Developing alternatives to adaptive silviculture: Thinning and tree growth resistance to drought in a *Pinus* species on an elevated gradient in Southern Spain

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ABSTRACT

Forest plantations are more vulnerable to the stress induced by biotic and abiotic factors than are naturally regenerated forests. These effects can be aggravated by a lack of management in large reforestation areas, and thinning could, therefore, help trees to reduce dieback and tree mortality related to drought. We address this question using a dendrochronology and modelling approach to improve the understanding of the growth response of high-density planted pine forests to thinning in drought-prone areas of Southern Spain. An experimental trial was, therefore, carried out with three species (*Pinus halepensis, P. nigra,* and *P. sylvestris*) and three thinning treatments (unthinned, moderate, and heavy thinning), after which growth-climate relationships and drought vulnerability indices were assessed. Three separate generalized linear mixed-effects models (GLMM), one for each species and location, were fitted using BAI as the response variable, and post-thinning growth trajectories and drought vulnerability indices were also simulated. Ten-year basal area showed strong growth responses following the thinning treatment (BAI_{10}, 72% for *P. halepensis* and 50% for *P. sylvestris* as regards heavy thinning and 51% for *P. nigra* as regards moderate thinning), with different responses to precipitation and temperature according to species and thinning intensity. The significant effects of thinning on drought vulnerability indices indicated that the thinning treatments had a positive effect, irrespective of the pine species, although this was more evident in the case of *P. sylvestris* (recovery F = 28.10, $p < 0.001$, and resilience F = 35.21, $p < 0.001$ respectively) and *P. halepensis* (recovery F = 10.97, $p < 0.001$ and resilience F = 16.91, $p < 0.001$). The models also showed that climatic effect was greater for *P. nigra* than for *P. sylvestris*. The simulation also provides information on the long-term effectiveness of thinning; in *P. sylvestris* the effect of thinning tended to be attenuated after 20 years, but this was not the case of *P. nigra* and *P. halepensis*. High values of modelled resilience were found after thinning, with a time to recovery of between two and four years after drought depending on thinning intensity. Our findings showed the advantages of thinning for growth under different climatic constraints, particularly drought. This work is a new contribution that demonstrates the urgent need for forest managers to take steps in order to help drought-vulnerable Mediterranean pine plantations to adapt to the risks posed by climate change.

1. Introduction

The climate of the future is expected to be characterised by rising temperatures and a higher frequency of extreme weather events such as droughts that will affect the performance of forest functions (Allen et al., 2010; IPCC, 2019). For example, climate aridification will have a negative impact on tree growth, thus increasing mortality rates, as shown by the many episodes concerning the demise of plant species

(Sanchez-Salguero et al., 2012). This set of circumstances is distinguished by a sharp decline in growth and increasing mortality rates. These changes will affect a wide range of ecosystems and will cause changes in the composition, structure, productivity, and climate interactions of forests (Bennett et al., 2015). Studies tackling the drought sensitivity of forests should, therefore, also consider local adaptations of tree stands to factors such as precipitation and temperature, soil characteristics and microtopography, along with forest management practices. These are crucial factors that determine forest decline, especially in areas in which climatic stress resulting from low temperatures or scarce water availability is higher, as is the case of high mountain territories in the Mediterranean region (Camarero et al., 2004). According to climate projections carried out in recent years, the trend towards greater aridity will be particularly severe in Southern Europe, where an increasing frequency of extreme climatic events is expected in the coming decades (IPCC, 2019). All these changes produce a marked increase in potential evapotranspiration (Vicente-Serrano et al., 2014), which implies an increase in atmospheric water demand and a consequent increase in the water stress suffered by the vegetation in environments ranging from semi-arid to sub-humid areas.

Several studies have shown that the increase in the frequency and severity of droughts is, together with rises in temperatures, one of the main drivers of forest decline processes in the Mediterranean basin (Greenwood et al., 2017). The result of these climatic dynamics will also produce an alteration in forest function and productivity, especially in populations that are farther away from their natural distribution limits (Gazol et al., 2017). This is particularly the case of populations in a more arid distribution boundary, as a consequence of increased water stress (Pasho et al., 2011; Férriz t al., 2021), thus making their study a key element as regards understanding forest drought sensitivity (Madrigal-Gonzalez et al., 2018). In this respect, previous surveys have shown that plantations may be more vulnerable to stress induced by biotic and abiotic factors than are naturally regenerated forests (Luyssaert et al., 2018; Navarro-Cerrillo et al., 2018). These effects are indeed most noticeable in decline episodes in artificial coniferous stands on a regional scale (Ariza et al., 2019). In Spain, an increase in mortality has been associated with climatic drought events in pine forests (Sánchez-Salguero et al., 2013, 2015; Gea-Izquierdo et al., 2014; Camarero et al., 2015; Navarro-Cerrillo, 2014, 2018; Manrique-Alba et al., 2020), coinciding with what is happening in forests in different regions worldwide (McDowell et al., 2016).

These effects can be aggravated by a lack of management during large reforestation initiatives owing to high stand density and competition, which increase vulnerability to droughts and mortality (Martín-Benito et al., 2010; Sánchez-Salguero et al., 2013, 2015; Vilà-Cabrera et al., 2013). Thinning could help the trees in these plantations grow faster by reducing competition for water and nutrients, increasing photosynthetic rates, and optimising water consumption and carbon uptake to reduce the dieback and tree mortality related to drought (Martin-Benito et al., 2010; Sánchez-Salguero et al., 2012, 2013; Navarro-Cerrillo et al., 2016, 2019, 2022; Manrique-Alba et al., 2021). Furthermore, thinning modifies microclimatic conditions and, as a result, forest water flows (e.g., evapotranspiration and groundwater recharge) (Ma et al., 2010). Thinning is consequently one of the most important forest management methods by which to reduce the risk of forest dryness (Sohn et al., 2016).

Dendrochronological studies continue to be an accurate approach with which to study the effect of thinning on stand vigor in a variety of stand and site situations, and it is, therefore, likely that this will also be true in semi-arid areas prone to drought-induced dieback (Fernandes et al., 2016). However, few thinning trials have compared the potential benefits of silviculture for Mediterranean pine plantations on a simultaneous pine species and climatic gradient under dieback risk conditions in xeric forests (but see Navarro-Cerrillo et al., 2019). Pine plantations in southern Europe are expected to suffer as a result of severe water limitations and increasing temperatures (Giorgi and Lionello, 2008), and

this is already leading to serious mortality processes in this type of forest (Sánchez-Salguero et al., 2012). It is, therefore, necessary to establish experimental trials in areas close to the rear edge limit of these species to develop silvicultural alternatives that will allow forest managers to make urgent decisions in the field (del Río et al., 2017).

To contribute to develop silvicultural alternatives, we have used dendrochronology to understand the growth response of high-density planted pine forests (*Pinus sylvestris* L.-1753 trees ha^{-1}, *P. nigra* Arnold.-1610 trees ha^{-1} and *P. halepensis* Mill., 992 trees ha^{-1}) to thinning in drought-prone areas of Southern Spain, where forest dieback processes have been observed since the early 2000 s (Sánchez-Salguero et al., 2012). Pine species considered in this work cover a wide ecological spectrum, from the basal semi-arid zones of the Iberian Peninsula, to the high-mountain zones (Gandullo and Sánchez Palomares, 1994). Experimental plots include distinct thinning intensities (unthinned stands, 30% and 60% of basal area removed), and several climatic factors on an elevated gradient (1000 to 1800 m.a.s.l). Our original hypothesis was that under water deficit, thinning permits a more plastic response to drought by increasing resilience which may facilitate the adaptation of pine plantations to global change. We attempted to achieve our goal by fitting a growth regression model (BAI) that considered climatology, previous year's growth (temporal self-correlation), long-term growth tendency, and management (thinning). The process of fitting the models to the observed data made possible to simulate growth trajectories after thinning and after drought for each location and treatment. According to the information available for drought-tolerant species, we expected that thinning would result in higher drought-resistant stands. Our objectives were to: (1) assess the impact of thinning on post-drought resilience, resistance, and recovery from BAI records, and (2) propose new, adaptive silviculture strategies for drought-prone Mediterranean pine plantations based on the use of thinning to reduce the consequences of intense droughts. This approach is useful to understand how drought and competition interact to affect post-drought resilience, in addition to guidance for adaptive silviculture in the management of even-aged Mediterranean pine plantations by reducing vulnerability to drought-induced dieback (Sohn et al. 2016; Navarro-Cerrillo et al., 2019, 2022).

2. Material and methods

2.1. Study site

The study area was located in the Sierra Nevada National Park (Southern Mountains of Andalusia region, Granada, Spain; Fig. S1 Supplementary Material). The climate is Mediterranean, with cold winters and hot summers and a mean annual precipitation of between 250 and 700 mm (stretching from east to west), with a marked two-month drought season (July-August). Mean annual temperatures vary considerably from the lowest part of the mountains (12–16 °C) to the highest elevations (<10 °C or even lower above 3000 m a.s.l.). The Standardised Precipitation-Evapotranspiration Index (SPEI) (12 months) had an average value of −0.152 from 1970 to 1994, −0.089 from 1995 to 1999, −0.635 from 2001 to 2006, −0.165 from 2007 to 2011, and −1.391 during 2012–2016 droughts (Fig. S2, Fig. S3 and Fig. S4 Supplementary Material).

There were pronounced climatic contrasts between the sunny dry south-facing slopes and the shaded wetter north-facing ones as a consequence of the sharp orography. The terrain has a considerable altitudinal gradient ranging from around 300 m to 3482 m a.s.l. (Mulhacen, the highest peak in the Iberian Peninsula). The work of Rivas Martinez (1991) was used as the basis on which to identify six bioclimatic belts. Remnants of natural forests are present throughout the miscellaneous landscapes, and are dominated by *Quercus ilex* L. subsp. *ballota* (Desf,), *Quercus pyrenaica* Willd., *Acer opalus* subsp. *granatense* (Boiss.) F.Q. & Rothm., and *Sorbus aria* (L.) Crantz (Pérez-Raya et al., 2001), reaching up to 20% of the total coverage. On the other side, four

planted pine species (*Pinus halepensis*, *P. pinaster* Aiton., *P. nigra* subsp. *salzmannii,* and *P. sylvestris*), which were established during the period 1960–1980, represent around 80% of the forested area of the National Park. Mixed stands formed of natural *Quercus* and natural *P. sylvestris* and *P. nigra* forests can also be found (Fig. S1).

2.2. Experimental design and measurements

In 2009, a randomized complete block thinning design was established in a 34–64-year-old pine plantation that is representative of a larger area of over 23,500 ha of continuous pine plantations. *Pinus halepensis* was the pine species chosen at the lower altitude (1200 to 2030 m a.s.l.) owing to its high tolerance to drought, whilst montane pines species (*P. nigra* and *P. sylvestris*) were selected at higher altitudes (above 1793 m a.s.l.). The Andalusian Forest Service developed an experimental trial in these forests using a factorial design with three species (*Pinus halepensis*, *P. nigra*, and *P. sylvestris*) and three thinning treatments (C-control-unthinned: 0%; MT-moderate thinning: 30% for *P. halepensis* and 50% for *P. sylvestris* and *P. nigra*, and HT- heavy thinning: 50% for *P. halepensis* and 70% for *P. sylvestris* and *P. nigra*), preferentially removing doubled, dead and overtopped trees (Aspizua et al., 2012; Table 1, Table S1 and Table S2 Supplementary Material). At each location, three blocks per treatments - each being 30 × 30 m with a 15-m-wide buffer strip around each block – were randomly located, considering the similarity of the canopy structural parameters, and with analogous microclimatic and edaphic characters. A total of three plots and 27 permanent 900 m^2 treatment blocks were established (Aspizua et al., 2012). There were no significant differences among treatments as regards the tree density of each species before thinning.

2.3. Dendrochronology

The measurements considered were the tree diameter at breast height (1.3 m above ground level –dbh- cm), obtained using a calliper (Haglöf Mantax, Långsele, Sweden), total height (H, m), obtained using a Vertex IV hypsometer (Haglöf, Sweden), stand density (N trees ha^{-1}) and basal area (G, m^2 ha^{-1}) of all trees with a diameter (dbh) of more than 10 cm (Table 1). At each treatment, 15 healthy and non-suppressed trees were selected, and two cores per tree were extracted at breast height (1.3 m), separated by 180° on the cross-slope sides of the trunk,

using a Pressler increment borer (Fritts, 2001), comprising a total of 270 samples from 135 trees. Upon arriving at the laboratory, the cores were carefully unpackaged and distributed to be air-dried at room temperature. They were subsequently glued to wooden mounts and progressively sanded to allow great ring visibility, after which ring series were visually cross-dated (Yamaguchi, 1991). Tree-ring width was measured to the nearest 0.01 mm using binocular microscopes and measuring devices (Lintab, F. RinnTech., Germany; Velmex Inc., USA). The COFECHA programme (Holmes, 1983), which monitors the moving correlations between each individual tree-ring series and the mean site series that comprise each chronology, was used as a complimentary tool, thus allowing us to attain accurate measurements. A transformation of the tree ring width data was then performed in order to obtain the basal area increment (BAI, cm^2), which best reflects the growth response for each thinning treatment because it is closely related to the sapwood area. We additionally followed the protocol established by Fritts (2001) and detrended each individual tree-ring width series by first fitting negative exponential and spline curves and then obtaining the residuals by dividing the observed values by the fitted ones. This was done owing to tree ageing and stem enlargement growth dynamics influenced by the long-term biological trends. The outcome of this was ring width indices (RWi), which were obtained by averaging the individual standardised series into site-level chronologies upon dividing the raw BAI by the expected values (Cook et al., 1990, Table 2). This series of steps was performed using the ´dplŔ package on the R platform (Bunn, 2008; R Core Team, 2020).

2.4. Climate-Growth relationships

Climatic data continuity constraints generated by weather stations adjoining the study site, which covers the range 1960–2020 led us to subject our dataset to a rigorous procedure with which to ensure data quality and homogeneity. Data regarding monthly mean temperature and precipitation was, along with index site characterisation (Rodriguez, 2008; Vicente-Serrano, 2012), extracted from The Andalusian Environmental Information Network (REDIAM, https://www.juntadean dalucia.es/medioambiente/portal/datos-ambientales?categoryVal=).

The growth response to climate was quantified by calculating correlation and bootstrapped response functions using residual chronologies as dependent variables and local monthly climatic data as

Table 1
General characteristics of the pine stands studied in Sierra Nevada after thinning interventions. Values are means ± standard errors (in brackets) and superscripts (a, b, c) indicate pairwise comparisons when these are significantly different ($p < 0.05$). Treatments' abbreviations: C, control or unthinned; MT, moderate thinning with 30–50% of basal area removed; HT, heavy thinning with 70% of basal area removed).

Species	Site	Treatment	Latitude (N)	Longitude (W)	Elevation (m a.s.l.=)	Exposure	Slope (%)	Density (trees ha^{-1})	DBH (cm)	Height (m)	G (m^2 ha^{-1})
Pinus sylvestris	Nevada A	C	37.0494	3.0518	2036	S	30	1752	21.97 (0.7)[a]	12.06 (0.2)[a]	43.96
		MT	37.0492	3.0527	2025	S	20	1051	21.30 (0.6)[a]	11.24 (0.2)[b]	20.66
		HT	37.0493	3.0508	2031	S-SW	20	526	18.17 (0.5)[b]	9.09 (0.3)[c]	9.02
Pinus nigra	Nevada B	C	37.0421	3.0556	1888	S	20	1610	16.50 (0.5)[a]	7.79 (0.2)[a]	26.51
		MT	37.0373	3.0444	1793	S-SW	20	966	18.63 (0.8)	8.77 (0.2)[b]	16.90
		HT	37.0380	3.0454	1810	S	25	483	18.75 (0.6)[b]	8.97 (0.2)[b]	10.27
Pinus halepensis	Dilar M	C	37.0485	3.5662	1256	W	20	992	24.04 (1.4)	13.17 (0.7)	28.50
		MT	37.0478	3.5666	1263	W	30	694	25.18 (1.5)	12.27 (0.5)	21.86
		HT	37.0475	3.5651	1301	NW	35	496	26.80 (0.8)	12.11 (0.4)	17.72

Table 2

Dendrochronological statistics of the sampled pine stands according to thinning treatments (C, control; MT, moderate thinning; HT, heavy thinning). Abbreviations: TRW, mean tree-ring width; BAI_{20}, mean basal area increment in the last 20 years; BAIpreT, mean basal area increment before thinning; BAIpostT, mean basal area increment after thinning; Rbar, mean correlation between tree-ring sereies; AC1, first-order autocorrelation coefficient; MS, mean sensitivity; EPS, expressed population signal. Values are means ± SD (in brackets) and superscripts (a, b, c) indicate pairwise comparisons when these are significantly ($p < 0.05$) different.

Species	Site	Treatment.	No. trees (No. cores)	Time span (years)	TRW ± SD (mm)	BAI_{20} (cm^2)	BAI preT (cm^2)	BAI postT5 (cm^2)	BAI postT10 (cm^2)	Rbar	AC1	MS	EPS
Pinus sylvestris	Nevada A	C	15 (30)	1977–2020 (44)	2.42 (0.05)	8.45 (0.50)	10.01 (0.53)[a]	7.93 (0.53)[a]	6.58 (0.48)[a]	0.82	0.78	0.37	0.98
		MT	15 (30)	1977–2020 (44)	2.23 (0.08)	7.12 (0.54)	6.52 (0.44)[b]	8.14 (0.71)[a]	6.95 (0.53)[a]	0.77	0.79	0.34	0.97
		HT	15 (30)	1977–2020 (44)	2.32 (0.05)	8.48 (0.38)	5.99 (0.34)[b]	11.44 (0.59)[b]	9.91 (0.48)[b]	0.77	0.66	0.34	0.97
Pinus nigra	Nevada B	C	15 (30)	1987–2020 (34)	2.30 (0.08)	5.46 (0.41)	5.84 (0.40)	5.21 (0.44)	3.87 (0.86)	0.82	0.69	0.46	0.99
		MT	15 (30)	1987–2020 (34)	2.41 (0.06)	5.77 (0.38)	6.01 (0.44)	5.84 (0.52)	5.87 (0.44)	0.84	0.75	0.43	0.99
		HT	15 (30)	1987–2020 (34)	2.55 (0.08)	6.34 (0.46)	7.00 (0.35)	6.33 (0.55)	5.69 (0.58)	0.85	0.83	0.37	0.98
Pinus halepensis	Dilar M	C	15 (30)	1957–2020 (64)	1.93 (0.09)	7.24 (0.97)	6.05 (0.59)	6.45 (1.05)[a]	6.83 (0.94)[a]	0.72	0.81	0.34	0.96
		MT	15 (30)	1960–2020 (61)	2.06 (0.11)	7.39 (1.12)	6.28 (0.69)	6.68 (1.07)[a]	7.45 (1.18)[a]	0.71	0.75	0.35	0.95
		HT	15 (30)	1960–2020 (61)	2.10 (0.07)	9.12 (0.59)	5.83 (0.42)	11.90 (0.88)[b]	11.81 (0.80)[b]	0.79	0.67	0.34	0.97

independent variables. Growth indices and monthly climatic series were correlated from the previous May up to October of the year of tree-ring formation by following the suggestions of Richter et al. (1991). Growth-climate relationships were quantified using Pearson correlation co-efficients and bootstrapped response function coefficients (Fritts, 2001). In order to assess the temporal stability of growth-climate associations, moving correlations were also obtained for the residual chronologies on the sole basis of monthly selected mean maximum temperatures and DRI. We calculated 25-year moving correlations for the period 1901–2005 by considering climatic variables highly related to growth. Correlation and response functions were calculated using the Dendroclim2002 programme (Biondi and Waikul, 2004). The Standardized Precipitation-Evapotranspiration Index (SPEI) for June on scales of 6 and 12 months was obtained from https://monitordesequia.csic.es (Vicente Serrano et al., 2017) upon analysing the best correlation with the BAI time series, and the best coalescence was established at each site. We selected the SPEI in order to describe the hydric conditions of each growing season because our study was concentrated on the impact of drought (Beguería et al., 2014). The 1995, 2005 and 2012 droughts were consequently appraised as being the best drought sequence for the study sites.

2.5. Drought vulnerability indices

An evaluation of the different responses during past low-growth behaviour was performed by analysing three drought vulnerability indices (CR) (Lloret et al., 2011): resistance (CR_T), recovery (CR_R) and resilience (CR_S), as follows:

$$CR_T = Dr/PreDr \qquad (1)$$

$$CR_S = PostDr/Dr \qquad (2)$$

$$CR_C = PostDr/PreDr \qquad (3)$$

where Dr corresponds to BAI during the drought year (1995, 2005 and 2012), and the PreDr and PostDr correspond to the average BAI of the 3 years pre and post the drought episode in order to avoid drought overlap (Sohn et al., 2016), considering normal growth regulations after this period (Gazol et al., 2017). Thinning treatments took place in different years on the selected sites (Fig. 1), signifying that the chosen

droughts were assessed differently, since they occurred before and after the marked events in order to quantify the tree growth responses.

2.6. Statistical modelling

2.6.1. Descriptive statistics

All the independent variables were normalised (i.e. transformed into variables with zero mean and unit variance) prior to the analyses. The effect of thinning was tested by analysing post-thinning growth as a function of the thinning treatment using a regular ANOVA model without random effect variables. The timeframe for the analyses was selected as the maximum number of years between the thinning treatment and the year of sampling (2021), which was common to all sites. The effect of thinning on the drought vulnerability index response to the extremely dry years (1995, 2005 and 2012) was similarly tested by employing a regular ANOVA model without the random effect variable as a function of pine species and thinning intensity.

2.6.2. BAI modelling

Following the suggestions of Manrique-Alba et al. (2022), we fitted three separate generalized linear mixed-effects models (GLMM), one for each species and location. The response variable was the BAI, while three variables were used as fixed effects: a scaled and centred time variable (Time), the natural logarithm of the BAI from the year before (BAI_{prev}), and the SPEI for the current year. Variable long-term impacts on the BAI, such as a gradual rise or reduction, were accounted for by the variable Time. Temporal autocorrelation, which is frequently present in tree-ring data, was accounted for through the inclusion of BAI_{prev}. Finally, the SPEI madeit possible to incorporate the drought effect on growth, including all the SPEI variants, and the model that yielded the lowest value of the Akaike Information Criterion (AIC) was chosen. In order to remove individual tree variability and better capture the fixed effects, each subject's id was introduced as a random effect. A total of twelve model coefficients (intercept and three fixed effects × three treatment levels), plus two residual standard deviations (the subject random effect and the random error) were fitted using the BOBYQA optimizer (Powell, 2009) as implemented in the function glmer in the lme4 and minqua R packages (Bates et al., 2015). The positive and skewed nature of BAI data distribution required the use of a Gamma
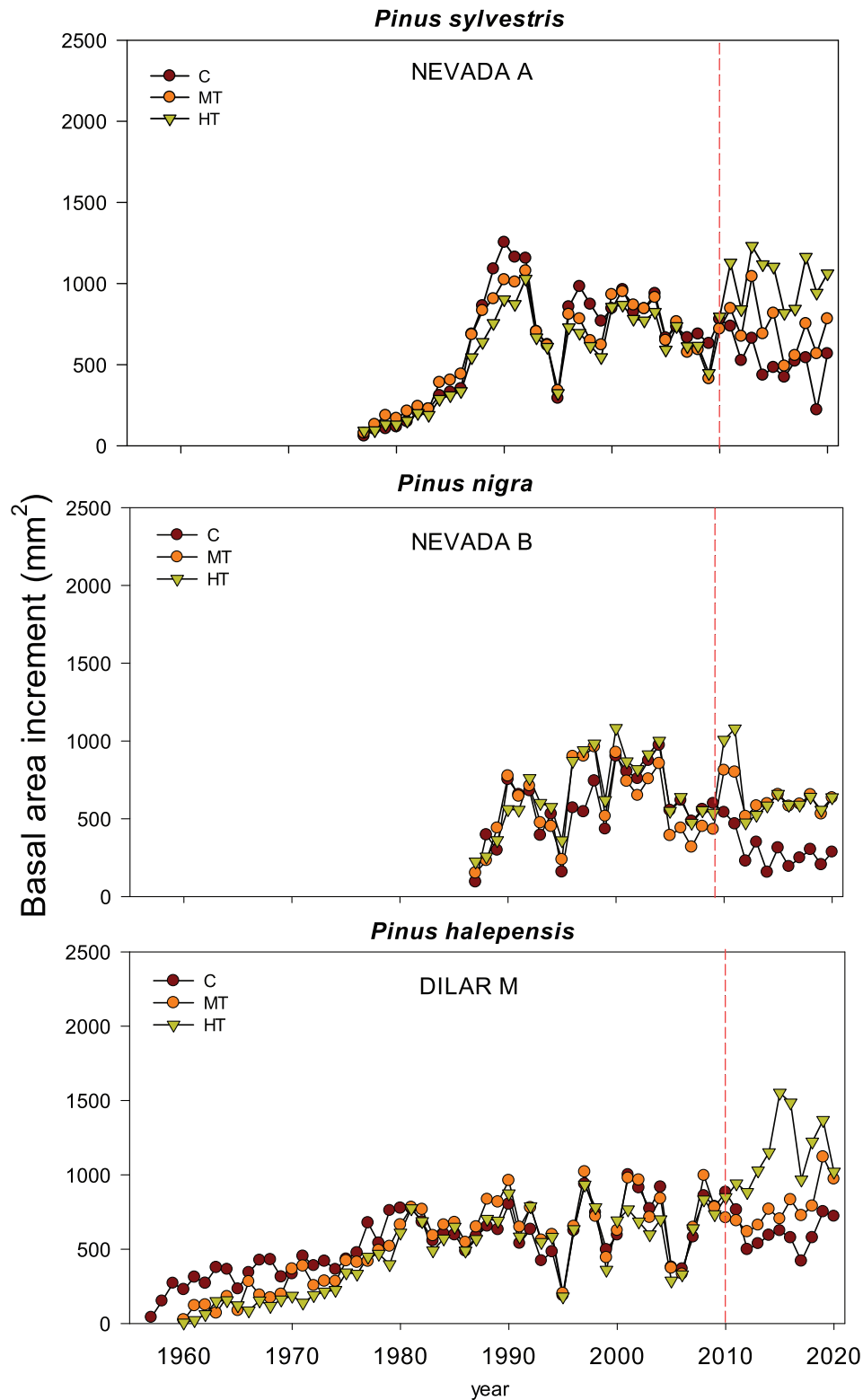
Fig. 1. Mean curves of basal area increment (BAI) chronologies for Pinus sylvestris, Pinus nigra and Pinus halepensis. Vertical red dashed lines correspond to the thinning year. Treatments correspond to different percentages of basal area (BA) removed: C, control or unthinned (0% BA removed); MT, moderate thinning (30–50% BA removed); and HT, heavy thinning (70% BA removed), Spain.

distribution family with a logarithmic link to connect the linear predictor to the conditional mean response. As a result, the whole model for observation I = 1,…, I matching subject (tree) s = 1,…, S in treatment t = (unthinned, moderate, heavy) had the following form:

$$\mathrm{E}(BAI|i,s,t) \; Gamma\left(\mu_{i,s,t}, \nu\right)$$
$$\mu_{i,s,t} = e^{\beta_{0,t} + \beta_{1,t} Time_i + \beta_{2,t} \log\left(BAI_{prev_i}\right) + \beta_{3,t} SPEI_i + \nu_s}$$

(4)

As the SPEI can be calculated for different moments during the year and at different aggregation time scales, the ideal timing of the year

(week, in the case of the dataset used) and time scale had to be chosen. Since few feasible models were available, we computed the models for all combinations of week and time scale (48 weeks × 18-time scales). The best model for each study site was, therefore, selected as being that which minimised the AIC. The AIC was also used to determine whether a full model including the three covariates and interactions with treatment levels was superior to less complex alternative model configurations. T-tests were used to determine the statistical significance of the model coefficients. The significance of the differences between treatments was evaluated by employing pairwise comparisons on the estimated marginal means, using a confidence level of α = 0.05 (Lenth, 2021).

2.6.3. Growth trajectory simulation

The recursive application of Eq. (1) over time (t) makes it possible to simulate average growth trajectories (BAI′t) for each site and species. In addition to the fitted fixed-effects parameters, an initial value at time zero (BAI′t=0) must be set. Setting BAI′t = 0 is difficult because its impact spans several timesteps. Since the observed BAI′t=0 is affected by several factors, including the long-term one, the mean observed BAI for each location and treatment was not the best approach and we, therefore, ran N = 100 simulations using the mean observed BAI for BAI′t=0 and neutral environmental circumstances (Time = 0; SPEI = 0). After visually determining that BAI′ had been converted into a stable value, we used the most recent iteration to initiate the simulations. When Time and SPEI are maintained at their present values, this value indicates the baseline growth.

Average post-thinning growth trajectories were mimicked by using increasing Time while maintaining neutral drought conditions (SPEI = 0). The use of this simulation makes it possible to assess the short- and long-term impacts of thinning, along with the rate at which the effect of thinning disappears over time. In order to determine the vulnerability to drought, we also calculated the response of post-drought growth. In this case, a drought was simulated in the first year by setting a value of SPEI = -1.28 (corresponding to a 10-year return period), followed by nine neutral years (SPEI = 0). Time was set at 0 in this simulation in order to avoid any long-term effects. This setup made it possible to determine the loss of growth during the drought event and the recovery trajectories afterwards for all sites and treatments.

Finally, drought vulnerability indices and the time to recovery (e.g., the time n required to achieve 95% of the reference growth, BAI′t=∞ in years, TR) were also simulated by following the suggestins of Manrique-Alba et al. (2022).

All statistical analyses were conducted in R version 4.1.1 (R Development Core Team, 2020), including the *MuMIn* (Barton 2016), *lmer4* (Bates et al. 2015), *emmeans*, and *AICcmodavg* (Mazerolle and Mazerolle, 2017) packages. The models were fitted with the *bobyqua* algorithm (Powell, 2009) implemented in the *lme4* package in R, using maximum likelihood (Bates et al., 2015).

3. Results

3.1. Stand-level growth responses

The longest series dated back to 1957 for *P. halepensis,* and the younger plantation reached the year 1987 for *P. nigra* (Fig. 1, Table 2). We found EPS values higher than 0.95 for all species and sites. Synchronous reductions in growth were found on all the study sites during 1995 and 2005, corresponding to droughts. A similar inter-annual variability (MS) of growth was also observed for the two species and populations, thus suggesting the increasing importance of climatic constraints on growth on the study site (Table 2). The remaining dendrochronological statistics confirm a common and coherent growth response of trees to climatic variability along the aridity gradient.

The twenty-year basal area (BAI20) was not significantly different among treatments but there were clear significant differences following

thinning (Table 2, Table S3 Supplementary Material). Short-term variations in the BAI after thinning followed similar patterns of variation for all species, with gently descending BAI trends for control and moderate thinning, and a sharp increase after heavy thinning, which was maintained or decreased in the stabilisation period (Fig. 1). The BAI5 and BAI10 after thinning were higher for the moderate and heavy treatments for the three species, although differences were significant only for *P. halepensis* (F = 10.48, p < 0.001 and F = 9.05, p < 0.001, respectively) and *P. sylvestris* (F = 10.42, p < 0.001 and F = 13.89, p < 0.001, respectively, Table 2). *Pinus nigra* did not attain significantly higher BAI5 and BAI10 values (p = 0.814, and p = 0.453).

3.2. Climate-growth relationships

With regard to the influence of precipitation on growth, we observed (Fig. 2) differences among species and thinning intensity. Winter precipitation (December-February) and mean temperature (December-April) enhanced the growth of *P. sylvestris* in the case of the extreme thinning treatments (C and HT). The growth of *Pinus nigra* was most closely related to spring precipitations (March and April), although autumn temperature had a higher positive impact on the HT treatment. Finally, *P. halepensis* growth was positively affected by a autumn the previous year and a spring in the current year with higher precipitations, and winter temperature had a positive effect on the control treatment.

3.3. Effect of thinning on drought vulnerability indices

The analysis of the data revealed significant effects of thinning on the drought vulnerability indices (Fig. 3). Specifically, the recovery (CRC) and resilience (CRS) drought indices were significantly higher for the heavy thinning treatments (F = 28.10, p < 0.001 and F = 35.21, p < 0.001 respectively) used with *P. sylvestris* during the last post thinning drought (2012). The response of *P. halepensis* to thinning was similar to that of *P. sylvestris* for the resistance (CRT) and resilience (CRs) drought indices in the same year (2012, F = 10.97, p < 0.001 and F = 16.91, p < 0.001 respectively). However, *Pinus nigra* was less sensitive to thinning, although the resistance (CRT) and resilience (CRs) drought indices were significantly different for moderate thinning (2012, F = 24.16, p < 0.001 and F = 21.94, p < 0.001, respectively). The response of CRS indicated that thinning treatments attained a more positive response to accumulated droughts, irrespective of the pine species, although this was more evident in *P. sylvestris* and *P. nigra*.

3.4. Statistical modelling of growth

Finding the appropriate season and time frame for the SPEI to predict growth (BAI) was part of the modelling process mentioned in the methods section. AIC charts for each potential model on each site are displayed in Fig. 4. The best combination that minimised the AIC is provided for each site, along with combinations of week and time scales that produced meaningful results (95% confidence intervals not overlapping zero).

A roughly linear link between time scale and season (week) was observed (Fig. 4). It is important to note the differences between the various species. The best model for *P. sylvestris* (Nevada A) was, therefore, obtained at week 40 (the final week of October), with an aggregate time scale of 11 months (that is, from the final week of November of the previous year). The best models were, however, found at the *P. nigra* location earlier in the year (week 21, the first week of June), with a time scale of 7 months (again from November of the previous year). The case of *Pinus halepensis* (Dilar) was rather unusual, since the AIC plots revealed larger AIC value dispersion. The lowest AIC corresponded to late summer, at week 35 (the final week of September) and spanned a 13-month period.

For each location, the full model with three variables and full interaction with treatment levels was chosen in preference to more basic
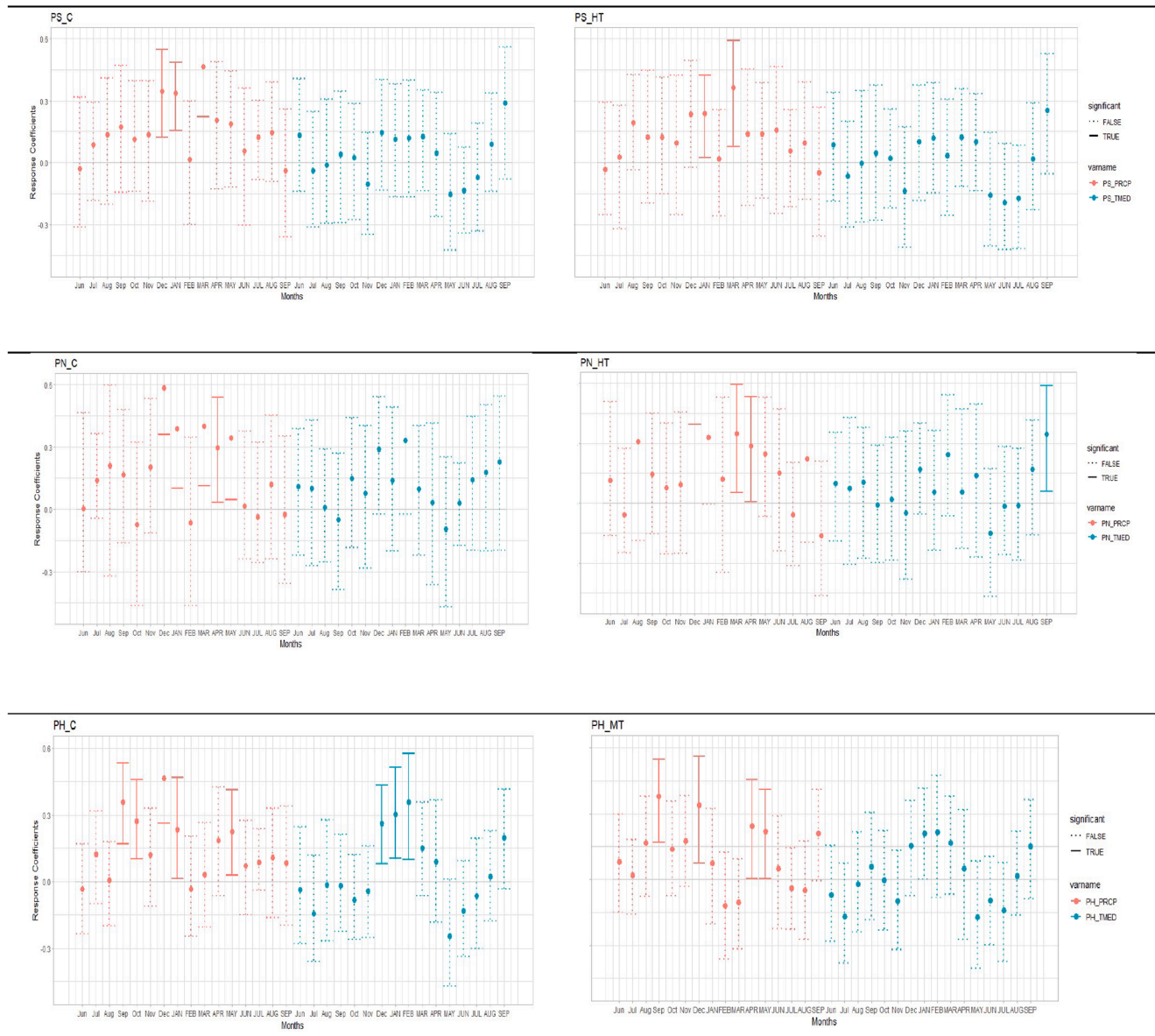
Fig. 2. Bootstrapped response function analysis relating tree-ring growth indices with monthly climate variables (PRCP, total precipitation –red symbols; Tmed, mean temperature –blue symbols) and considering control (C) or unthinned stands vs. stands subjected to high thinning (HT) intensity of Pinus silvestris (PS), Pinus nigra (PN) and Pinus halepensis (PH). Response coefficients were calculated from previous June to current September and significant (p < 0.05) values are shown with filled symbols.

arrangements. The average model coefficients and associated 95% confidence intervals are displayed in Fig. 5. The plot for each site additionally includes letters indicating significant differences among treatments. The Supplementary Material provides the precise values of the model coefficients, confidence intervals, standard errors, and standard deviation of the random effects (Table S4, Table S5).

The model intercepts show significant differences in mean growth among the three treatment levels (control, moderate and heavy) for *P. sylvestris* (Nevada A), with an increasingly positive effect. A positive effect on the control was apparent only after heavy thinning and not for a moderate treatment in *P. halepensis* (Dilar). The Time (long-term, linear effect) coefficients mirrored the behaviour of the intercepts. Thinning, therefore, tended to reduce the model coefficient for *P. sylvestris*, thus making the trend negative, while it increased it for *P. nigra* and had a mixed effect on *P. halepensis*. Thinning also affected the short-term self-correlation, as shown by the BAI_prev coefficients. The model coefficients for BAI_prev were positive and ranged between

0.2 and 0.7, revealing a relatively strong short-term autocorrelation in the BAI time series. This means that the previous year's growth has a remarkable effect on the current year's growth. In Nevada, A BAI_prev underwent a reduction after thinning, as was the case of Dilar after heavy thinning. The effect of climate, which was captured by the SPEI coefficient, had a more consistent response with higher values for heavy and, to a certain extent, moderate treatments after thinning. However, thinning on the *P. halepensis* reduced the SPEI coefficient. The mean BAI_{10} increased by 50% for heavy (9.91 cm^2, *P. sylvestris*) and moderate (51%, 5.87 cm^2, *P. nigra*) treatments, respectively, and was even higher for *P. halepensis* (72%, 11.81 cm^2, Table 2).

Finally, the SPEI model coefficients were positive in each case, demonstrating that the availability of water affects growth. *Pinus halepensis* had lower coefficients than *P. sylvestris* and *P. nigra*, thus indicating a lower climatic control for the first species. The climatic effect was higher for *P. nigra* than for *P. sylvestris*. With regard to the influence of thinning, the coefficients tended to be higher after thinning, with the
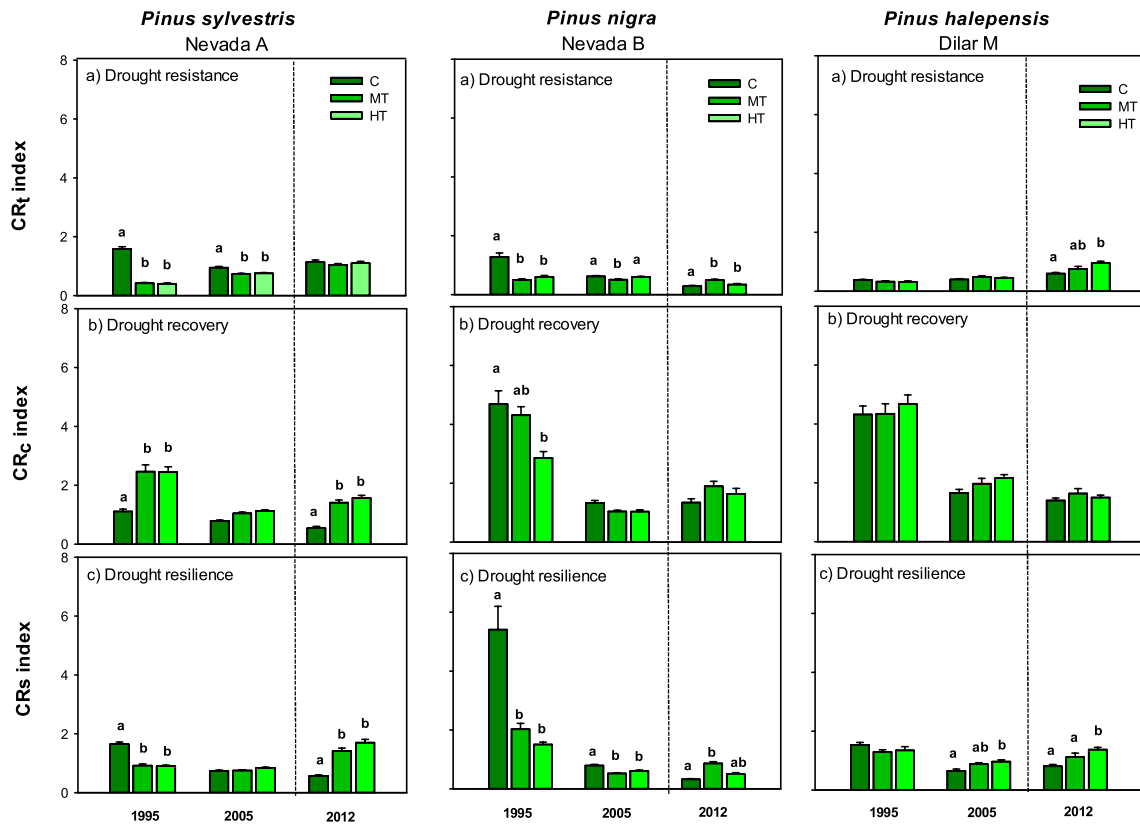
Fig. 3. Resistance (CRT), recovery (CRC), and resilience (CRS) growth indexes calculated for Pinus sylvestris, Pinus nigra and Pinus halepensis during three extreme dry years (1995, 2005 and 2012-post thinning) corresponding to three treatments(C, control or unthinned; MT, moderate thinning; HT, heavy thinning). Values are means ± standard error. Different letters indicate significant differences (p < 0.05) among treatments within each year. Vertical red dashed lines correspond to the thinning year.

exception of *P. halepensis*.

3.5. Modelling post-thinning and post-drought growth trajectories

Fig. 6 shows the simulated long-term evolution of the BAI after thinning while keeping drought effects neutral (SPEI = 0). In the case of *P. sylvestris*, the BAI increased after thinning (year 1) and underwent a progressive reduction in subsequent years. The highest BAI in year 1 reached between almost 15.0 cm^2 for *P. halepensis* and almost 12.0 cm^2 for *P. sylvestris* after heavy thinning, while the lowest was around 2 cm^2 for *P. nigra*. The long-term effectiveness of the thinning (Fig. 6) was also related to species and thinning intensity, while the trend of *P. sylvestris* was to converge the difference between the BAI on unthinned and thinned plots in the simulation after 20 years, as evidenced by the difference between the BAI on unthinned and thinned plots, for which there was a clear positive effect of the thinning of *P. nigra* in the short term (<4 years). In the case of *Pinus halepensis*, the effect of moderate thinning increased, and was higher after ten years with respect to the control and heavy thinning treatments, which reduced growth.

We also simulated post-drought growth trajectories after a one-year drought (SPEI = − 1.28) on unthinned vs. thinned plot levels (Fig. 7). The trajectories are expressed as the ratio to the reference BAI that would be obtained asymptotically under a neutral climatic condition (SPEI = 0), and ΔBAI is used as a function of time (years). The value of ΔBAI = 1 (the highest possible), therefore, corresponds to full recovery, although here a value of 0.95 was used as the threshold to compute the time to recovery. The values of ΔBAI at time 1, which are highlighted with rectangles in the figure, represent the growth loss as a result of drought, while in previous years there had been growth recovery after the perturbation. Growth loss owing to drought was higher for *P. sylvestris* (0.70 to 0.77) and *P. nigra* (0.63 to 0.71) than for *P. halepensis*

(0.74 to 0.86). Post-growth trajectories, however, recovered more quickly in the case of *P. sylvestris* and *P. nigra*, and more slowly in that of *P. halepensis*. The differences were also apparent across treatments. Post-drought recovery was, therefore, significantly slower for *P. sylvestris* and *P. halepensis* under control conditions than under thinning conditions, and was faster under heavy rather than moderate thinning conditions. The results were rather mixed for *P. nigra*, whichrecovered more slowly when subjected to heavy thinning when compared to the two other treatment levels. If we consider that 0.95 (that is, 95% of the baseline growth) is full recovery, this state was reached after 4 years under unthinned conditions and after 1 year after thinning on the *P. sylvestris* plots. Full recovery was achieved much later on the *P. halepensis* site, requiring 4 years of no thinning and moderate thinning and 3 years of heavy thinning. The values on the *P. nigra* site were 3 and 2 years for no thinning and moderate thinning, and 4 years for heavy thinning.

3.6. Drought vulnerability indices

The drought vulnerability indices calculated from the post-drought growth simulations are displayed in Table 3. The drought resistance (CR$_T$) index was higher for unthinned (C) plots in the case of *P. sylvestris* and *P. nigra,* but was higher for moderate thinning (MT) in that of *P. halepensis*. All species and treatments had high drought resilience values (CR$_S$, greater than1), and resilience was higher after heavy thinning (HT) for *P. sylvestris* and *P. nigra,* and after unthinned (C) for *P. halepensis*. Furthermore, the drought recovery (CR$_C$) values attained for species and treatments were similar, but greater recovery values were attained for thinned treatments (HT, *P. sylvestris* and *P. halepensis*, and MT, *P. nigra*).

In order to determine the time to recovery (TR) more precisely, we examined the post-drought growth trajectories (Fig. 6, Table 3). With
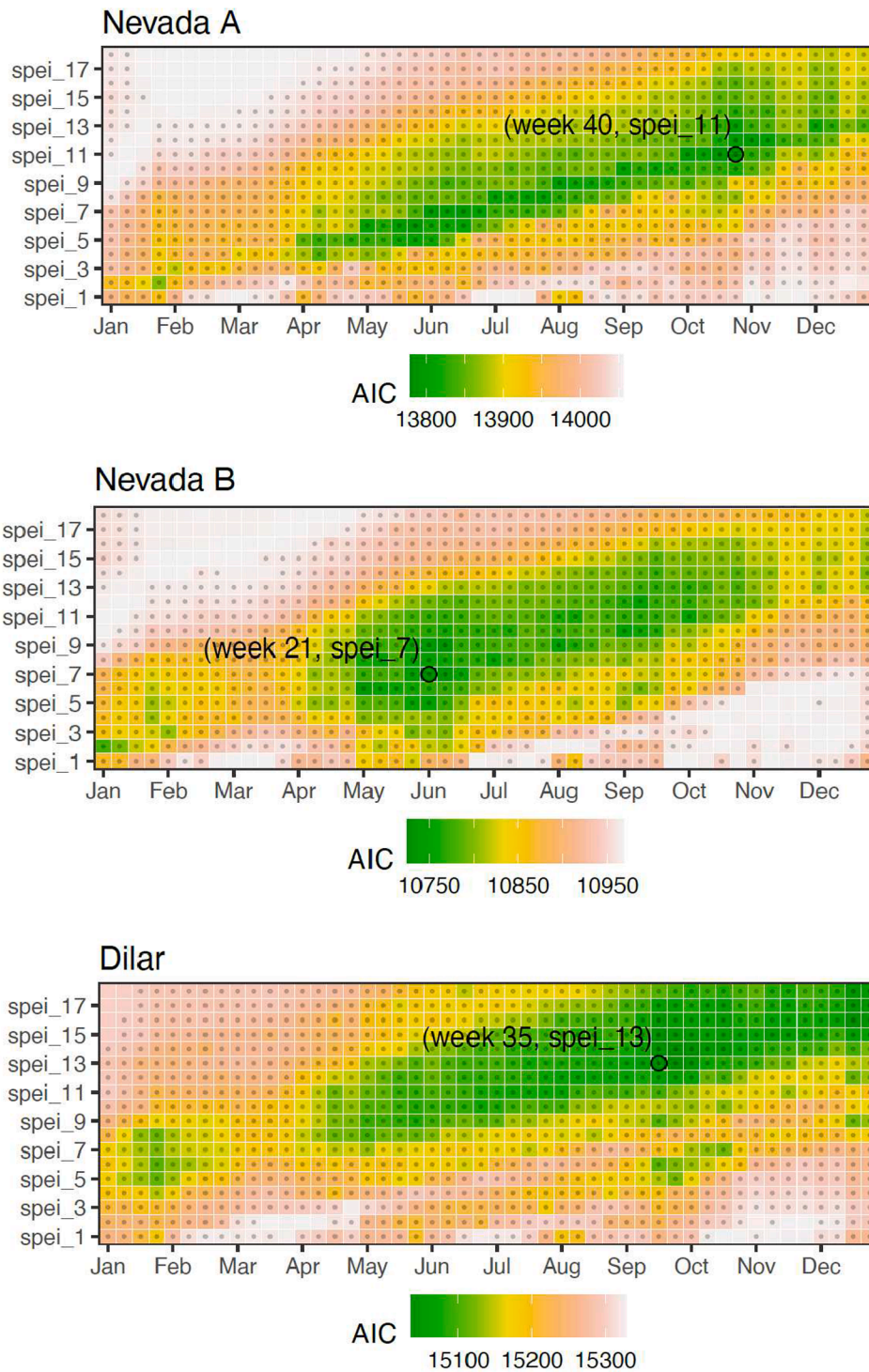
Fig. 4. Selection of the optimum time of the year (x-axis) and aggregation time (y-axis) of the SPEI by minimising the Akaike Information Criterion (AIC, colour scales) in the three study sites, Pinus silvestris (Nevada A), Pinus nigra (Nevada B) and Pinus halepensis (Dilar). Circles indicate the combination with the lowest AIC.

the exception of *P. sylvestris*, which took a time to recovery between 0.5 (HT) and 1.5 (MT), full recovery was typically achieved between two and four years after a drought. Time to recovery typically took place sooner on thinned than on unthinned plots, but was modulated by the species (HT, *P. sylvestris* and *P. halepensis;* MT, *P. nigra*).

4. Discussion

Thinning is a recognised means of efficient silvicultural treatment

that is used to adapt forest plantations to the expected drier climatic conditions and to improve growth and reduce mortality (Sohn et al., 2016). Thinning affects forest structure, growth, and physiology (Bréda et al. 1995), but several questions remain unanswered, including how thinning intensity (e.g., the basal area removed) impacts on climate sensitivity, resilience and long-term growth recovery (Manrique-Alba et al., 2022). These questions should be answered for forests located on ecological gradients under different climatic risk conditions. Here, we have compared three different thinning treatments for three pine species
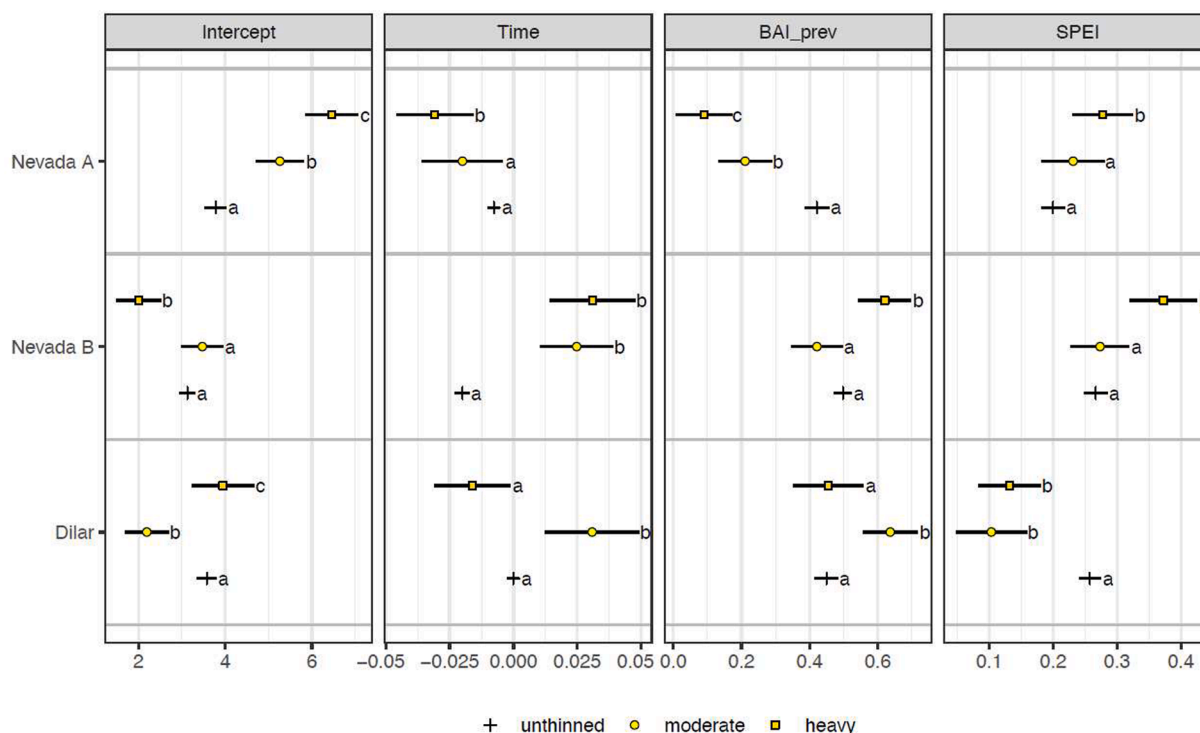
Fig. 5. GLMMs' coefficients (mean values and 95% confidence intervals) for basal area increment (BAI) in all study sites, for control or unthinned plots (black cross) and thinned plots, with different treatment intensities: moderate (yellow circle) and heavy (orange square). For each site and coefficient (Intercept, β_0; Time, β_1; BAI_prev, β_2; SPEI, β_3), different groups are marked with different letters.

growing under Mediterranean conditions characterised by dry summers on an elevated gradient. The growth, dendroclimatic and resilience indexes of *P. sylvestris, P. nigra* and *P. halepensis* stands varied significantly with different thinning intensity. Our original hypothesis was confirmed, and our data suggest that when there is a deficit of water, thinning permits a more plastic response to drought by increasing resilience. Thinning resulted in lower climate sensitivity in *P. sylvestris* and higher sensitivity in *P. nigra* and *P. halepensis,* partially coinciding with the results of earlier studies that suggested a weaker or uncoupled association between growth and climate after thinning (Manrique-Alba et al., 2020). Based on this finding, and according to drought vulnerability indices, *P. sylvestris* and *P. halepensis* were positively affected by heavy thinning while *P. nigra* attained the best response to moderate thinning.

4.1. Effects of thinning on radial growth

Several studies have quantified the effects of thinning on growth and productivity in drought-prone pineforests (Martín-Benito et al., 2010; Fernandes et al., 2016; Manrique-Alba et al., 2020; Lucas-Borja et al., 2021), but few of them have considered the responses of three species on a climatic gradient. Thinning treatments increased tree growth rates similarly for the three pine species studied, with significant differences among them. Here, the growth increment in the three species was more pronounced for the heavily thinned stands (HT), in accordance with previous studies (e.g. Mäkinen and Isomäki, 2004; Saarinen et al., 2020) and also coinciding with studies on *P. sylvestris, P. nigra* and *P. halepensis* forests throughout Spain (e.g. Martín-Benito et al., 2010; Del Campo et al., 2014; Moreno-Fernández et al., 2014; del Río et al., 2017; Navarro-Cerrillo et al., 2019, 2022; Manrique-Alba et al., 2020, 2022; Cachinero-Vivar et al., 2021). The overall increments in tree diameters averaged after thinning (BAI$_{10}$, 72% for *P. halepensis* and 50% for *P. sylvestris* after heavy thinning and 51% for *P. nigra* after moderate thinning, Table 2) showed rapid growth responses following the thinning treatment. Our results showed a similar response for *P. sylvestris*

and *P. nigra,* which are more sensitive to droughts than *P. halepensis,* with *P. nigra* being the species with the lowest growth values after thinning. This result has been obtained previously elsewhere (Navarro-Cerrillo et al., 2022; Manrique-Alba et al., 2022).

The different response of *P. nigra* to moderately thinned when compared to heavily thinned stands may be owing to the limited effects (e.g. a reduction in stand transpiration, the interception of precipitation and competition, both aboveground and belowground) of low thinning intensities, resulting in low levels of resource readjustment (e.g. soil water content, competition and nutrients, Bréda et al., 1995, 2006). Heavy thinning is typically applied to overstocked evenly aged-planted stands in order to increase productivity and, more recently, to adapt forests to climate change (Sohn et al., 2016). It is characterised by the removal of about half of the basal area and the harvesting of dominant and codominant trees, targeting similarly-sized trees in order to improve age-diameter structural diversity, although one usual goal is to produce biomass as part of adaptive silvicultural treatments (Acuña et al., 2021). In this case, response seems to be related to the timing of stem wood production relative to physiological processes (Seibt et al., 2008) and the allocation of photosynthates for below-ground growth at the expense of above-ground growth (del Río et al., 2017).

4.2. Thinning modifies climate-growth relationships

Thinning generally enhances the influence of precipitation and temperature on growth (Fig. 2), although there was no common pattern among species or thinning intensities. In the case of *P. sylvestris,* changes in growth phenology did not differ among thinning treatments. However, autumn temperature had a high positive impact on the growth of *P. nigra* under heavy thinning conditions, whereas winter temperature had a positive effect on the growth of *P. halepensis* in the case of the unthinned control treatment. This response was the opposite owing to the temperaments of the different species. *P. nigra* was more sensitive to climate variability in heavily thinned stands, while *P. halepensis* was more sensitive in unthinned stands (Fig. 2). *Pinus nigra* grows more when
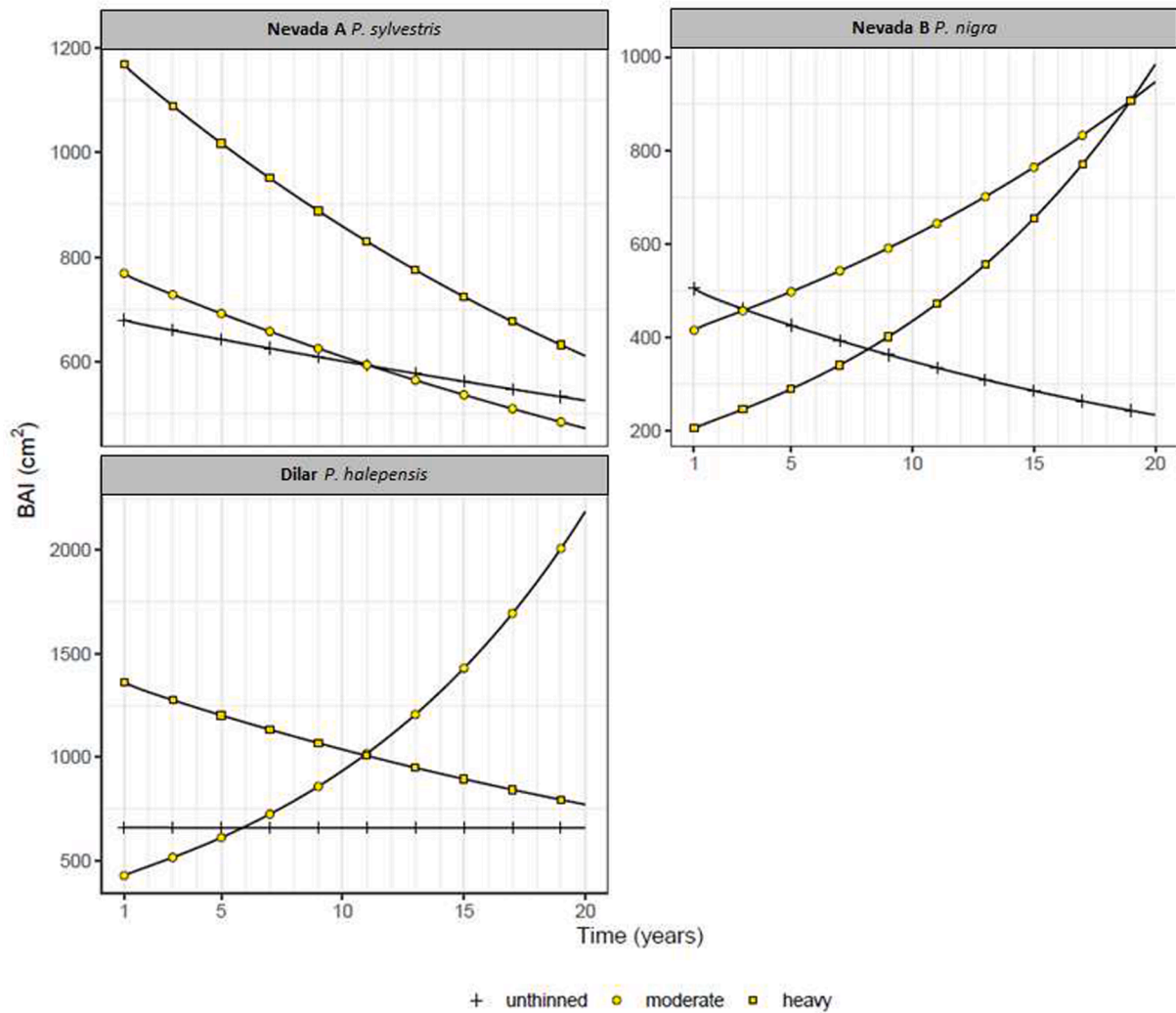
Fig. 6. Simulated post-thinning growth (BAI) trajectories for unthinned, moderately and heavily thinned plots. BAI was simulated during 20 years after thinning in the three species, with normal climate conditions assuming no drought impact (SPEI = 0).

maintaining a more favourable water status and rates of gas-exchange and photosynthesis for trees subjected to low competitive stress (Deligöz et al., 2021). Trees subjected to high competition are less sensitive to water availability, probably because they allocate more resources to above-ground growth in order to grow higher (Gleason et al., 2017).

When modeling growth with SPEI (Figs. 4 and 5), *P. sylvestris* had a shorter growing season than the other two species, but the highest increase in growth following thinning. These characteristics may be linked to the species' hazardous hydraulic strategy, which relies on a higher hydraulic conductivity to encourage rapid growth and a rapid stomatal closure in response to evaporative water demand (Domec and Gartner, 2002). Furthermore, the best growth model for *P. halepensis* was in September, with the strongest dependence on the SPEI and the weakest dependence on growth from the previous year, and with higher responsiveness to climate in the control stands. *P. halepensis*, a species that avoids drought, has a lower rate of stomatal conductance, which results in a lower water-spending strategy (Martínez-Vilalta et al., 2004; Klein et al., 2011), suggesting that heavy thinning may increase drought stress because of water soil loss which accelerates stomatal closure and reduce photosynthesis rates (Molina et al., 2021). The fact that it is dominant on both mid-elevation Mediterranean mountains and dry sites in central Europe makes *P. nigra* ecophysiologically intermediate (Pasho et al., 2011; Camarero et al., 2015) between the Eurosiberian water-

spender *P. sylvestris*, and the Mediterranean water saver *P. halepensis*, and it has the best growth responses to moderate thinning treatments. This is related to the relative improvement of the supply of water and light caused by thinning determines its (Martín-Benito et al., 2010) in water-limited environments (Giuggiola et al., 2016). Thinning, therefore, promotes a more positive response to climate in thinned stands, suggesting that thinning may reduce drought stress as a consequence of an increase in water soil and photosynthesis rates under water-limiting conditions.

4.3. Thinning modifies drought vulnerability indices

It has been shown that thinning can increase growth during droughts, thus changing drought vulnerability indices (Navarro-Cerrillo et al., 2019; Lucas-Borja et al., 2021; Castagneri et al., 2022), although results are not consistent (Schmitt et al., 2020). This inconsistency may be related to the synergetic effects of droughts (Rodriguez-Vallejo and Navarro-Cerrillo, 2019). Our findings imply that when comparing different species and local climatic conditions, thinning changes drought vulnerability indices more in thinned than in unthinned stands for *P. sylvestris, P. nigra* and *P. halepensis*. This response seems to be related to the benefits of thinning as regards soil water availability for all species, thus reducing growth dependence from previous drought events. This finding is consistent with previous studies carried out in seasonally
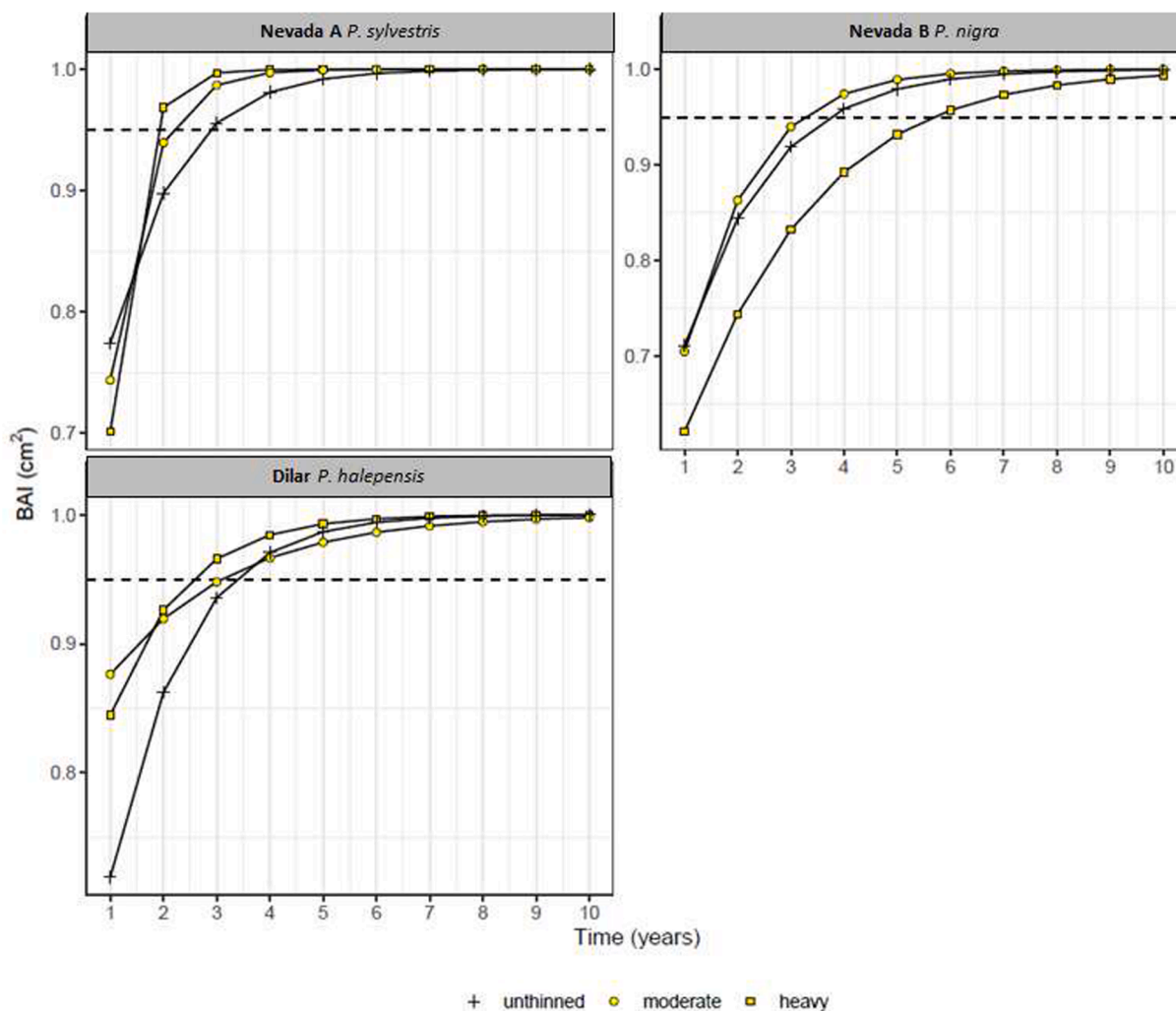
Fig. 7. Simulated post-drought growth trajectories: evolution of ΔBAI (ratio of modelled BAI to the BAI of a normal year) during ten years after the drought. The moments when 95% of normal year BAI is reached correspond to the time of recovery (dashed horizontal line).

Table 3
Drought vulnerability indices (Resistance CR_T, recovery CR_C, and resilience CR_S) and time of recovery (TR) simulated for post-drought growth trajectories for *Pinus sylvestris, Pinus nigra* and *Pinus halepensis*. R_T values correspond to ΔBAI at time 1 in Fig. 7, and R_S and R_C were computed using the estimated BAI three years after the drought.

Species	Treatment	CR_T	CR_S	CR_C	TR
Pinus sylvestris	HT	0.698	1.431	0.999	0.500
	MT	0.738	1.345	0.993	1.568
	C	0.772	1.219	0.941	3.392
Pinus nigra	HT	0.621	1.438	0.892	4.717
	MT	0.705	1.382	0.974	2.310
	C	0.710	1.351	0.959	2.763
Pinus halepensis	HT	0.819	1.174	0.962	2.565
	MT	0.859	1.084	0.931	4.344
	C	0.753	1.234	0.929	3.831

dry Mediterranean conifer forests (Navarro-Cerrillo et al., 2018, 2019; Rodriguez-Vallejo et al., 2021), showing that growth temporal persistence drives mid- and long-term growth responses, and consequently adaptability to climate, following successive severe droughts (Gazol et al., 2020). However, we observed a non-significant impact on drought recovery for *P. nigra* and *P. halepensis*, probably because growth

reduction during droughts produces similar recovery values on thinned and unthinned plots (Gazol et al., 2018; Manrique-Alba et al., 2020, 2022). Unlike previous works (Manrique-Alba et al 2022), in our case, drought vulnerability indices seem to have a more consistent response regarding the thinning effects. In *P. sylvestris* and *P. halepensis*, the highest values of indices were attained on the heavy thinning plots, while in *P. nigra* they were attained when employing the moderate thinning treatment. However, in *P. nigra*, where growth loss began to occur before 1995 drought, it is possible that resilience after this drought could affect the resilience response of the species (Schwarz et al., 2020). This is consistent with the results of Manrique-Alba et al. (2022), who, when using a different approach, found that thinning consistently enhanced drought vulnerability indices, and particularly resilience. Recovery response to thinning may be explained by the interdependence between the resilience components (Gazol et al., 2018) related to less growth reduction during a drought, which was an indicator of better resistance, followed by a higher recovery on thinned plots after a drought.

4.4. Mid-term effects of thinning on tree growth

Recovery time after thinning is one of the most significant factors to impact on tree-level growth responses to treatment and drought. Growth responses after several droughts from 1995 to 2012, therefore, showed that the time response was reduced, demonstrating that thinning can

help pine plantations to cope with the effects of severe and cumulative drought stress. The period to recovery was positively affected by heavy thinning in the case of *P. sylvestris* and *P. halepensis*. In that of *P. nigra,* the shortest recovery time was obtained with moderate thinning. These results coincide with those of previous findings (Anderegg et al., 2015; Ovenden et al., 2022; Manrique-Alba et al., 2020, 2022). However, these comparisons must be made carefully owing to the difficulty of estimating the duration to recovery in observational research. *P, sylvestris* occupies areas in which there is some water compensation based on a faster stomatal closure in response to evaporative water requirement (Domec and Gartner, 2002), while *P. halepensis* is resistant to drought thanks to its low water-spending strategy (Klein et al., 2011). However, *P. halepensis* recovers more slowly after a drought because its capacity to increase growth after drought events is lower (less elasticity, Di Filippo et al., 2021). *P. nigra* is, meanwhile, more sensitive to droughts in dense plantations (Esteban et al., 2012; Sánchez-Salguero et al., 2013) and can be considered intermediate in terms of drought tolerance (Martinez-Vilalta et al., 2004; Camarero et al., 2015).

In concordance with drought vulnerability indices, growth persistence might prevent post-drought growth legacies and contribute to the temporary reduction in thinning benefits (Navarro-Cerrillo et al., 2019). There is, to the best of our knowledge, still a lack of studies on how growth persistence related to thinning might prevent post-drought growth legacies. Our results showed that simulated post-thinning growth under constant neutral climatic conditions gradually disappear in the case of *P. sylvestris* but not in that of *P. nigra* and *P. halepensis* (Fig. 6). These results appear to indicate that the thinning response of the different species is very different. *P. sylvestris* underwent a long-term reduction in growth (<20 years) when subjected to all the thinning treatments, as has been observed in other studies (Navarro-Cerrillo et al., 2019; Manrique-Alba et al., 2022). The thinning effect is limited in time for this species, and thinning does not imply a permanent change in the growth trend of the plantations. This may be owing to the fact that these plantations are located on the rear edge of species distribution (Sánchez-Salguero et al., 2012) or to inadequate species selection (Fernández-Cancio et al., 2011). However, *P. halepensis* and *P. nigra* responded to thinning with a marked effect on medium-term growth. The modelled growth of the unthinned plots showed a clear downward trend (*P. nigra*) or stagnation (*P. halepensis*), while growth increased on the thinned plots. The growth models for these species indicated a positive effect of thinning, and, therefore, a contribution to better responses to stress in the medium and long term (Calev et al., 2016; Manrique-Alba et al., 2021). These results highlight the importance of considering the long-term effectiveness of thinning in drought-prone forests (Navarro-Cerrillo et al., 2019, Manrique-Alba et al., 2020, 2021).

These results are reinforced by the different response times to thinning of the different species. With regard to unthinned plots, time to recovery was normally between three and four years, while it typically varied between one and four years for thinned plots. These results are similar to the findings of Anderegg et al. (2015), who identified an average TR of between 1 and 4 years in a global review of tree-ring series from natural forests. When analysing the time to recovery of each species, *P nigra* responded more quickly to moderate thinning, while *P sylvestris* and *P. halepensis* responded better to heavy thinning. This could be related to the pre-thinning density (lower in *P. halepensis*), drought-species sensitivity (higher in *P. nigra* and *P. sylvestris*) and the plantation origin of forests when compared to natural forests.

4.5. Silvicultural implications

In dry Mediterranean mountains under a high risk of growth decline, dieback and tree mortality events (Camarero et al., 2015), it is important to quantify the trade-offs between stand growth and stability. Thinning is, therefore, more oriented towards adaptive silviculture (Castagneri et al., 2022) than towards enhancing productivity (del Río et al., 2017; Acuña et al., 2021). Thinning intensity, rotation, and the growth

response of several species growing in the same location are consequently the outcomes required in order to design silvicultural schemes. Mid-term reductions in growth after thinning were observed for *P. sylvestris* and *P. nigra*, which reinforces the idea that thinning benefits are simply a transitory solution by which to mitigate the negative impacts of drought (Navarro-Cerrillo et al., 2019), and implies the need for different thinning strategies. However, although thinning impacts are limited, this type of silvicultural practice is useful because it enables the gradual adaptation of the forest structure, especially at low or very low densities, in an economically viable manner, avoiding sudden mortality processes that cause irreversible damage and great social alarm (Navarro-Cerrillo et al., 2019; Manriquez-Alba et al., 2022). Our findings demonstrate that the beneficial legacy effect of thinning, in terms of growth improvement, persists for sufficient time (10 years) to develop silvicultural schemes throughout the whole rotation cycle. The three species have extensive geographic ranges and inhabit a variety of environmental gradients, but thinning impact when considered in the same location was consistently positive in all cases. However, as other authors have pointed out (Manrique-Alba et al., 2022; Moreau et al., 2022), the time to recovery on the basis of observational research must be estimted carefully. Thinning also plays an important role in some pine species establishment (Tíscar et al., 2017), thus, thinning studies should also integrate the effect on stand regeneration.

5. Conclusions

Pine plantations in dry Mediterranean areas demand different thinning strategies with which to reduce their vulnerability to the risks associated with global warming and maintaining ecosystem function and services in the long term. The effects of thinning on the growth of Mediterranean pine species under different climatic conditions are, therefore, of great interest. In these conditions, thinning is more oriented towards reducing drought vulnerability. We make a new contribution to assessing the benefits of thinning as regards pine stand growth and drought vulnerability, along with simulated growth trajectories in controlled settings, in order to provide silvicultural scenarios with which to support the opportunity of thinning trees at climatic risk in vulnerable plantations. Our results reveal evidence that moderate (*P. nigra*), and heavy (*P. sylvestris* and *P. halepensis*) thinning promotes growth, thus increasing the resistance and resilience of forests. Post-thinning growth simulations showed that the effects of thinning virtually disappear in the case of *P. sylvestris,* but not in that of *P. nigra* and *P. halepensis*. According to the post-drought trajectories modelled, the drought vulnerability indices showed that thinning consistently increased drought recovery. Finally, with regard to thinned plots, it took around a year less to recover from drought when compared to unthinned stands. Despite the fact that our results suggest that thinning is an effective method with which to reducethe vulnerability of forests to drought in Mediterranean areas, it should be adapted to each species, thus paving the way towards the implementation of long-term adaptive management strategies. This work is a new contribution that demonstrates the urgent need for forest managers to take steps to help drought-vulnerable Mediterranean pine plantations to adapt to the risks posed by climate change.

CRediT authorship contribution statement

Rafael M. Navarro-Cerrillo: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Project administration. **Antonio M. Cachinero-Vivar:** Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Project administration. **Óscar Pérez-Priego:** Methodology, Investigation. **Rut Aspizua Cantón:** Conceptualization, Resources. **Santiago Begueria:** Methodology, Formal analysis. **J. Julio Camarero:** Methodology, Investigation, Writing – original draft.

Declaration of Competing Interest

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2023.120936.

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