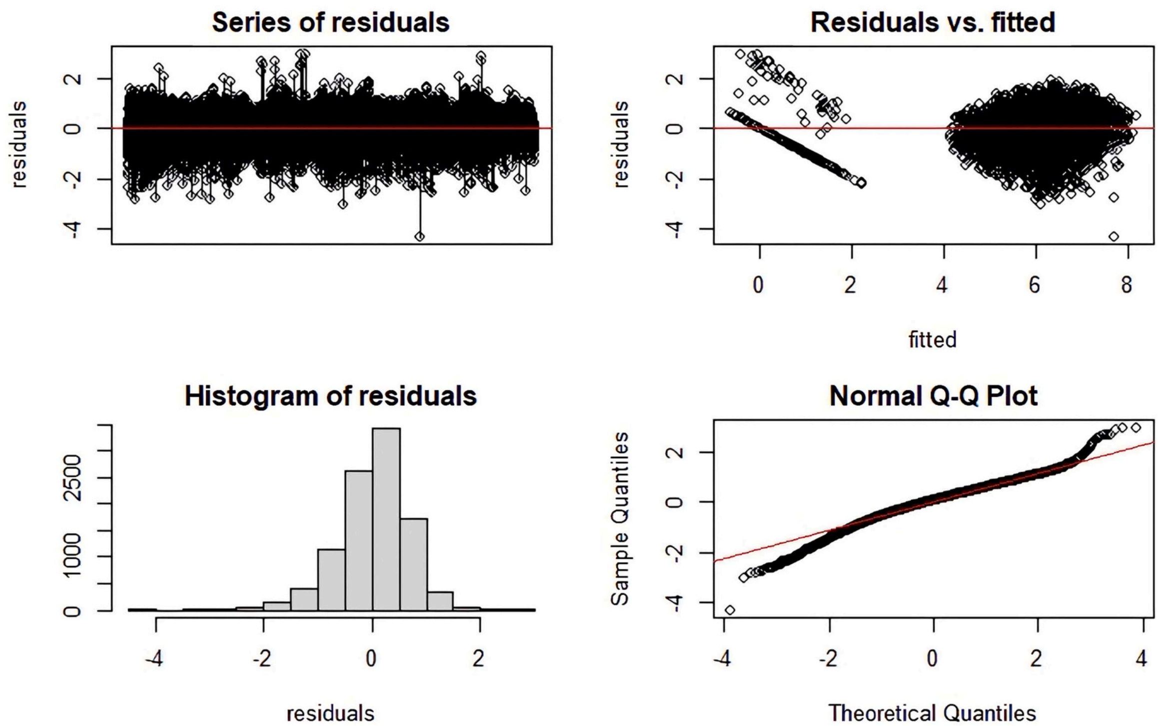

Fig. 10. Diagnostic plots of the model residuals with train data.

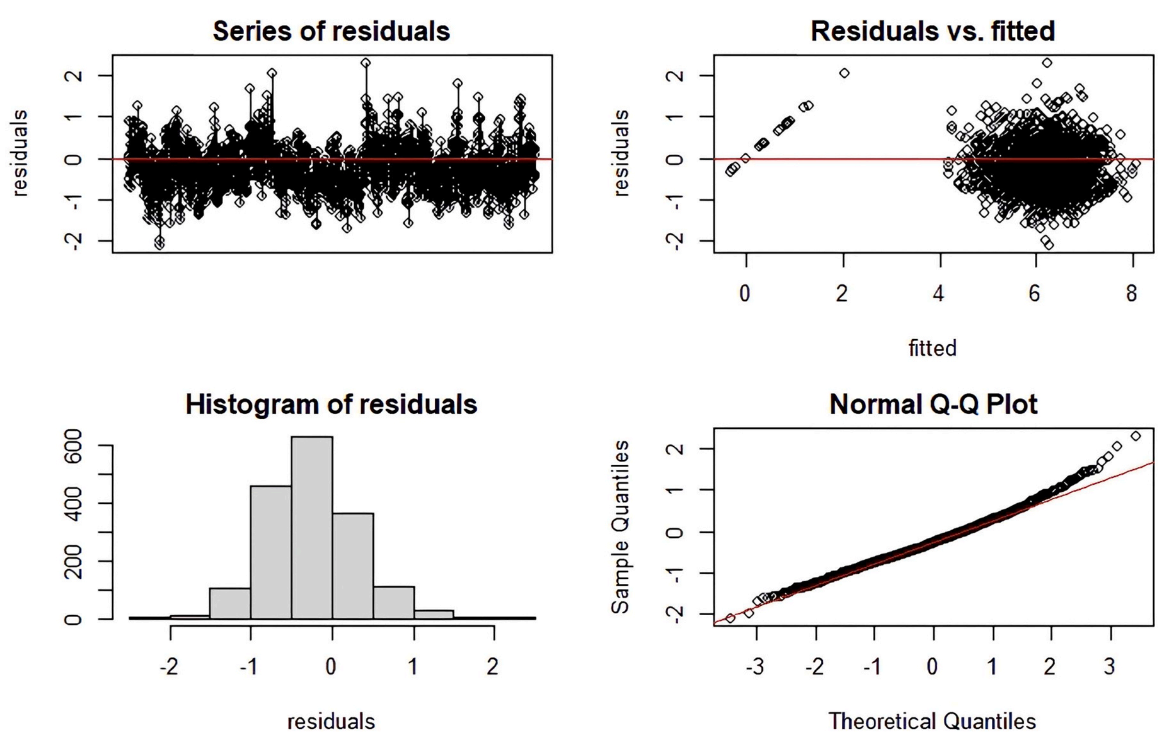

Fig. 11. Diagnostic plots of the model residuals with validation data.

(Reich and Oleksyn, 2008; Bauwe et al., 2015). Observational data also support these predictions, i.e. long-term negative trends of forest growth have been reported and related to climate change in several studies in the last decade (e.g. Piovesan et al., 2008; Natalini et al., 2016b; Gea-Izquierdo et al., 2021a; Colangelo et al., 2021).

Given the highly probable loss of forest productivity in the future, there is a rising interest in adaptive forest management measures. Some authors suggest for *P. pinea* some optimal stand structure and allometric relationships to achieve the maximum vigor of the system, namely stand density, crown diameter, height/diameter ratio, and cone production (see Mechergui et al., 2021). Nevertheless, there is still some uncertainty about the effectiveness of forest management to buffer climate change impact. For instance, the model simulations by Pardos et al. (2015) in Central inner Spain indicate that *Pinus pinea* productivity (and even

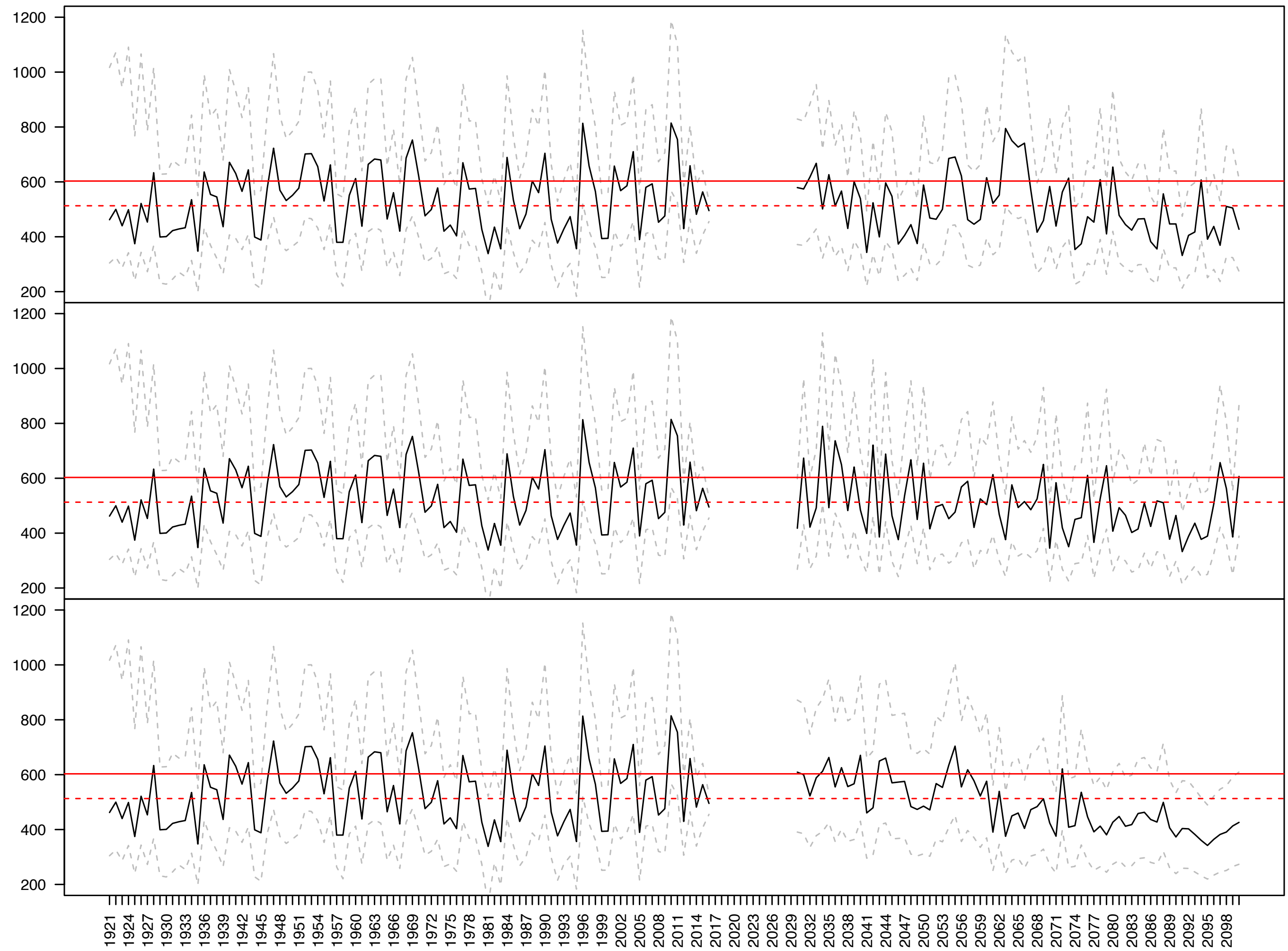

Fig. 12. Estimated BAI (mm^2) over the historical period (1921–2016) and over the forecast period (2023–2100). The black solid line is the median of the BAIs within each year, the upper and lower grey dotted lines are the first and third quartile of the BAIs within each year. The forecasts are for RCP 4.5 (top, right), RCP 6.0 (center, right) and RCP 8.5 (bottom, right). The horizontal solid red line is the overall mean BAI during the historical period, and the horizontal dashed red line is the median BAI of the historical period.

survival, on soils with low/medium fertility and water holding capacity) may be at risk regardless of the management alternatives.

In dense old-growth forests, tree age and tree diameter are not related because the natural stand dynamics are complex and shade-tolerant species can survive without reaching the highest levels of the canopy (Piovesan et al., 2008; also see the description of Fig. 2 in Di Filippo et al., 2021). In contrast, in our *P. pinea* stands ages and diameters show a relationship because in such managed forests the growth of young trees is promoted and the largest trees are usually logged, so the biggest trees are typically the oldest as well. On the other hand, we found no direct relationship between age and BAI, which means that the increment of tree mass does not decline with age. Theoretically, the increment should be asymptotic but not declining (Pretzsch, 2020), although even this assumption is not always confirmed, e.g. in old-growth trees it has been observed that the increments do not flatten (Pretzsch, 2020; Colangelo et al., 2021).

In our modelling approach, we used data from trees of different age classes, assuming an equal response to climate although this could depend on age (Carrer and Urbinati, 2004; Colangelo et al., 2021). Indeed, in a previous study we observed some differences in the growth-climate correlations between young and old trees, but the correlation patterns always suggested sensitivity to water availability and the shifts over time of the growth response were similar, suggesting a common climatic driver regardless of the age (Natalini et al., 2015). Similarly, other authors have reported that site-specific conditions can override age-specific response. For instance, in Colangelo et al. (2021), the lack of age-dependent differences in growth response to summer water balance in one study site was related to the different environmental characteristics of the sites. Moreover, growth decline has been similarly observed in all age classes when climate change is a factor of the decline (Natalini et al., 2016b; Gea-Izquierdo et al., 2021a, 2021b).

The residuals of our model have an odd pattern when the actual and predicted values are around zero and away from the other points of the scatter plot (Figs. 10 and 11). This is due to the missing rings, that in fact may be considered outliers. However, they provide valuable ecological information because they are related to especially adverse climatic conditions (Novak et al., 2016a). Indeed, in a previous investigation in SW Spain we modeled the probability of *P. pinea* rings being absent, and we found that the most significant covariate is precipitation (Vázquez-Piqué et al., 2019). Moreover, when we were measuring the mean chronology of a tree, we may have recorded a ring as missing just because it was absent on both samples from that tree; but in fact that ring may have been partially formed and the increment borer may not have reached it. In addition to climate, other physiological mechanisms can be implicated in the partial or complete absence of a ring (Novak et al., 2011, 2016b), and our binary variable tries to account for these unknown factors as well. All things considered, we could have lost information if we had omitted the years of the missing rings in our analyses, and in fact the binary variable improved our model.

5. Conclusions

In this study we present the first growth forecast of *Pinus pinea* in SW Spain where there are the largest populations of this species. Our forecast covers a long period until the end of the 21st century, showing a decline in growth. As a working hypothesis, we postulated growth reductions at least in the climate change scenario with the highest increase of temperatures, but in fact we found negative trends also in the intermediate and less pessimistic scenarios. Our forecasts clearly indicate that the productivity of these ecosystems is very likely to decrease. The reduction of productivity is implicated in a likely loss of multifunctionality in Mediterranean forests, and adaptive forest management might buffer the impact of the future warmer and drier climate, but the effectiveness of management is controversial and was beyond the scope of this study. Further investigations could deepen into the possible significant age-dependence of growth response to climate, but our forecasts are coherent with previous knowledge about the historical climate-growth relationships (both in our study region and in other Mediterranean areas), are unprecedented in SW Spain and provide a valuable reference for ecological studies and forest management.

CRediT authorship contribution statement

Fabio Natalini: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Reyes Alejano:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Javier Vázquez-Piqué:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Marta Pardos:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Rafael Calama:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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