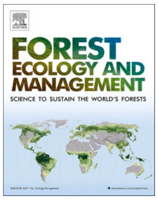
Forest Ecology and Management 597 (2025) 123120

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco



Consideration of *Abies cilicica* for central European reforestation

Ulf Büntgen[a,b,c,*,1], Alper Kaan Kadioglu[a], Kasia Charcinska[a], Edurne Martinez del Castillo[d], Alexis Arizpe[a], Tatiana Bebchuk[a], Jan Esper[b,d], Mirek Trnka[b], Clive Oppenheimer[a], Nesibe Köse[e], Ünal Akkemik[e], Hüseyin Tuncay Güner[e]

[a] *Department of Geography, University of Cambridge, Cambridge CB2 3EN, United Kingdom*
[b] *Global Change Research Institute (CzechGlobe), Czech Academy of Sciences, Brno 603 00, Czech Republic*
[c] *Department of Geography, Faculty of Science, Masaryk University, Brno 613 00, Czech Republic*
[d] *Department of Geography, Johannes Gutenberg University, Mainz 55099, Germany*
[e] *Faculty of Forestry, Department of Forest Botany, Istanbul University-Cerrahpaşa, Bahçeköy-Sarıyer, Istanbul 34473, Turkey*

ARTICLE INFO

Keywords:
Climate change
Dendrochronology
Drought
Forest management
Global warming
Resilience
Tree rings

ABSTRACT

A sequence of central European summer droughts since 2018 has intensified the quest for suitable reforestation species. The fact that newly planted trees will experience a warmer, drier and likely also more variable climate, however, challenge the forest sector. Here, we explore the drought resistance and resilience of Taurus fir (*Abies cilicica* (Ant. & Kotschy) Carr.), and discuss its potential for ecosystem service, timber production and carbon storage under future climate change. We measured earlywood and latewood widths of 109 Taurus firs from two neighbouring sites in southern Türkiye. Average summer temperatures at the species' biogeographic heartland are comparable to those of the exceptional central European heatwave in 2018, while precipitation at our sites is still much lower. Mean tree age is 89 years, and the average growth rate of 1.5 mm is dominated by 75 % earlywood. The various tree-ring chronologies correlate significantly with May to July precipitation ($r > 0.7$; 1960–2022), and their tailed positive distributions are indicative of arid baseline conditions. We suggest *Abies cilicica* as a potential candidate for mixed-species reforestation on appropriate soils in central Europe. Acknowledging the long-term consequences of silvicultural decisions, stronger collaborations between stakeholders and researchers are needed to prepare the forestry sector for direct and indirect effects of anticipated climate change.

1. Introduction

The observed and predicted increase in the frequency and intensity of summer droughts poses a combined threat to natural and societal systems alike. Anthropogenic climate change has been reported to impact water availability, food security and ecosystem productivity around the world (Ciais et al., 2005; Samaniego et al., 2018; Trnka et al., 2019; Gampe et al., 2021). Forests are no exception in this regard, and their vulnerability to hydroclimatic extremes is likely to increase under global warming (Allen et al., 2010; Anderegg et al., 2015; Vitali et al., 2017; Martinez del Castillo et al., 2024; Tew et al., 2024).

Exceeding the well-documented central European heatwaves of 1976 and 2003 in magnitude and duration, the exceptional summer drought of 2018 was unparalleled in the past 2000 years (Büntgen et al., 2021a). The hydroclimatic extreme triggered widespread forest dieback across much of the continent (Schuldt, 2020; Senf and Seidl, 2021; Knutzen et al., 2025), followed by a cascade of ecological and economic consequences across different spatiotemporal scales (Obladen et al., 2021; Treml et al., 2022). In addition to the immediate physiological vulnerability of forest ecosystems to severe water stress (Bose et al., 2024), successive bark beetle outbreaks were particularly devastating for spruce-dominated central European forests (Bottero et al., 2021; D'Andrea et al., 2023; Hlásny et al., 2021; Knutzen et al., 2025).

Since regional rates of tree mortality have reached up to 100 % in parts of Germany, France, Switzerland, Austria, and the Czech Republic, there is an urgent need to identify alternative tree species and improve forest management practices (Vacek et al., 2023; Tew et al., 2024). Among innovative sylvicultural considerations is the afforestation of

---

* Corresponding author at: Department of Geography, University of Cambridge, Cambridge CB2 3EN, United Kingdom.
E-mail address: ulf.buentgen@geog.cam.ac.uk (U. Büntgen).

[1] ORCID 0000–0002-3821–0818

https://doi.org/10.1016/j.foreco.2025.123120

drought-resistant and pest-tolerant broadleaf and conifer species with high resilience levels to biotic and abiotic stressors (del Río et al., 2021). Assisted migration and the introduction of non-native species into central Europe are also gaining attention to prepare forest ecosystems for a warmer and drier climate (Chakraborty et al., 2024; Dumroese et al., 2015; Pedlar et al., 2012; Streit et al., 2024; Williams and Dumroese, 2013). Assisted migration refers to the introduction of trees species into new regions, such as Douglas fir (*Pseudotsuga menziesii*) in central Europe (Isaac-Renton et al., 2014; Hintsteiner et al., 2018), or western larch (*Larix occidentalis* Nutt.) in northern British Columbia (Roskilly and Aitken, 2024). Despite its suggested benefits, assisted migration has potential risks as relocated species can become invasive or disruptive. Moreover, little attention has been given to understanding the growth rates and climate responses of niche species from Mediterranean climates. While the demand for reforestation in central Europe has considerably increased since 2018 (Schuldt, 2020; Bottero et al., 2021; Hlásny et al., 2021; Obladen et al., 2021; Senf and Seidl, 2021; Treml et al., 2022; D'Andrea et al., 2023; Bose et al., 2024; Knutzen et al., 2025), and priorities have rapidly shifted away from extensive monocultures (Tew et al., 2024), much remains unknown about the natural range in which forest ecosystems can operate.

The widespread dieback of Norway spruce and Scots pine in many parts of central Europe since 2018 further emphasises the need for more drought-resistant tree species (Bottero et al., 2021; Castagneri et al., 2022). Although Norway spruce is amongst the economically important tree species on the continent, its high level susceptibility to summer droughts and subsequent bark beetle outbreaks limits its cultivation potential under future climate change (Knutzen et al., 2025). Although Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franko) and black pine (*Pinus nigraschul*, F. F. Arnold.) have been proposed as potential surrogates for Norway spruce (*Picea abies* (L.) Karst.), as well as Scots pine (*Pinus sylvestris* L.) (Hintsteiner et al., 2018; Thiel et al., 2012; Vitali et al., 2017, 2018), more research into the suitability of conifer species from arid environments for mixed-stand reforestation programmes north of the Alpine arc is needed (Lindenmayer et al., 2016; Sánchez-Salguero et al., 2017). This is particularly the case since contrasting results have been reported for silver fir (*Abies alba* Mill.) (Bosela et al., 2016, 2018; Vitasse et al., 2019; Walder et al., 2021; Rybar et al., 2023; Marcis et al., 2025).

Here, we introduce the Taurus fir (*Abies cilicica*) as a possible surrogate species for mixed-species reforestation programmes under suitable site conditions across Europe. We assess ring width variability and climate sensitivity at two neighbouring forest sites at the species' biogeographic centre in southern Türkiye. We analyse the species' summer drought resistance and resilience. Comparison of the climatology of the warm and dry eastern Mediterranean region with that of the Harz mountain in central Germany suggests that the hitherto overlooked Taurus fir is potentially suitable for central European silviculture under predicted climate change.

2. Materials and methods

2.1. Study region and species description

Our two sampling sites are located next to each other in the central Taurus mountains, north of the harbour city of Mersin in southern Türkiye (Fig. 1 inset). The circa 50–100 km wide mountain range stretches parallel to the Mediterranean coastline and extends over ~2000 km from the Aegean Sea ~28° East to the Iranian border ~44° East (Parolly, 2015). With several summits > 3500 m asl and a distinct Oro-Mediterranean climate (Atalay et al., 2014; Kavgacı et al. 2021; Çetin and Meydan 2023), the Taurus mountains contain a rich endemic

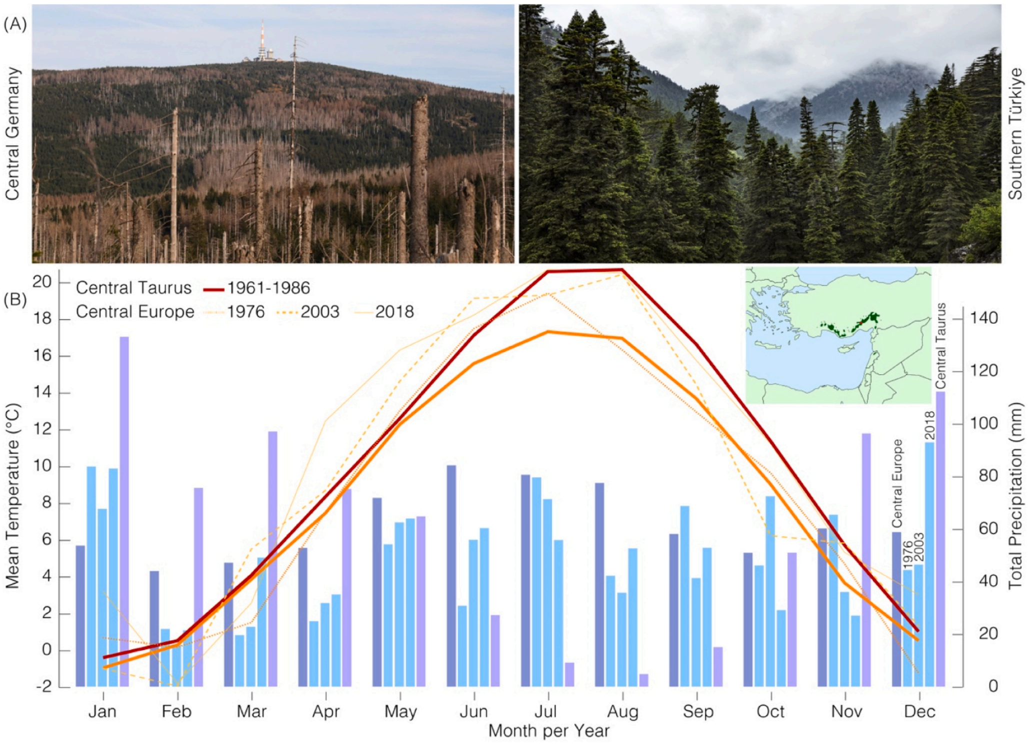


Fig. 1. (**A**) Example of spruce (*Picea abies*) mortality at the Harz mountain in central Germany triggered by the 2018 summer heatwave (left), and an example of a healthy Cilician or Taurus fir (*Abies cilicica*) forest in the central Taurus mountains near Camlıyayla in southern Türkiye (right). (**B**) Monthly mean temperatures (lines) and precipitation totals (bars) obtained from the meteorological station in Pozantı circa 40 km northeast of our dendrochronological sampling sites (i.e., Central Taurus), and gridded climate data averaged over 48–52°N and 4–18°E to represent larger scale climatology (i.e., Central Europe). We applied a 0.5°C lapse rate to cool the monthly temperatures from Pozantı by 4°C to best represent the conditions at our sampling sites. All values are calculated over the common period 1961–1986 defined by the rather short Pozantı record. The inset map shows the natural distribution of *Abies cilicica* in southern Türkiye and the Near East (Caudullo et al. 2017), with the red square referring to our sampling sites around 37°10' North and 34°32' East.

flora and extensive pastoralism. Summers are hot and dry (Fig. 1), but winters are cold and snowy. Mean monthly winter temperatures at our study sites are similar to those of central Europe (Fig. 1B), but summers and autumns are on average 2–3°C warmer. Winter and spring precipitation totals at our study site almost double those of central Europe, whereas summer rainfall between June and September is approximately one tenth that of central Europe. Summer temperatures during the exceptional 2003 and 2018 heatwaves in central Europe were comparably high as the long-term mean at our study region, whereas the very dry summer of 1976 was less hot. The climatological comparison between our study region and central Europe underlines the severity of summer drought *Abies cilicica* withstands each year.

As part of a regional national park, healthy fir (*Abies cilicica*) forests near the village of Çamlıyayla have been designated as one of 79 official gene protection zones in Türkiye. Commonly known as Cilician or Taurus fir, *Abies cilicica* is one of four native fir species in southern Türkiye, northern Syria and the Lebanon (Aussenac, 2002). The species can be separated morphologically into a western lineage with smooth shoots and resin-rich buds (*Abies cilicica* subsp. *isaurica*) and an eastern lineage with young, hairy shoots and resin-free buds (*Abies cilicica* subsp. *cilicica*). The species often co-occurs with *Cedrus libani* A. Rich., *Juniperus excelsa* M. Bieb., *J. drupacea* Labill., *J. foetidissima* Willd. and *Pinus nigra* and covers an estimated extent of 1700 km^2 in Türkiye (Bozkuş 1988). Pure *Abies cilicica* forests are widespread on the north facing slopes near Çamlıyayla (Atalay et al., 2014). Amongst other circum-Mediterranean fir species (Aussenac, 2002), *Abies cilicica* occupies the largest area (350,000 ha) (Bozkuş 1988).

The shade tolerant species usually grows on shallow and well-drained calcareous substrate, where tree heights can reach 30–35 m (Farjon, 2017). Needle lengths vary between 2 and 3 cm, and cylindrical, reddish-brown female cones of 15–30 cm length mature after one year. Up to 2 m thick stems and distinct taproot structures make *Abies cilicica* resistant to winds (Farjon, 2017), and sensitive stomata allow thriving under xeric conditions (Parolly, 2015; Aussenac, 2002). *Abies cilicica* can produce 2–6 m^3/ha/year of timber and has a water potential corresponding to partial and total transpiration controls of -1.8 and -2.6 MPa (Aussenac, 2002), respectively. Dendrochronological, climatological and paleo-ecological investigations of the species are rare (Akkemi̇k, 2000; Sánchez-Salguero et al., 2017).

2.2. Sample collection and data investigation

We selected two undisturbed, neighbouring forest sites at the biogeographic centre of the natural distribution of *Abies cilicica* at the fringe of a protected seed bank near Çamlıyayla around 37°10’ North and 34°32’ East (Table 1). Both sampling sites L23 and H24 are characterised by calcareous limestone and sandy soils in an undisturbed *Abies cilicica* forest of approximately 24.4 ha. Existing sylvicultural estimates suggest mean stand density of 708 stems/ha, mean annual increment of 8 m^3 /ha, and a growing stock volume of 340 m^3 /ha (Bozkuş 1988).

We extracted two 5 mm increment cores at breast height from 53 and 56 randomly selected, healthy and mature *Abies cilicica* trees in July 2023 at around 1500 m asl (L23) and in September 2024 at around 1600 m asl (H24) (Table 1). Assigned with a unique ID, each sample was air dried for subsequent analyses. Cores were glued onto wooden mounts with their cross-sectional view upwards to ensure visibility of ring boundaries after sanding with progressively finer grain sizes up to 800 grit size. Visual cross-dating under microscopic magnification was supplemented by skeleton plots to associate each ring with a calendar year. Cores were then scanned and high-resolution images processed with the CDendro & CooRecorder software package (Maxwell and Larsson, 2021) to measure earlywood (EWW), latewood (LWW) and total ring width (TRW) separately at a resolution of 0.01 mm. Pith-offset was estimated and measurement accuracy statistically validated with COFECHA (Holmes, 1983).

An integrative ensemble approach was applied to evaluate and remove non-climatic, age-related trends in the raw EWW, LWW and TRW measurement series. We averaged the parameter- and site-specific dimensionless timeseries from single series detrending with cubic smoothing splines with 50 % frequency cut-off at 50, 75, 100, and 125 years, negative exponential functions (Cook and Peters, 1981), and the Regional Curve Standardisation technique (RCS; Briffa et al., 1992; Esper et al., 2003). Combined with index calculation as ratios or residuals after power transformation (Cook and Peters, 1997), these detrending options resulted in an ensemble of 12 slightly different versions for each EWW, LWW and TRW chronology from the two sites L23 and H24 (i.e., $12 \times 3 \times 2 = 76$). Pith-offset estimates were considered for RCS detrending, and inter-series correlation (Rbar) and the Expressed Population Signal (EPS; Wigley et al., 1984) were calculated over 30-year windows lagged by 15 years.

To account for methodological biases (Büntgen et al., 2021b, 2024), minimum and maximum annual values of the individual ensemble members were used for uncertainty estimates. The parameter- and site-specific ensemble means were averaged for growth-climate analysis. Monthly and seasonal minimum, mean and maximum temperatures, as well as precipitation totals were obtained from the gridded 0.25° × 0.25° E-OBS land surface dataset (v30.02; updated from Cornes et al., 2018). A split period approach was used to test for temporal stability, and temperature and precipitation measurements from the nearby meteorological station in Pozantı were used for comparison with the gridded product (WMO station 17351.2). A 0.5°C/100 m lapse rate was used to adjust the monthly temperature means at Pozantı to conditions at our sampling sites (i.e., 4°C was subtracted from the station values to account for the elevational difference of circa 750 m between Pozantı and our sampling sites). The gridded 0.5° × 0.5° CRU TS 4.08 dataset (Harris et al., 2020) was used to compare the occurrence of ground frost days at our sampling sites in southern Türkiye with those of the Harz mountain in central Germany. We also employed a gridded monthly sea level pressure dataset (HadSLP2; Allan and Ansell, 2006) to derive composite maps for combinations of positive and negative EWW, LWW and TRW anomalies.

The raw TRW measurements were transformed into basal area increment (BAI) to assess the species' resistance, resilience and recovery using the bai.out function of the dplR package (Bunn, 2008; Martinez del Castillo et al., 2024). The resulting BAI data were detrended using a 100-year spline method to remove long-term age trends while retaining interannual variability relevant to climate extremes. Resistance, resilience and recovery metrics were calculated over four-year pre- and post-disturbance intervals, using the ten driest regional summers with the lowest precipitation totals between May and August recorded at Pozantı (1–10: 1984, 1989, 1966, 2006, 1978, 1974, 1994, 2005, 2004, 1996), as well as the next ten driest years (11–20: 1961, 2021, 2020, 1990, 2019, 2013, 1991, 2010, 1965, 1960). The resistance metric evaluates the immediate impact of a disturbance event, such as summer drought stress, on radial stem growth, while the resilience metric reflects the capacity of trees to return to pre-disturbance growth levels. The species' resistance, resilience and recovery were also evaluated against

Table 1
Characteristics of the tree-ring datasets from both sampling sites L23 and H24.

Site	Latitude	Longitude	Elevation	Trees	Cores	Start	End	MSL	M EWW	M LWW	M TRW
H24	37°10'11" N	34°32'20" E	1600 m asl	56	103	1851	2024	96	0.918	0.342	1.260
L23	37°10'25" N	34°33'40" E	1500 m asl	53	105	1897	2022	82	1.236	0.425	1.661

the years with the highest number of ground frost days in April and May

3. Results

The mean segment length of all 208 core samples is 89 years (Fig. 2 A), with little difference between L23 and H24 (82 and 96 years). Sample size and signal strength are very high at both sites (Fig. S1). The EPS calculated for the individual, raw EWW, LWW and TRW measurement series exceeds 0.85 at both sites from the 1930s onwards. The inter-series correlation (Rbar) ranges between 0.2 and 0.5 over the past seven decades. The mean annual growth rate is 1.66 and 1.26 mm at L23 and H24, respectively. EWW-LWW proportions are similar at both sites, with TRW being dominated by EWW (75 %). There is a clear relationship between decreasing growth rates with increasing segment lengths as rings are getting narrower with increasing tree age. When aligning the raw EWW, LWW and TRW measurement series by their innermost rings, the so-called regional curves reveal different growth rates and trends for the two sites (Fig. 2B). None of the parameter-specific regional curves shows a marked juvenile growth increase at L23, whereas the first 20–40 years of cambial age at H24 exhibit inflated stem growth. This pattern does not change when considering pith-offset estimates that are similar for both sites (Fig. 2B). A closer look at germination and sapling formation suggests that almost half of the trees at H24 established before the 20th century (Fig. 3), whereas most of the trees at L23 started to grow in the first two decades of the 20th century.

The grand average correlation between the three parameter-specific raw chronologies without detrending is 0.87 for L23 and 0.90 for H24, when using the 1917–2022 period during which sample size in each dataset exceeds ten series (Fig. S2). The highest correlations of 0.98 are found between EWW and TRW at both sites. The lowest, though still highly significant correlations of 0.76 and 0.81 are found between EWW and LWW at L23 and H24, respectively. The parameter-specific chronologies after detrending exhibit exceptional agreement at the site level (Fig. 4). The site-specific ensemble means for EWW, LWW and TRW correlate at 0.80, 0.83 and 0.82 (1917–2022), respectively. The first-order autocorrelation is highest for the EWW chronologies (0.30 and 0.49) and lowest for the LWW chronologies (-0.02 and 0.15), with values for TRW ranging in between (Fig. 4). Multi-year growth depressions in all chronologies are most pronounced from 1927–1929, 1965–1967, and 2002–2008.

Unlike most tree-ring chronologies, the annual values in our chronologies, and especially for LWW, are slightly skewed towards more extreme positive growth anomalies (Fig. S3). This tailed distribution reflects a drought-induced lower growth baseline and positive anomalies result from sporadic summer wetness. The three parameter-specific chronologies, averaged over both sites, reveal similar correlation maps against gridded May-August precipitation totals over 1960–2022 (Fig. 4). Significant positive correlations are evident for much of Türkiye ($p < 0.01$), with the highest correlations > 0.6 found over the Taurus mountains and surrounding Anatolia. A similar pattern, with the exception of additional significant positive correlations over the Balkan Peninsula, is found when calculating measured May-August precipitation totals from the Pozantı station against the gridded E-OBS product (Fig. S4). Significant positive correlations are found for all monthly and seasonal precipitation totals between May and August ($p < 0.01$) (Fig. S5).

Composite maps of mean May-August sea level pressure for the 20 most positive (negative) growth anomalies > 1.15 (<0.80) describe distinct patterns over the North Atlantic/European sector and the Mediterranean basin (Fig. 5). Increased tree growth coincides with two anomalously high-pressure cells over the Atlantic west of France and the Iberian Peninsula, as well as over the Baltic and into Russia. Reduced tree growth, however, coincides with a distinct longitudinal belt of anomalously high pressure from the North Atlantic, south of Iceland, over the British Isles, into France and across the Mediterranean to the Near East. Even more pronounced are the pressure patterns obtained

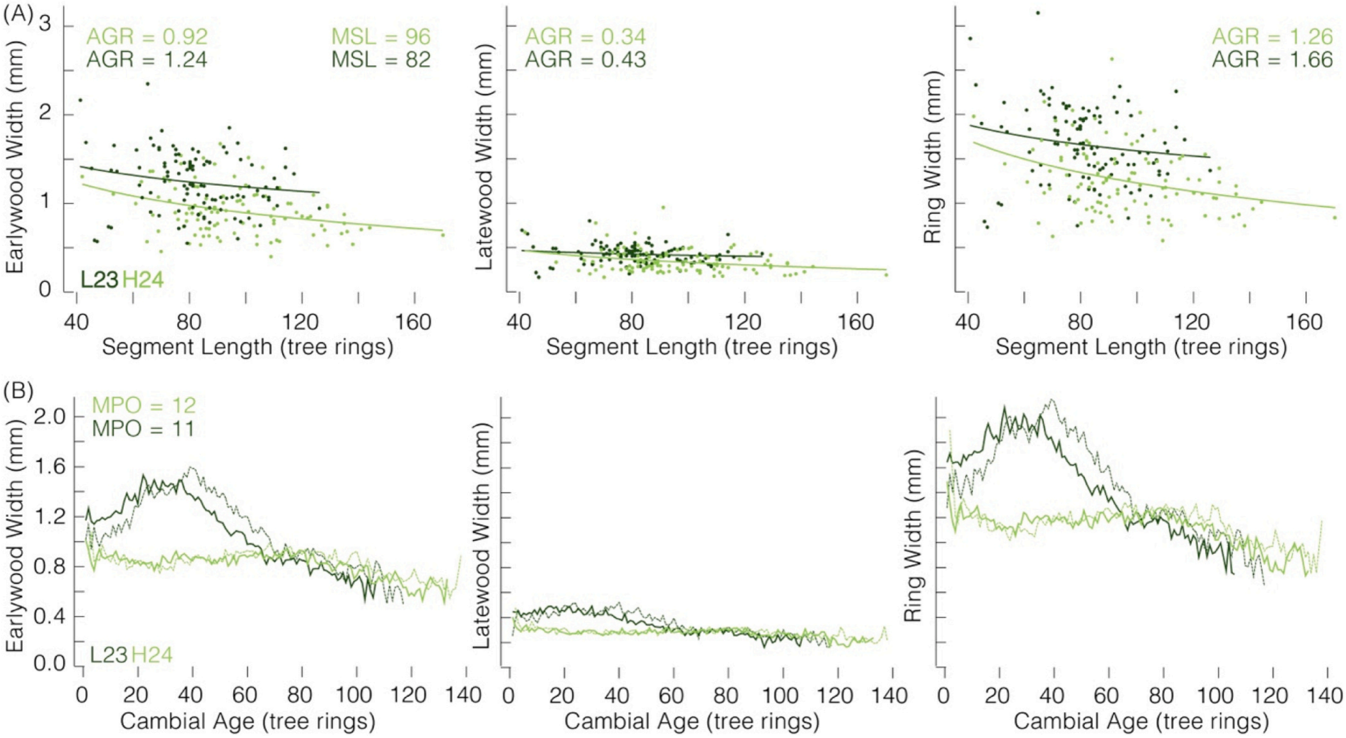


Fig. 2. (**A**) Relationship between segment length (i.e., the number of annual tree rings per core) and growth rate (i.e., earlywood width, latewood width and total ring width) in all 105 and 103 samples from the two sites L23 and H24, respectively. The mean segment length (MSL) and average growth rate (AGR) are provided for each site and parameter. (**B**) Age-related growth trends (i.e., Regional Curves) of all tree-ring parameters, calculated with and without considering pith-offset estimates (dashed and solid lines, respectively). The mean pith-offset (MPO) is indicated for each site.

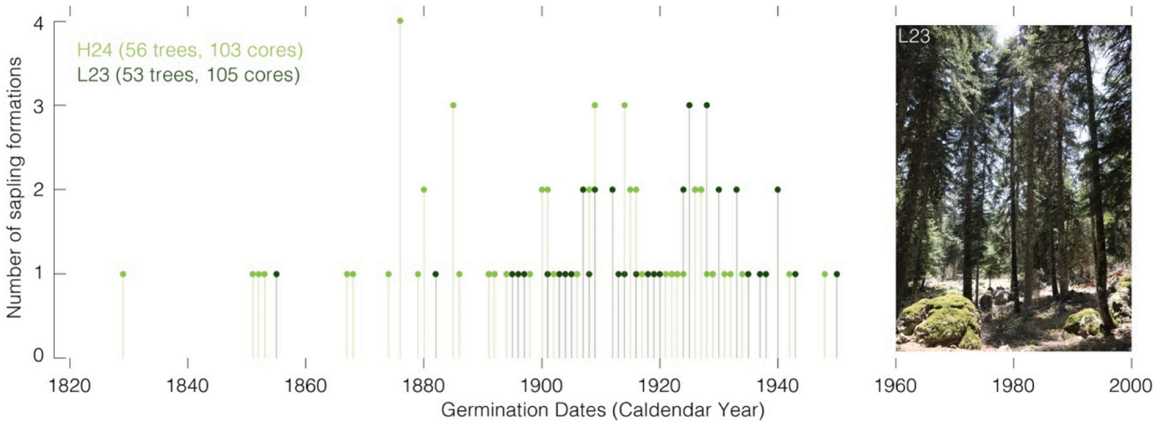


Fig. 3. Stand history of the two sites L23 and H24, for which we estimated pith-offset for each core sample, subtracted 8–12 years depending on average growth rate, and used the oldest date per tree for sapling formation. The picture shows site L23 in July 2023.

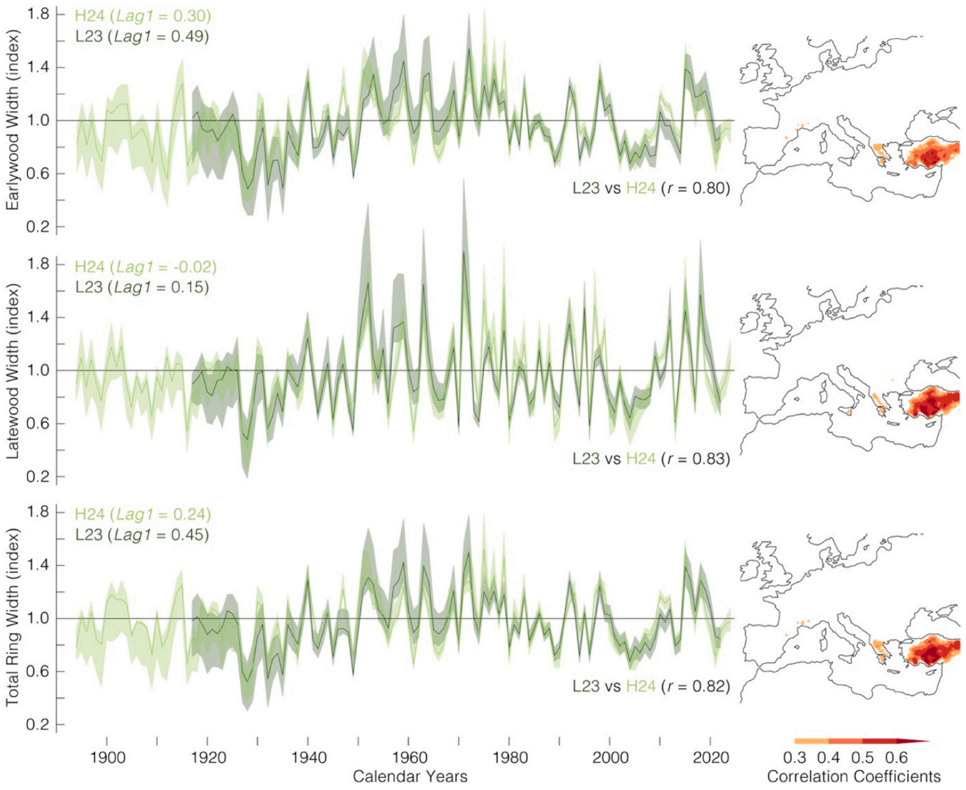


Fig. 4. Parameter-specific ensemble mean chronologies for both sites (L23 in dark green and H24 in light green), and their uncertainty based on the minimum and maximum ensemble members per year (shadings). The ensemble means are based on 12 chronology versions truncated at a sample size of 11 series (see Figs. S2-S3 for data characteristics). The first-order autocorrelations were calculated over the common period 1917–2022 (Lag1). The correlation maps are based on the mean of the two site-specific ensemble means and using gridded May-August precipitation totals over the period 1960–2022 that is defined by reliable climate data and chronology length (see Fig. S4 for station-grid correlation fields and Fig. S5 for individual climate responses).

from the EWW and LWW chronologies (Fig. S6). These findings corroborate the assumption that high pressure blocking of westerly airflow causes dry summers in the Taurus mountains during which radial stem growth of *Abies cilicica* is reduced. Low pressure and increased precipitation, however, enhance forest productivity. Contrary to common expectations, the number of ground frost days in the central Taurus mountains is higher than in the Harz mountain in central Germany (Fig. S7).

Similar resistance, resilience and recovery rates at both sites underline the species' overall drought tolerance (Fig. 6), whereas no systematic negative TRW responses to spring frosts were found (not shown).

4. Discussion

The montane *Abies cilicica* forests on the north-exposed slopes of the central Taurus mountains in southern Türkiye exhibit considerable drought resistance. The species' high proportion of EWW is indicative of rapid resource utilization in response to seasonal precipitation shortfalls (Yang et al., 2024). Our data also suggest minimal growth reductions during prolonged summer drought (Fig. 4), which is particularly relevant as hydroclimatic extremes are likely to increase in central Europe until the end of the century (Chakraborty et al., 2024; Spinoni et al., 2018; Suarez-Gutierrez et al., 2023). The tailed distribution of *Abies*

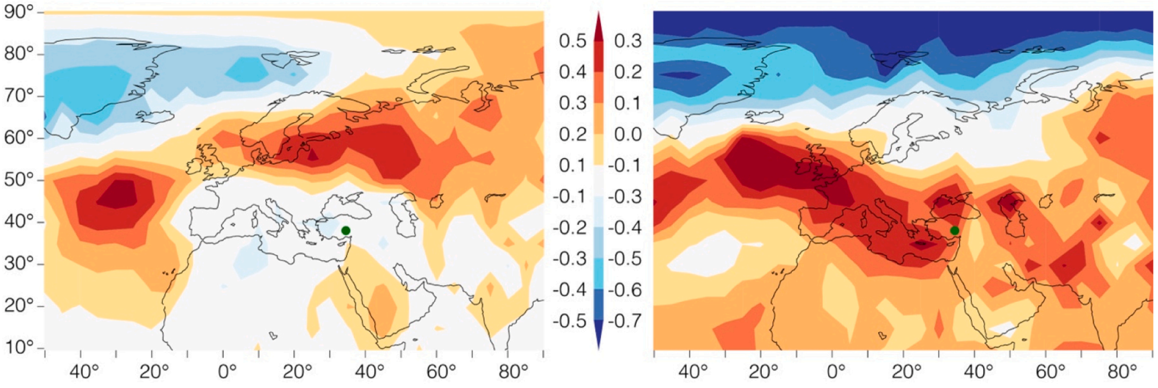


Fig. 5. Composite maps of mean May-August sea level pressure (SLP) for the 20 most positivise (left map) and negative (right map) tree-ring width (TRW) indices > 1.15 and < 0.80 (Table S1), respectively (note different scales). Both maps are based on the combined ensemble means of both sites L23 and H24 (green dot) and the gridded HadSLP2 dataset (Allan and Ansell, 2006). See Fig. S6 for SLP composite maps of the earlywood and latewood chronologies (EWW and LWW).

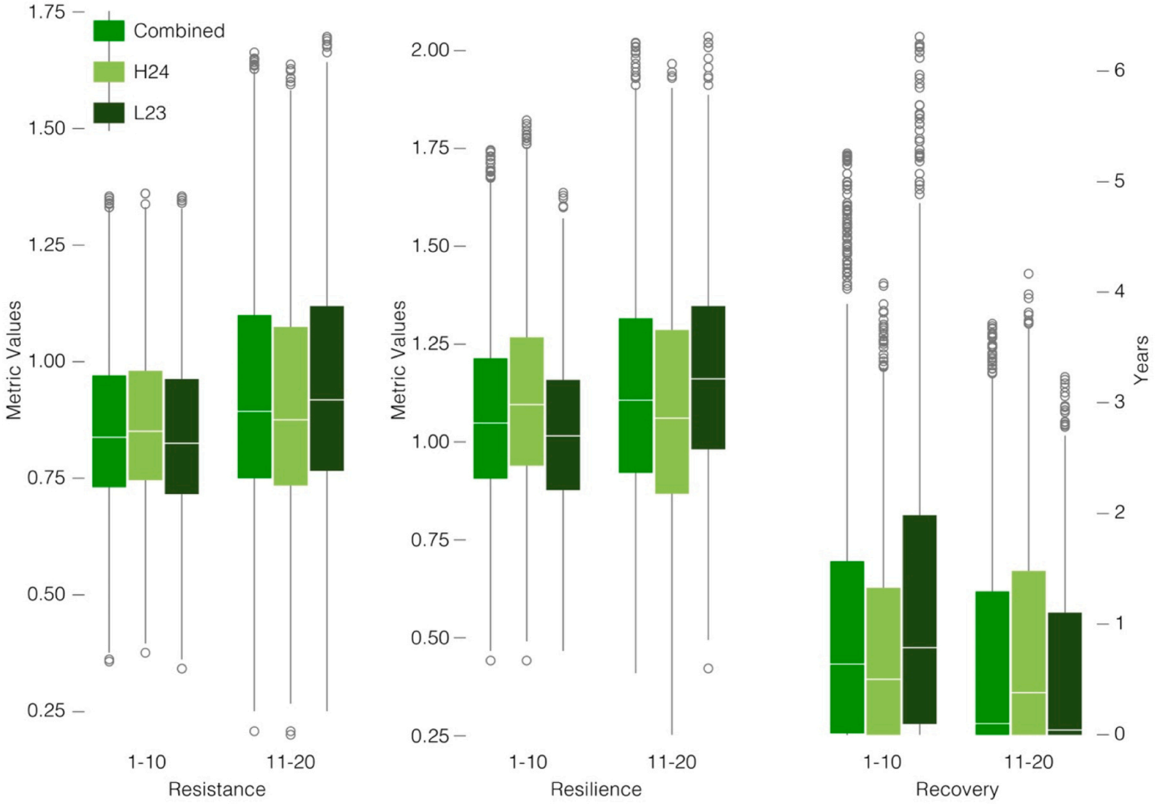


Fig. 6. Resistance, resilience and recovery indices for *Abies cilicica* trees during the first ten (1–10) driest years and the next ten (11–20) driest years between 1960 and 2023 CE. Calculated for individual trees, the metric values are summarised in boxplots for both sampling sites L23 and H24, as well as for the combined dataset including both sites. Boxplots present median values (horizontal lines), upper- and lower quartiles (box), outliers (vertical lines), and extreme outliers (circles).

cilicica growth anomalies differs from most temperature-sensitive tree-ring chronologies, because radial stem growth is water- rather than temperature-limited. Although we did not expect temperature changes to play an important role in tree growth at our sampling sites, we were surprised by the strong agreement between summer precipitation and ring width formation. At the same time, the species exhibits a high degree of resistance and resilience to summer droughts compared with other Mediterranean conifer species (Gazol et al., 2018; Ovenden et al., 2021; Martínez del Castillo et al., 2024).

Genetic evidence further suggests the ability of fir to thrive in a warmer and drier environment (Coşgun et al., 2025). This is consistent with our findings and indicates that fir might be a suitable surrogate for reforestation north of the European Alps. More research is, however, needed to integrate dendrophenotypes in genetic association studies to understand the response of individual fir trees to heat and drought stress (Heer et al., 2018). Dendrochronological investigations of other Mediterranean forest species, including *Pinus halepensis* Mill. *Pinus nigra*, *Quercus robur* L., or *Quercus ilex* L. are also needed to increase the portfolio of possible surrogates for central European reforestation policies. A critical factor in selecting candidate species is their frost tolerance (Mátyás et al., 2021), because species that are adapted to Mediterranean climates may struggle with harsh winters and the occurrence of spring frosts. Although late frosts can trigger growth reductions and impact seed viability and regeneration (Lisella et al., 2025), we found no effect of frost events in April and May on the resistance and resilience of *Abies cilicica*. This finding, i.e., the absence of negative influences of spring frosts on radial stem growth, is even more striking since the frequency of ground frost days in the Taurus mountains is higher than in the Harz mountain in central Germany (Fig. S7). This tolerance to late frosts emphasises the importance of *Abies cilicica* as a potential surrogate species for central European reforestation on suitable soils. The species may therefore increase the portfolio of mixed reforestation programmes.

CRediT authorship contribution statement

Alexis Arizpe: Formal analysis, Data curation. **Tatiana Bebchuk:** Writing – original draft, Visualization, Formal analysis. **Jan Esper:** Writing – original draft. **Mirek Trnka:** Writing – original draft, Conceptualization. **Güner Hüseyin:** Project administration, Methodology, Investigation. **Kadioglu Alper:** Methodology, Investigation. **Kasia Charcinska:** Formal analysis. **Edurne Martinez del Castillo:** Writing – original draft, Formal analysis. **Clive Oppenheimer:** Writing – original draft, Investigation. **Nesibe Köse:** Supervision, Conceptualization. **Ünal Akkemik:** Supervision, Conceptualization. **Buentgen Ulf:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare no competing interests.

Acknowledgements

This study was supported by the Czech Science Foundation (# 23–08049S; Hydro8), the İstanbul University-Cerrahpaşa Project & Tecnology Office (PROTEK-KAP # 2022–23), the ERC Advanced Grant (# 882727; Monostar), and the ERC Synergy Grant (# 101118880; Synergy-Plague). EMC received funding from the Deutsche Forschungs-Gemeinschaft (DFG project ARiD–539441548). We are thankful to the General Directorate of Forestry and the Department of Foreign Relations, Education and Research (permission no-date 06.04.2022–355048). The Regional Directorate of Forestry in Mersin and Çamlıyayla provided local sampling support, accommodation and logistics. We are also thankful to all colleagues who supported fieldwork in 2023 and 2024, and who stimulated discussion during the past years.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.123120.

Data availability

Data will be made available on request.

References

Akkemik, Ü., 2000. Tree-ring chronology of *abies cilicica* carr. In the Western Mediterranean region of Turkey and its response to climate. Dendrochronologia 18, 73–81.

Allan, R., Ansell, T., 2006. A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850–2004. J. Clim. 19, 5816–5842.

Allen, C.D., et al., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259, 660–684.

Anderegg, W.R.L., et al., 2015. Tree mortality from drought, insects, and their interactions in a changing climate. N. Phytol. 208, 674–683.

Atalay, I., Efe, R., Öztürk, M., 2014. Effects of topography and climate on the ecology of Taurus mountains in the Mediterranean region of Turkey. Procedia Soc. Behav. Sci. 120, 142–156.

Aussenac, G., 2002. Ecology and ecophysiology of circum-Mediterranean firs in the context of climate change. Ann. For. Sci. 59, 823–832.

Bose, A., Gessler, A., Büntgen, U., Rigling, A., 2024. Tamm review: Drought-induced Scots pine mortality – trends, contributing factors, and mechanisms. For. Ecol. Manag. 561, 121873.

Bosela, M., Lukac, M., Castagneri, D., Sedmák, R., Biber, P., Carrer, M., Konôpka, B., Motta, R., Nagel, T., Popa, I., Roibu, C., Svoboda, M., Trotsiuk, V., Büntgen, U., 2018. Contrasting effects of environmental change on the radial growth of co-occurring beech and fir trees across Europe. Sci. Total Environ. 615, 1460–1469.

Bosela, M., M., Popa, I., Gomory, D., Longauer, R., Tobin, B., Kyncl, J., Kyncl, T., Nechita, C., Petrás, R., Sidor, C., Seben, V., Büntgen, U., 2016. Effects of post-glacial phylogeny and genetic diversity on the growth variability and climate sensitivity of european silver fir. J. Ecol. 104, 716–724.

Bottero, A., et al., 2021. Growth resistance and resilience of mixed silver fir and Norway spruce forests in central Europe: contrasting responses to mild and severe droughts. Glob. Change Biol. 27, 4403–4419.

Bozkuş H.F. Toros Göknarı (*Abies cilicica* Carr.) *nin Türkiyedeki Doğal Yayılış ve Silvikültürel Özellikleri*. Tarım Orman ve Köy İşleri Bakanlığı, Orman Genel Müdürlüğü Yayınları, Ankara (1988).

Briffa, K.R., Jones, P.D., Schweingruber, F.H., 1992. Tree-ring density reconstructions of summer temperature patterns across Western North America since 1600. J. Clim. 5, 735–754.

Bunn, A.G., 2008. A dendrochronology program library in r (dplR). Dendrochronologia 26, 115–124.

Büntgen, U., et al., 2021b. The influence of decision-making in tree ring-based climate reconstructions. Nat. Commun. 12, 3411.

Büntgen, U., et al., 2021a. Recent european drought extremes beyond common era background variability. Nat. Geosci. 14, 190–196.

Büntgen, U., et al., 2024. Recent summer warming over the Western Mediterranean region is unprecedented since medieval times. Glob. Planet. Change 232, 104336.

Castagneri, D., et al., 2022. Meta-analysis reveals different competition effects on tree growth resistance and resilience to drought. Ecosystems 25, 30–43.

Caudullo, G., Welk, E., San-Miguel-Ayanz, J., 2017. Chorological maps for the main european woody species. Data Brief. 12, 662–666.

Cetin, M., Meydan, A., 2023. Topography and climate of mount karanfil (Pozantı/Adana). Environ. Syst. Res. 12 (1).

Chakraborty, D., et al., 2024. Assisted tree migration can preserve the european forest carbon sink under climate change. Nat. Clim. Change 14, 845–852.

Ciais, P., et al., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533.

Cook, E.R., Peters, K., 1981. The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. TreeRing Bull. 41, 45–53.

Cook, E.R., Peters, K., 1997. Calculating unbiased tree-ring indices for the study of climatic and environmental change. Holocene 7, 361–370.

Cornes, R., van der Schrier, G., van den Besselaar, E.J.M., Jones, P.D., 2018. An ensemble version of the E-OBS temperature and precipitation datasets. J. Geophys. Res. Atmosphere 123, 9391–9409.

Coşgun, S., et al., 2025. Genetic differentiation of abies alba outside its main range under warm meso-and sub-Mediterranean conditions in Italy and Switzerland. Ecol. Evol. 15, e70909.

D'Andrea, G., Šimůnek, V., Pericolo, O., Vacek, Z., Vacek, S., Corleto, R., Olejár, L., Ripullone, F., 2023. Growth response of Norway spruce (*picea abies* [L.] Karst.) in central bohemia (Czech Republic) to climate change. Forests 14, 1215.

Dumroese, R.K., Williams, M.I., Stanturf, J.A., Clair, J.B.S., 2015. Considerations for restoring temperate forests of tomorrow: forest restoration, assisted migration, and bioengineering. N. For. 46, 947–964.

Esper, J., Cook, E.R., Krusic, P.J., Peters, K., Schwingruber, F.H., 2003. Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. TreeRing Res. 59, 81–98.

Farjon A. *A Handbook of the World's Conifers*. 2nd Edition. Boston, BRILL (2017).

Gampe, D., Zscheischler, J., Reichstein, M., O'Sullivan, M., Smith, W.K., Sitch, S., Buermann, W., 2021. Increasing impact of warm droughts on Northern ecosystem productivity over recent decades. Nat. Clim. Change 11, 772–779.

Gazol, A., et al., 2018. Forest resilience to drought varies across biomes. Glob. Change Biol. 4 2143–2158.

Harris, I., Osborn, T.J., Jones, P., Lister, D., 2020. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Sci. Data 7, 109.

Heer, K., et al., 2018. Linking dendroecology and association genetics in natural populations: stress responses archived in tree rings associate with SNP genotypes in silver fir abies alba (Mill. Mol. Ecol. 27, 1428–1438.

Hintsteiner, W.J., van Loo, M., Neophytou, C., Schueler, S., Hasenauer, H., 2018. The geographic origin of old Douglas-fir stands growing in central Europe. Eur. J. For. Res. 13 447–461.

Hlásny, T., Zimová, S., Merganičová, K., Štěpánek, P., Modlinger, R., Turčáni, M., 2021. Devastating outbreak of bark beetles in the Czech Republic: drivers, impacts, and management implications. For. Ecol. Manag. 490, 119075.

Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement. TreeRing Bull. 43, 69–78.

Isaac-Renton, M.G., Roberts, D.R., Hamann, A., Spiecker, H., 2014. Douglas-fir plantations in Europe: a retrospective test of assisted migration to address climate change. Glob. Change Biol. 20, 2607–2617.

Kavgacı, A., Balpınar, N., Öner, H.H., Arslan, M., Bonari, G., Chytry, M., Carni, A., 2021. Classification of forest and shrubland vegetation in Mediterranean Turkey. Appl. Veg. Sci. 24, 212589.

Knutzen, F., et al., 2025. Impacts on and damage to european forests from the 2018–2022 heat and drought events. Nat. Hazards Earth Syst. Sci. 25, 77–117.

Lindenmayer, D., Messier, C., Sato, C., 2016. Avoiding ecosystem collapse in managed forest ecosystems. Front. Ecol. Environ. 14, 561–568.

Lisella, C., Bottero, A., Antonucci, S., Santopuoli, G., Tognetti, R., 2025. Resilience to late frost and drought of mixed forests with Turkey oak and silver fir in Southern Italy. For. Ecol. Manag. 580, 122539.

Marcis, P., Vido, J., Kurjak, D., Lestianska, A., Poltak, D., Rybar, J., Bosela, M., 2025. A combined effect of heat and drought limits the growth of central european silver fir. Agric. For. Meteorol. 371, 110610.

Martinez del Castillo, E., Torbenson, M.C.A., Reinig, F., Konter, O., Ziaco, E., Büntgen, U., Esper, J., 2024. Diverging growth trends and climate sensitivities of individual pine trees after the 1976 extreme. Sci. Total Environ. 946, 174370.

Mátyás, C., Beran, F., Dostál, J., Čáp, J., Fulín, M., Vejpustková, M., Božič, G., Balázs, P., Frýdl, J., 2021. Surprising drought tolerance of fir (*abies*) species between past climatic adaptation and future projections reveals new chances for adaptive forest management. Forests 12, 821.

Maxwell, R.S., Larsson, L.-A., 2021. Measuring tree-ring widths using the CooRecorder software application. Dendrochronologia 67, 125841.

Obladen, N., Dechering, P., Skiadaresis, G., Tegel, W., Keßler, J., Höllerl, S., Kaps, S., Hertel, M., Dulamsuren, C., Seifert, T., Hirsch, M., Seim, A., 2021. Tree mortality of european beech and Norway spruce induced by 2018-2019 hot droughts in central Germany. Agric. For. Meteorol. 307, 108482.

Ovenden, T.S., Perks, M.P., Clarke, T.-K., Mencuccini, M., Jump, A.S., 2021. Life after recovery: increased resolution of forest resilience assessment sheds new light on post-drought compensatory growth and recovery dynamics. J. Ecol. 109, 3157–3170.

Parolly, G., 2015. The High-Mountain flora and vegetation of the Western and central Taurus mts. (Turkey) In The Times of climate change. In: Öztürk, M., Hakeem, K., Faridah-Hanum, I., Efe, R. (Eds.), Climate Change Impacts on High-Altitude Ecosystems. Springer, Cham.

Pedlar, J.H., McKenney, D.W., Aubin, I., Beardmore, T., Beaulieu, J., Iverson, L., O'Neill, G.A., Winder, R.S., Ste-Marie, C., 2012. Placing forestry in the assisted migration debate. BioScience 62, 835–842.

del Río, M., Löf, M., Bravo-Oviedo, A., Jactel, H., 2021. Understanding the complexity of mixed forest functioning and management: advances and perspectives. For. Ecol. Manag. 489, 119138.

Roskilly, B., Aitken, S., 2024. Weak local adaptation to climate in seedlings of a deciduous conifer suggests limited benefits and risks of assisted gene flow. Evolut. Appl. 17, e70001.

Rybar, J., Sitkova, Z., Marcis, P., Pavlenda, P., Pajtik, J., 2023. Declining radial growth in major Western carpathian tree species: insights from three decades of temperate forest monitoring. Plants 12, 4081.

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., Wood, E.F., Marx, A., 2018. Anthropogenic warming exacerbates european soil moisture droughts. Nat. Clim. Change 8, 421–426.

Sánchez-Salguero, R., Camarero, J.J., Carrer, M., Gutiérrez, E., Alla, A.Q., Andreu-Hayles, L., Hevia, A., Koutavas, A., Martínez-Sancho, E., Nola, P., Papadopoulos, A., Pasho, E., Toromani, E., Carreira, J.A., Linares, J.C., 2017. Climate extremes and predicted warming threaten Mediterranean holocene firs forests refugia. Proc. Natl. Acad. Sci. USA 114, E10142–E10150.

Schuldt, B., 2020. A first assessment of the impact of the extreme 2018 summer drought on central european forests. Basic Appl. Ecol. 45, 86–103.

Senf, C., Seidl, R., 2021. Persistent impacts of the 2018 drought on forest disturbance regimes in Europe. Biogeosciences 18, 5223–5230.

Spinoni, J., Vogt, J.V., Naumann, G., Barbosa, P., Dosio, A., 2018. Will drought events become more frequent and severe in Europe? Int. J. Climatol. 38, 1718–1736.

Streit, K., Brang, P., Frei, E.R., 2024. The Swiss common garden network: testing assisted migration of tree species in Europe. Front. For. Glob. Change 7, 1396798.

Suarez-Gutierrez, L., Müller, W.A., Marotzke, J., 2023. Extreme heat and drought typical of an end-of-century climate could occur over Europe soon and repeatedly. Commun. Earth Environ. 4, 415.

Tew, E.R., et al., 2024. A horizon scan of issues affecting UK forest management within 50 years. For. Int. J. For. Res. 97, 349–362.

Thiel, D., Nagy, L., Beierkuhnlein, C., Huber, G., Jentsch, A., Konnert, M., Kreyling, J., 2012. Uniform drought and warming responses in pinus nigra provenances despite specific overall performances. For. Ecol. Manag. 270, 200–208.

Treml, V., Mašek, J., Tumajer, J., Rydval, M., Čada, V., Ledvinka, O., Svoboda, M., 2022. Trends in climatically driven extreme growth reductions of *picea abies* and *pinus sylvestris* in central Europe. Glob. Change Biol. 28, 557–570.

Trnka, M., et al., 2019. Mitigation efforts will not fully alleviate the increase in water scarcity occurrence probability in wheat-producing areas. Sci. Adv. 5, eaau2406.

Vacek, Z., Vacek, S., Cukor, J., 2023. European forests under global climate change: review of tree growth processes, crises and management strategies. J. Environ. Manag. 332, 117353.

Vitali, V., Büntgen, U., Bauhus, J., 2017. Silver fir and douglas fir are more tolerant to extreme droughts than Norway spruce in south-Western Germany. Glob. Change Biol. 23, 5108–5119.

Vitali, V., Büntgen, U., Bauhus, J., 2018. The effects of past and projected seasonal climate change on growth of native and exotic conifers in central Europe. Dendrochronologia 48, 1–l9.

Vitasse, Y., Bottero, A., Cailleret, M., Bigler, C., Fonto, P., Gessler, A., Levesque, M., Rohner, B., Weber, P., Rigling, A., Wohlgemuth, T., 2019. Contrasting resistance and resilience to extreme drought and late spring frost in five major european tree species. Glob. Change Biol. 25, 3781–3792.

Walder, D., Krebs, P., Bugmann, H., Manetti, M.C., Pollastrini, M., Anzillotti, S., Conedera, M., 2021. Silver fir (*abies alba* Mill.) is able to thrive and prosper under meso-Mediterranean conditions. For. Ecol. Manag. 498, 119537.

Wigley, T.M.L., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. Am. Meteorol. Soc. 23, 201–213.

Williams, M.I., Dumroese, R.K., 2013. Preparing for climate change: forestry and assisted migration. J. For. 111, 287–297.

Yang, K., Zhang, J., Fan, H., Yan, Y., 2024. Climatic implications in earlywood and latewood width indices of Chinese pine in north central China. J. For. Res. 35, 50.