



Higher growth synchrony and responsiveness to drought in managed-young than in unmanaged-old sessile oak stands during a shift to hotter summers

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ABSTRACT

Historical management legacies may condition recent responses of forests to climate warming. In Eastern Europe, unique and well-preserved old-growth sessile oak forests remain. They represent a perfect setting for comparing their radial-growth responses to climate variability, particularly drought stress, with respect to younger managed forests in a region experiencing ongoing aridification. We assessed radial-growth variability and responses to climate variables in three stands dominated by sessile oak (*Quercus petraea* (Matt.) Liebl.) located in western Romania: a very old unmanaged stand, an old managed stand from seed origin and a young managed stand from sprout origin. There was a shift towards warmer and drier conditions from the 1980s onwards which could have contributed to reduce temporal growth variability, but it did not increase growth coherence among coexisting trees. Very old and old stands showed a higher growth variability among conspecifics comparing with the young stand, which presented a higher growth synchrony. Warm and dry summers and elevated vapor pressure deficit reduced sessile oak growth. The highest responsiveness of growth indices was found for 12-month long droughts ending in summer in the case of young and old managed stands, whereas the very old unmanaged stand showed the lowest responsiveness. Improving tree growth of younger and even old managed stands may make them more responsive to summer soil and atmospheric drought, thus increasing their vulnerability to further water shortage. A better knowledge on how oak growth variability and responsiveness to drought depend on root-to-shoot ratios is needed to manage oak forests and make them more resilient to aridification.

1. Introduction

Climate change is leading to more frequent hotter droughts which constrain tree growth at local to global scales, thus impairing the capacity of forests to uptake carbon and mitigate ongoing climate warming (Babst et al., 2019). Compound climate events characterized by soil and atmospheric hotter droughts are contributing to growth decline and tree death across European forests (Gazol and Camarero, 2022). Climate warming is fueling the increase in atmospheric water demand by rising vapor pressure deficit (VPD), which could reduce stomatal conductance, and cascade down decreasing photosynthesis and growth rates and increasing the risks of carbon starvation and hydraulic failure (Grossiord et al., 2020). It is assumed that a warming-triggered increase in VPD

would more negatively impact growth of isohydric species such as pines, which hold a more constant leaf water potential under dry conditions by closing stomata, than anisohydric species such as ring-porous oaks, which allow drops in water potential by keeping open stomata (Tardieu and Simonneau, 1998). However, ring-porous oaks have also responded to severe droughts by showing growth decline, reduced theoretical hydraulic conductivity, canopy dieback and tree death (Corcuera et al., 2004, 2006; Gea-Izquierdo and Cañellas, 2014; Colangelo et al., 2017a; Gentilesca et al., 2017). Therefore, anisohydric oak species are also vulnerable to severe droughts.

Tree growth response to climate extremes such as droughts is influenced by past management history, which determined the current stand and age structures as has been observed in oak lowland forests from

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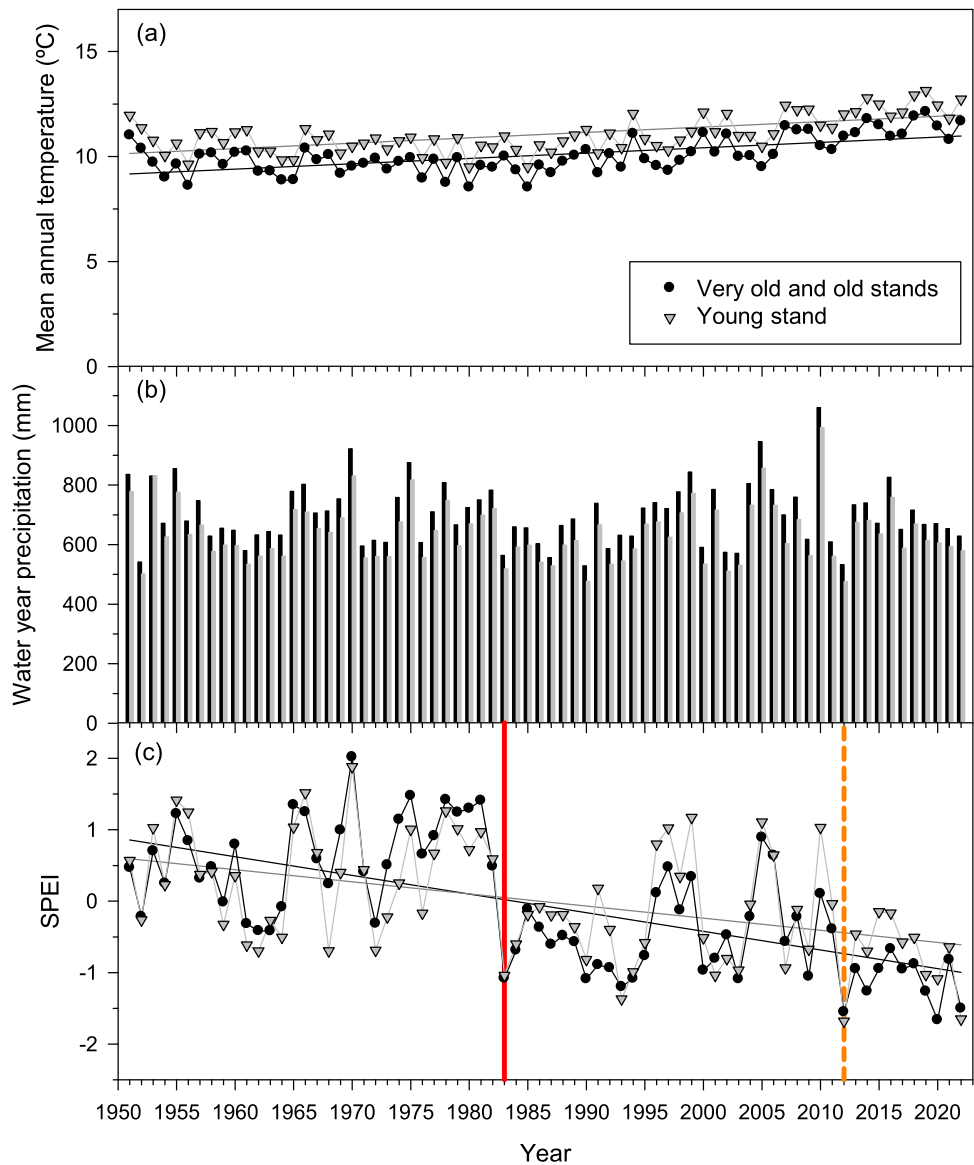


Fig. 1. Trends in annual climate variables observed in the study stands (a, mean temperature; b, precipitation of the water or hydrological year; c, hydrological-year SPEI). In the lowermost plot (c), vertical lines show regime shifts of the SPEI detected in 1983 and 2012 in the three stands.

Table 1
Structural features and tree-ring width statistics measured in the study oak stands. DBH is the diameter at breast height. TRW and BAI are the tree-ring width and basal area increment averaged for the common 1950 – 2022 period. The rbar and EPS values correspond to maximum values found during the best-replicated period 1950 – 2022 (see Fig. 3). Values are means ± SD. Mean values followed by different letters are significantly different (Kruskal-Wallis H test, $p < 0.05$).

Site type (name)	Reproduction type	No. trees	DBH (cm)	Height (m)	Timespan	Age at 1.3 m (years)	TRW (mm)	BAI (cm ² yr ⁻¹)	AR1	MSx	rbar	EPS
Very old stand (Runcu)	Seed	29	62.0 ± 1.6b	34.0 ± 0.3b	1815 – 2022	179 ± 22c	1.13 ± 0.02a	18.33 ± 0.46b	0.75 ± 0.12a	0.21 ± 0.03a	0.60	0.93
Old stand (Julița)	Seed	30	60.0 ± 1.1b	33.5 ± 0.3b	1895 – 2022	123 ± 5b	1.68 ± 0.04b	23.46 ± 0.54c	0.66 ± 0.16a	0.23 ± 0.03a	0.68	0.95
Young stand (Conop)	Sprout	30	42.0 ± 1.1a	24.2 ± 0.2a	1931 – 2022	85 ± 3a	1.85 ± 0.06c	14.28 ± 0.48a	0.63 ± 0.11a	0.25 ± 0.02a	0.71	0.99

central Europe (Stojanović et al., 2016). In many European oak forests, stands were formerly managed through coppicing, coming from vegetative reproduction (sprouting) to produce timber and charcoal (Buckley, 1992), but their management ceased in many cases during the early 20th century impacting their secondary growth variability and vulnerability to water shortage. Several features make formerly coppiced old oaks stands theoretically less responsive to climate

variability, and particularly drought severity, than managed young stands. First, formerly coppiced oak stands could show less negative leaf water potentials due to a deeper and more developed root system, with better access to profound soil layers, and a higher root-to-leaf surface area ratio than young stands of seed origin (tall forests) (Ripullone et al., 2020; Urban and Urban, 2024). Second, coppicing increased water use and photosynthesis rates of young sprouts both under dry and favorable

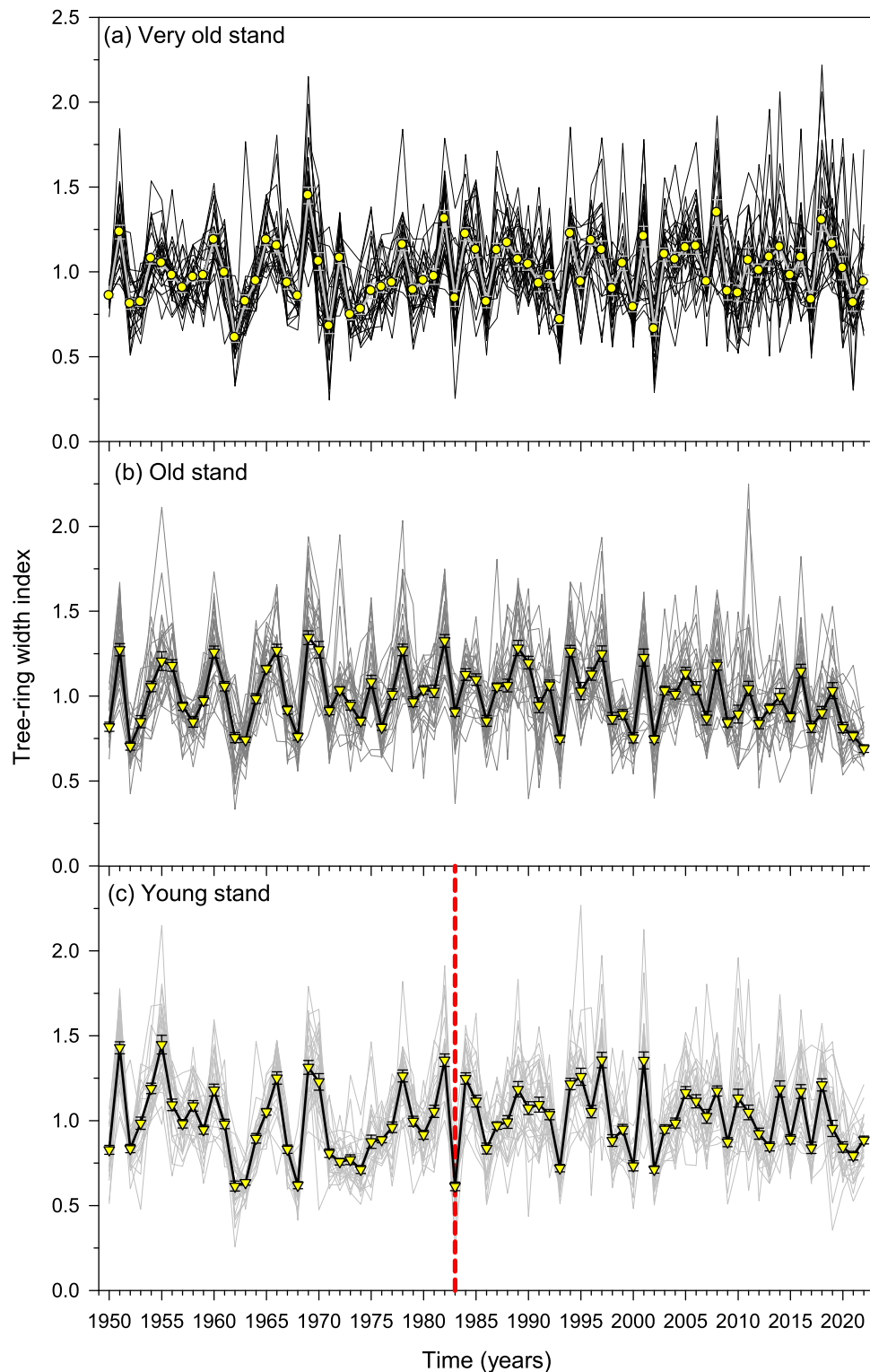


Fig. 2. Individual (thin lines) and mean series (thick lines) of ring-width indices in the (a) very old, (b) old, and (c) young stands. Means are shown with SEs (error bars). The vertical dashed line indicates a significant regime shift of the mean series of ring-width indices in the case of the young stand.

climate conditions as observed in sessile oak (*Quercus petraea* (Matt.) Liebl.) (Matoušková et al., 2022). This could lead to higher growth variability among conspecifics (lower growth coherence or synchrony) as compared with young, managed stands. On the other hand, coppiced stands are characterized by multi-stemmed individuals with too elevated root-to-shoot ratios and low growth rates (Vrška et al., 2016). This makes their conversion to high forests through thinning difficult, as

observed in seasonally dry Spanish *Quercus pyrenaica* Willd. forests (Corcuera et al., 2006; Salomón et al., 2016). Therefore, despite the ability of old formerly coppiced oak to uptake deep water sources, too severe droughts may cause their growth decline and death in conjunction with stem-to-stem competition as found in Romanian sessile oak forests after the 1980s dry spells (Petritan et al., 2021). Overall, our understanding on the interactions between historical legacies (e.g.,

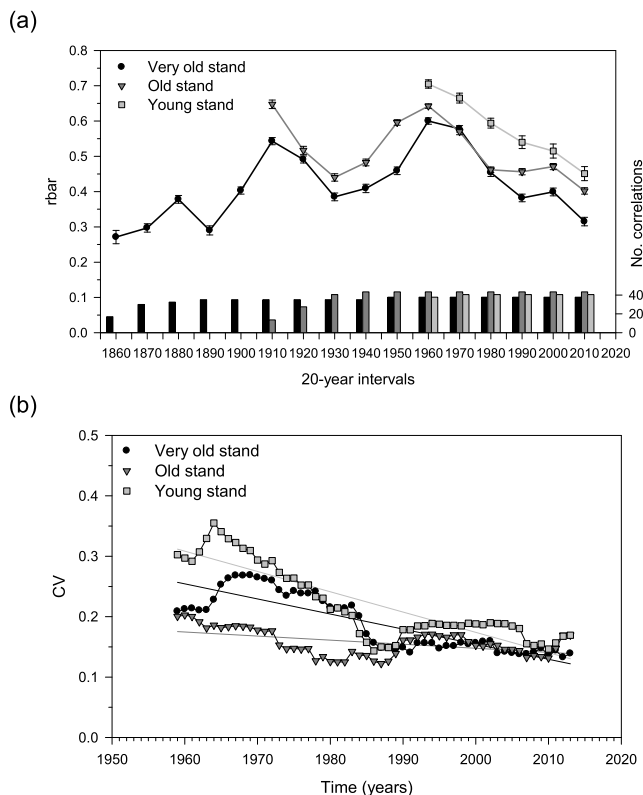


Fig. 3. (a) Running $\bar{r}$ values (means $\pm$ SE) of very old, old and young stands calculated for 20-year intervals overlapping every 10 years. The bars show the number of correlations for each interval (right y axis). (b) Running CV of the mean series of ring-width indices of very old, old and young stands calculated for 20-year intervals lagged every year. Linear regressions are fitted to the running CV values.

coppicing, pollarding) on recent tree growth variability and responses to drought stress is still incomplete (e.g., Camarero et al., 2024), despite its relevance to develop adaptive forest management under current high climate variability (Sohn et al., 2016).

In the past, sessile oak was widely managed as simple coppice with a rotation period up to 30 years and as coppice-with-standards silvicultural systems with a rotation age of coppice cohort up to 30–40 years in Romania (Nicolescu, 2010, 2018). After the nationalization of all forests in 1948, all former oak coppices were converted to high forests by ageing the vegetative regeneration. However, taking into consideration that over 50 % of Romanian forestland corresponds to private owner and due to economic changes (e.g., increasing in firewood prices) an increase in sessile oak coppice is expected in the future (Nicolescu, 2018). Furthermore, the preservation of old oak trees in some of these stands, with a high density of cavities and decaying wood, is required because those ancient trees are habitats for many plant and insect species (Nicolescu et al., 2018). Therefore, investigating how sessile oak stands with different management histories (high forest, managed coppices and reference old-growth forests) respond to drought is relevant for their management.

Here, we compared the secondary growth variability and coherence (synchrony) and the responsiveness to climate variability, paying special attention to drought severity, of three Romanian sessile oak stands of different management history (an unmanaged very old and a managed old of generative origin stands and a younger managed stand of vegetative origin, probably originated from coppicing). We capitalize on recent climate shifts towards warmer and drier conditions observed in Romania during the past fifty years leading to aridification (Ionita et al., 2016). There, the period 1979–1995 was characterized by frequent moderate to extreme drought conditions, particularly in the 1980s,

whereas a major drought in 2000–2001 affected most of the country and it was followed by moderate droughts in the 2010s (Dumitrescu et al., 2015). This aridification trend was accompanied by longer and warmer summer conditions and negatively affected Carpathian forested areas. For instance, the 2000 and 2012 droughts, characterized by low precipitation and high temperatures during the growing season, lead to severe growth reduction of Romanian Scots pine (*Pinus sylvestris* L.) forests (Sidor et al., 2019).

Our specific objectives were: (i) to quantify growth variability in three sessile oak stands (two with generative origin very old unmanaged and old managed stands and a younger with vegetative origin managed stand), paying particular attention to growth coherence within sites and regime shifts or step-like changes (cf. Rodionov, 2004), and (ii) to assess how growth indices are related to climate variables (temperature, precipitation, drought severity). We hypothesized that very old unmanaged oak stand will show a higher tree-to-tree growth variability (lower synchrony) and a lower responsiveness to soil and atmospheric drought, measured respectively with a drought index and VPD, than younger managed stands.

2. Material and methods

2.1. Study sites and field sampling

We selected for sampling an unmanaged, old-growth stand (Runcu site, located in the best-preserved part of “Runcu Grosi Natural Reserve”, 22.07° E, 46.11° N, 570–685 m a.s.l.), an old managed (Julița site, 22.09° E, 46.10° N, 450–490 m a.s.l) stand, both of seed origin and a managed young stand of sprout origin (Conop site, 21.51° E, 46.09° N, 460–540 m a.s.l). These sites are dominated by sessile oak, a species widely distributed across lowlands of western Romania, and have a basal area of the trees with a diameter at breast height (DBH) greater than 7 cm ranged between 45.4–57.5 m² ha⁻¹ and a tree density of 518–833 stems ha⁻¹. They are mixed forests where sessile oak accounted more than 61 % of the basal area and coexist with other broadleaf tree species including *Fagus sylvatica* L., the main occurring species after sessile oak, and *Carpinus betulus* L., *Sorbus torminalis* L., *Tilia cordata* Mill, *Acer pseudoplatanus* L., and *Acer platanoides* L.

The Runcu site is an old-growth (hereafter very old stand), unmanaged stand considered one of the best-preserved mixed natural oak forests in eastern Europe (Petritan et al., 2012), characterized by a high number of large trees (Petritan et al., 2014). Whereas the maximum DBH of trees was 113 cm in this very old stand, in the young stand, it reached only 73.4 cm. The young stand is an example of one of the formerly coppiced forests transformed towards high forest after forest nationalization.

The study stands are located at the transition from sub-Mediterranean to temperate climate conditions (Fig. S1). In the very old unmanaged and in the old managed stand, mean annual temperature calculated on 1950–2022 period is 10.1°C, whereas in the young managed stand it is 11.0 °C. The mean maximum temperatures of the hottest month (July) and their corresponding VPD values are 26.2 °C and 1.41 kPa and 27.7 °C and 1.58 kPa in the very old and old and in the young stands, respectively. The total annual precipitations are 637 and 707 mm, in the same order. The monthly precipitation peaks in June (98 and 88 mm in the very old and old stands and in the young stand, respectively), during the growing season. The estimated annual climate water balances are 49 mm in the very old and old stands and 58 mm in the young stand (Fig. S1). Soils are of luvisol type, developed on clay and show a low water-storage capacity storage during dry periods.

Field work was carried out from summer 2023 to early 2024. In each stand, 30 trees located at least 30 m apart from each other were selected to reduce the chances of including genetic related trees in the sample. The biometric data about the stand were collected from two sampling square plots (75 × 75 m) previously established in each stand. We extracted one core per tree at 1.3 m using 5-mm increment borers. The

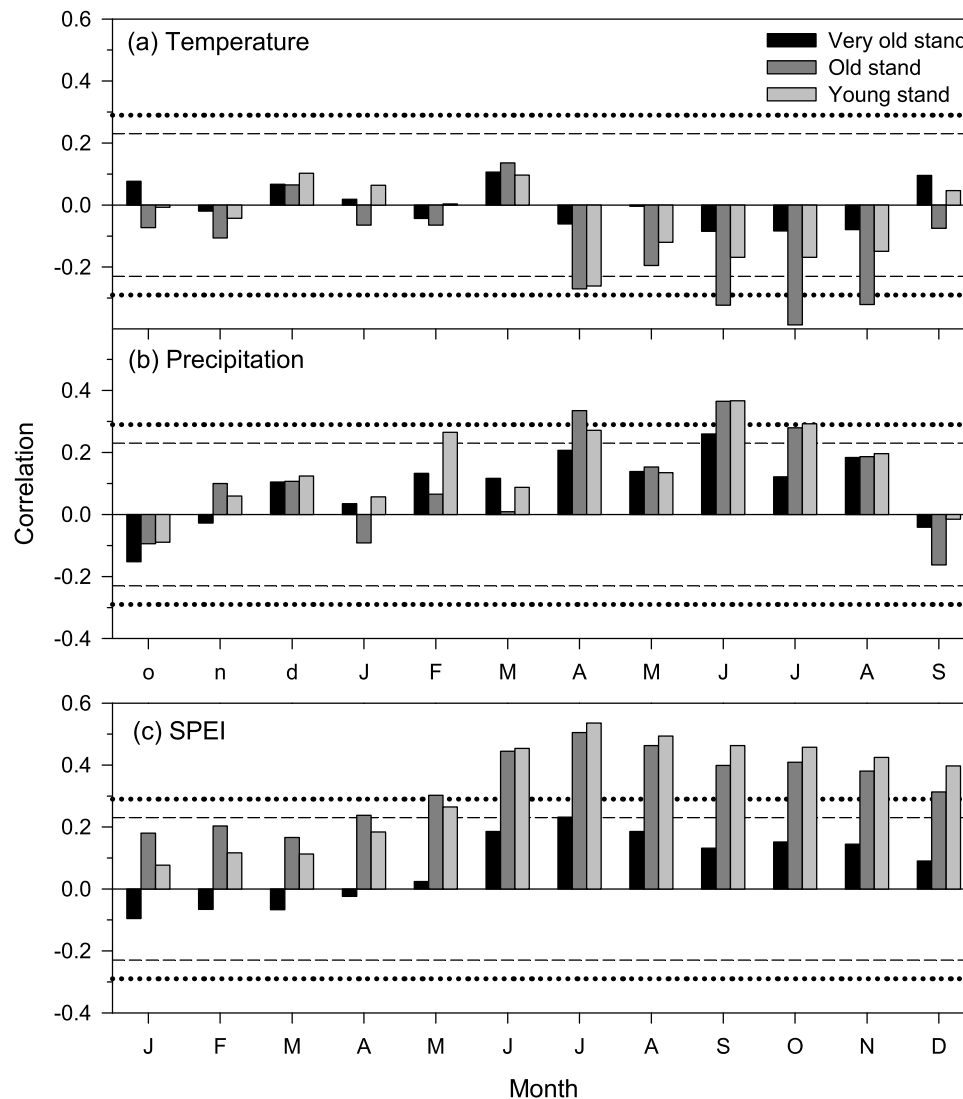


Fig. 4. Climate–growth relationships based on Pearson correlations calculated between series of ring-width indices of very old, old and young stands and monthly climate variables (a, mean temperature; b, total precipitation; c, 12-month long SPEI). Months of the previous and current years are abbreviated by lowercase and uppercase letters, respectively. The horizontal dashed and dotted lines correspond to the 0.05 and 0.01 significance levels, respectively. A 12-month long SPEI in July corresponds to the August-to-July SPEI.

DBH and height of all sampled trees were measured using tapes and a Vertex IV, respectively.

2.2. Climate data and drought index

Because local stations lacked long-term homogeneous series of climate data, we used 0.25°-interpolated monthly climate data (mean temperature, total precipitation and relative humidity) corresponding to grids situated over the Conop, Julița and Runcu sites. We selected the period 1950–2022 and retrieved climate data from the homogenized and quality-checked climate E-OBS dataset ver. 27.0e (Cornes et al., 2018).

To assess drought severity, we used the Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), which is calculated based on the CRU climate dataset. The SPEI is based on cumulative monthly climate water balances based on the difference between precipitation and reference evapotranspiration. High and low SPEI values correspond to wet and dry relative conditions, respectively. The time scale over which water surplus or deficit accumulate is critical to calculate the SPEI and the growth responses. For this reason, we considered SPEI values calculated at several monthly scales during

which the water deficit and surplus are accumulated. We also calculated the 12-month SPEI for the calendar year (e.g. from January to December) and for the water or hydrological (e.g. from prior October to current September) year. The VPD was estimated using ambient and dew point temperatures and relative humidity data following Lowe and Ficke (1974).

2.3. Tree-ring data

Wood cores were extracted from summer 2023 to early 2024. They were air dried in the laboratory, glued onto wooden supports and surfaced with progressively finer grades of sandpaper until tree rings were clearly distinguishable (Fritts, 2012). Then, they were scanned at 2400 dpi resolution. Ring widths were measured with a 0.001 mm resolution using scanned images and cross-dated using the CooRecorder-CDendro ver. 8.1 semiautomatic measuring software (Maxwell and Larsson, 2021). The quality of the visual cross-dating was checked using the COFECHA software which calculates moving correlations between individual series of ring-width values and the mean sites series (Holmes, 1983).

The growth rates among stands were compared based on tree-ring

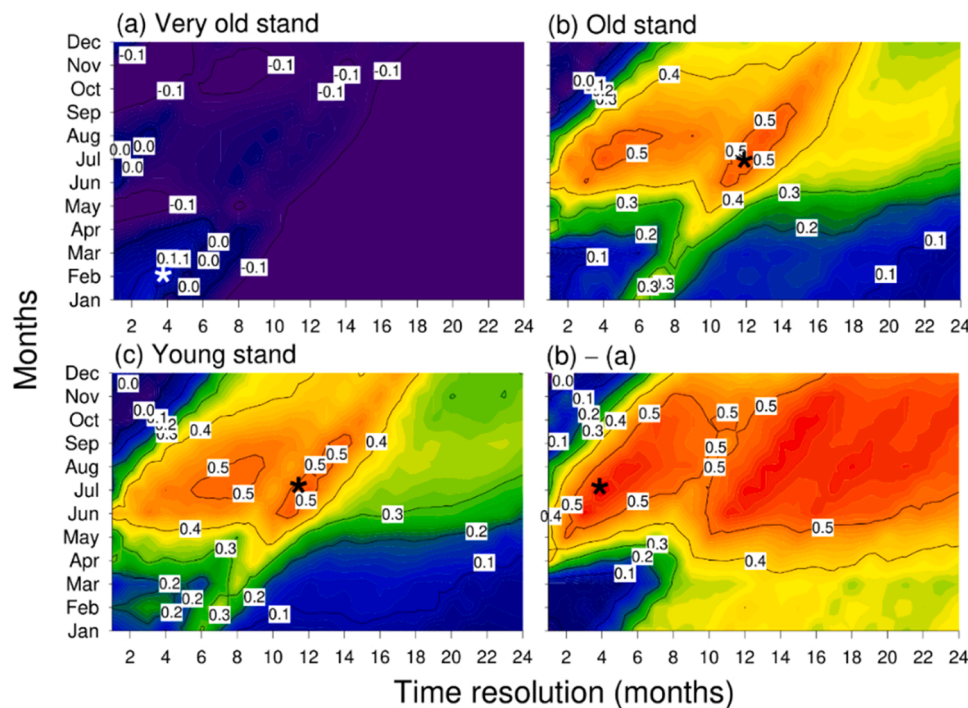


Fig. 5. Drought-growth relationships based on Pearson correlations calculated between monthly series of the SPEI drought index (y axes), calculated at several scales (1- to 24-month time resolutions; x axes), and series of ring-width indices of the (a) very old, (b) old and (c) young oak stands. The last plot “(b)–(a)” shows the difference in correlations between (b) and (a) plots, which showed the highest ($r = 0.542$) and lowest maximum ($r = 0.158$) correlations, respectively. Asterisks show the time resolution and month when the maximum correlation was obtained in each stand. Correlations higher than $r = 0.23$ and $r = 0.29$ are significant at the 0.05 and 0.01 significance levels, respectively.

width series and basal area increments (BAI). The BAI was used because it accounts for the increase in tree size and age and better reflects changes in radial growth as related to sapwood conducting area and leaf transpiring area (Biondi and Qeadan, 2008). When cores did not contain the pith, the missing core length was estimated to calculate the BAI by subtracting the core length to the tree radius measured in the field without bark. The resulting series were statistically characterized calculating mean tree-ring width and basal area increment values, first-order autocorrelation of ring widths (AR1) and mean sensitivity (MSx) of not pre-whitened indices to measure the relative change in width among consecutive rings (Fritts, 2012).

Since the tree-ring width series contain long-term trends due to non-climate variables (i.e. age or changes in competition), to determine the main climatic drivers of tree growth we converted them into series of ring-width indices. First, the long-term trends of the raw tree-ring widths were removed for each tree by fitting 32-year long cubic smoothing splines and then dividing observed by fitted values. Second, these individual detrended series were pre-whitened fitting autoregressive models. Third, to obtain mean series of growth indices for each stand, the individual indexed series were averaged using bi-weight robust means. The statistical quality of each chronology was checked by calculating mean correlations ($\bar{r}$) among indexed series within each site and the Expressed Population Signal (EPS) (Wigley et al., 1984). These procedures were carried out using the ‘dplR’ package (Bunn, 2008, 2010; Bunn et al., 2023) in the R statistical software (R Development Core Team R, 2024).

2.4. Relationships between climate variables and growth indices

Prior to Pearson correlation analyses, we removed the trends of climate variables by fitting linear regressions and keeping the resulting residuals. Correlations with temperature, precipitation and VPD data were calculated for the common period 1950–2022 and considering the climate window from previous October to current September. In the case

of SPEI, correlations were calculated from January to December considering 1- to 24-month-long SPEI values. To assess the stability of climate-relationships, running correlations between series of ring-width indices and selected variables (April and July VPD, 12-month summer SPEI values, i.e. from prior September to current August) were calculated on 20-year intervals lagged every year. Lastly, individual series of ring-width indices were correlated with the summer SPEI to compare drought responsiveness among the three stands. These analyses were done using the ‘treeclim’ R package (Zang and Biondi, 2015).

2.5. Regime shift detection

To investigate regime shifts, Rodionov (2004,2005) developed a method that detects abrupt changes in means or variances using sequential t - and F -test analyses, respectively. To reduce the effect of autocorrelation (or red noise) in the analyses, standardization and pre-whitening of the analyzed time series are carried out as it is usual in the case of ring-width data (Rodionov, 2006). Later, a new analysis to detect regime shifts in correlation between time series assuming they are linearly related (Rodionov, 2015) was performed.

2.6. Statistical analyses

The normality of data was checked by using Shapiro-Wilk tests. Comparisons between variables were carried out using Mann-Whitney U tests for pairs of stands or Kruskal-Wallis H tests for the three stands. For example, the difference in 20-year $\bar{r}$ values between young and very old stands was tested by using Mann-Whitney U tests, whereas differences in correlation coefficients of ring-width index – summer SPEI between sites were tested using Kruskal-Wallis H test. Linear regressions were fitted to SPEI, running CV values, moving correlations between site series of ring-width indices and between SPEI and growth indices to assess their tendencies. For instance, linear regressions were fitted between April VPD or summer SPEI and growth indices to assess their

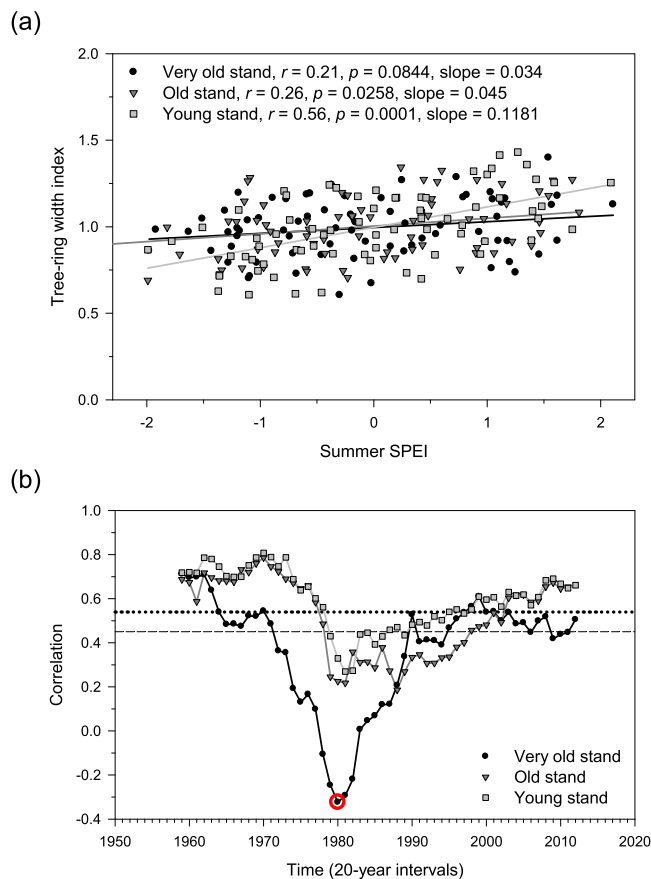


Fig. 6. (a) Linear regressions fitted to series of ring-width indices of very old, old and young stands as a function of the 12-month summer SPEI. The statistics correspond to the fitted lines. (b) Running correlations between series of ring-width indices of very old, old and young stands and 12-month summer SPEI values based on 20-year intervals lagged every year. Horizontal dashed and dotted lines indicate the 0.05 and 0.01 significance levels, respectively. The red circle indicates a significant shift in the correlation between both series in the case of old trees.

tendencies. Slopes were compared among sites using ANCOVA tests.

To quantify changes through time in internal growth coherence or variability, $\bar{r}$ and CV (coefficient of variation) values of ring-width indices were calculated using 20-year intervals overlapping every 10 and 1 years, respectively and afterwards, linear regressions were fitted to the running CV values, whereas their slopes were compared among sites using ANCOVA tests. Running Pearson correlations coefficients were also calculated between the stands' series of ring-width indices, using again 20-year intervals, to assess changes in growth coherence among sites.

We also investigated changes in regime shifts of annual and monthly climate variables (temperature, precipitation, SPEI). Then, we assessed if there were shifts in site series of ring-width indices. Finally, regime shifts in the correlation between growth indices and selected variables tightly related with them (April and July VPD, July and summer SPEI) were tested. These analyses were carried out using the STARS ver. 6.3 package (Rodionov, 2004).

3. Results

3.1. Climate trends and variability

Temperatures increased since the 1950s in all sites leading to a decrease in the hydrological-year SPEI (Fig. 1). Regarding the SPEI data, two regime shifts were detected in 1983 and 2012.

3.2. Growth coherence and variability

The young stand showed smaller stem diameter, height and age at 1.3 m than the very old and old stands (Table 1). However, the highest mean ring-width, $\bar{r}$ and EPS values corresponded to the young stand, indicating a higher growth coherence among individual sessile oaks. A regime shift was detected in 1983 in the mean series of growth indices of the young stand. The highest mean BAI value was found in the old stand (Fig. 2).

The 20-year $\bar{r}$ values were higher in the young stand than in the other two stands, with significant differences between young and very old stands ($U = 6.0$, $p = 0.04$; period 1950 – 2022; Fig. 3a). The running CV of the growth indices significantly decreased in the three stands with slopes differing among them (ANCOVA, $F = 39.49$, $p < 0.001$), being the steepest decrease observed in the young stand, where the highest CV was found (Fig. 3b).

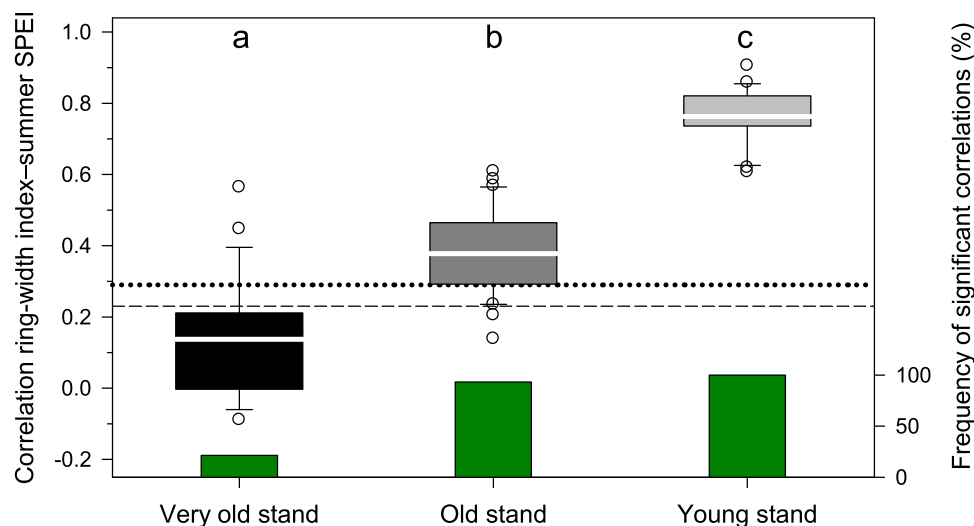


Fig. 7. The box-plots show correlations between individual series of ring-width indices and 12-month long summer SPEI in very old, old and young stands. The white horizontal lines show mean values. Different letters indicate significant ($p < 0.05$) differences between stands (Kruskal-Wallis test, $p < 0.05$). The right y axis shows the percentage of significant individual correlations (green bars).

The running correlations calculated between stands also decreased through time, being the lowest those between the very old and young stands (Fig. S2).

3.3. Growth responsiveness to climate variables

The old stand showed the greatest responsiveness to temperature, with warm conditions from mid spring to summer leading to reduced growth (Fig. 4). This was only observed for April in the young stand. Young and old stand were the most responsive to summer precipitation and the SPEI. Wet conditions from prior late winter to summer improved growth in the young and old stands, with the 12-month SPEI peaking in July, i.e. from prior August to current July.

The old stand also showed the greatest responsiveness to VPD from April to August with growth indices decreasing as VPD increased (Fig. S3). The old stand mainly responded to July VPD, but the young stand was more responsive to April VPD. Running correlations of growth indices with April VPD showed minimum values in dry periods (1980s, mid 1990s), but recently increased. However, the slopes of the linear regressions between April VPD and the series of growth indices of old and young trees did not significantly differ (ANCOVA, $F = 1.99$, $p = 0.1601$). Running correlations of growth indices with July VPD reached minimum values from the mid-1990s onwards, being again the old stand the most responsive.

3.4. Growth responsiveness to drought severity

The correlations of the growth indices and SPEI values showed the highest responsiveness in the young stand with a maximum correlation of $r = 0.54$, corresponding to the 12-month July SPEI. The old stand also showed a high responsiveness to drought severity with a maximum correlation of $r = 0.53$, corresponding to the 12-month July SPEI, whereas the very old stand showed the lowest responsiveness with a maximum correlation of $r = 0.16$, corresponding to the 4-month February SPEI (Fig. 5). The differences in correlations between the very old and old stands showed a maximum value of $r = 0.59$ for the 4-month July SPEI.

In terms of rate of change, the slope between summer SPEI and growth indices peaked in the young stand (0.1181), followed by the old (0.045) and very old stands (0.034; Fig. 6). The slopes of the linear regressions between summer SPEI and the series of growth indices of old and young trees significantly differed (ANCOVA, $F = 5.23$, $p = 0.0061$). In the running correlations between growth indices and the SPEI, these two stands showed higher values than the very old stand. Interestingly, we detected a regime shift in the relationships between growth and drought variability in the very old stand. Here, SPEI-growth correlations decreased in the 1980s and increased afterwards. This regime shift corresponded to a summer drying trend which started in that decade (Fig. S4).

Regarding the relationships between summer SPEI and growth indices evaluated at the individual level, they were significantly higher in the young stand (mean $\pm$ SE, $r = 0.76 \pm 0.01$, followed by the old ($r = 0.38 \pm 0.02$) and very old ($r = 0.14 \pm 0.03$) stands (Kruskal-Wallis H test = 67.52, $p = 0.001$; Fig. 7). The percentage of trees showing significant correlations between growth indices and the summer SPEI increased from 21 % in the very old stand, to 93 % and 100 % in the old and young stands, respectively.

4. Discussion

Our findings supported our hypotheses that the very old oak stand should show lower tree-to-tree growth coherence and responsiveness to drought than the old and young stands. However, it was not the young stand but the old stand which showed a higher responsiveness to VPD, despite the highest growth synchrony (r_{bar}) and temporal variability (CV) of the young stand and its slightly warmer and drier climate

conditions than those experienced by the very old and old stands. Therefore, the different growth coherence and responsiveness to climate and drought of old and young stands compared with the very old stand must depend on their contrasting structure, including vegetative (in the young stand) vs. reproductive origin (in the old and very old stands), and historical management rather than on different climate conditions. Of course, other variables not measured could contribute to explain their differences including tree age, competition degree, soil features or genetic composition.

We considered that increasing aridity made sessile oak trees growing more synchronously, but at least other two interpretations are possible. First, decreasing synchrony in tree growth within a site may indicate differential individual responses to unfavorable climatic conditions, and can be considered a proxy of higher climate stress and impending tree death as in many events of forest dieback (Cailleret et al., 2017). This could explain the lower growth synchrony of the very old unmanaged stand. However, we did not detect increasing defoliation or mortality rates in this stand which could indicate a loss of tree vigor. Second, lower growth synchrony could also reflect more different local-scale growing conditions within a site, but we did not have microclimate or soil data to test this idea.

We also detected a climate shift towards warmer and drier (lower SPEI) conditions in the 1980s, which was previously described for central Europe (Reid et al., 2016) and Romania (Ionita et al., 2016). Specifically, there was a 175 % decrease in the summer SPEI confirming the shift towards warmer and drier conditions in the study area. This shift could explain the rapid reduction in growth temporal variability (CV) and the strengthening of growth-SPEI relationships observed in the running correlations, with long summer droughts (12-month July SPEI) negatively impacting oak growth. Spatial correlations indicated that the influence of these droughts on forest growth spread over western Romania (Fig. S5).

Our results concurred with those published on other Romanian and Czech oak forests showing a higher sensitivity to warming-related drought events in terms of growth loss and die-off in managed high stands than in old-growth (unmanaged) stands (Stojanović et al., 2017; Petritan et al., 2021) and also in beech forests from Germany (Mausolf et al., 2018). According to Mausolf et al. (2018), management may alter crown size and enhance growth rates and climate sensitivity, making managed beech stands more vulnerable to hotter droughts (Fichtner et al., 2013). In contrast, unmanaged stands may have larger root systems with better access to deep soil layers, making them less coupled to atmospheric dry conditions (Ripullone et al., 2020, Urban and Urban, 2024). However, our findings do not fully concur with those of Maes et al. (2019), who found a higher sensitivity to temperature in European coppiced oak forests. This discrepancy may be due to the 1980s shift towards drier conditions driving the main growth responses to drought of our study sessile oak forests.

Unexpectedly, the old stand showed the highest growth rate (BAI) and also high correlations with summer SPEI, temperature and VPD considering site mean series of growth indices, whilst the young high forest responded more to April VPD. However, the responsiveness to a climate variable should be measured in terms of rate of change and, in that case, the young stand presented the highest slope with respect to summer SPEI and also the highest temporal variability in growth indices indicating a strong coupling with hydroclimate variability. In addition, all sampled trees in the young stand significantly responded to drought, emphasizing the need to consider individual growth variability in climate-growth analyses (Maes et al., 2019). Further research could compare the phenology of stem increment in unmanaged vs. managed oaks to understand why responses to VPD occurred in different months.

From a management point of view, converting very old oak coppices into old and high forests may improve growth and wood production, but may also make them vulnerable to drought stress if further shifts toward warmer summers and higher VPD and evapotranspiration rates occur as the one observed in the 1980s (Mausolf et al., 2018). To buffer those

stands against forecasted aridification, a more balance root-to-shoot ratio should be accomplished (Fichtner et al., 2013), particularly for oak species showing a good post-drought resilience such as *Q. cerris* and *Q. frainetto* (Ciceu et al., 2020; Bose et al., 2024). Trade-offs may be multifactorial because in these resilient oak species small, slow-growing trees are more prone to show drought-induced dieback and death (Colangelo et al., 2017b). Overall, the climate-drought relationships described for sessile oak were already characterized for oak forests across central and eastern Europe (Friedrichs et al., 2009; Mérian et al., 2011; Popa et al., 2013; Cufar et al., 2014; Dobrovolný et al., 2016), but our findings indicate that some of these associations could strengthen as the dependence of oak growth variability on growing-season water shortage and atmospheric demand (VPD). If further warming and drying negatively impacts some managed, mixed young oak stands leading to growth loss and mortality, sessile oak, which shows a poor post-drought resilience (cf. Bose et al., 2024), could be progressively replaced by more resistant broadleaf species such as *Q. cerris* (Petritan et al., 2021). The conversion from coppice to high forests should reduce root sprouting, if possible, and favor mixed sessile oak stands whenever possible to improve their resilience to warmer and drier climate scenarios (Rubio-Cuadrado et al., 2018).

Lastly, our analyses presented some limitations which must be explicitly mentioned and discussed. First, the different ages of the stands might have influenced the results because trees show age-dependence sensitivity to climate variability in some cases (e.g. Camarero et al., 2024). For instance, very old stands or trees often show very low growth rates compared to young ones and therefore they can potentially show weaker climatic signals (Carrer and Urbinati, 2004; Gallardo et al., 2022). However, management type and age covaried and, therefore, their respective roles are challenging to disentangle. Second, the compared stands are subjected to slightly different climate conditions (e.g. the young stand experiences warmer conditions) which could have affected the growth responsiveness to drought severity. Third, the historical management of the three stands was not explicitly analyzed. Therefore, the relative importance of historical management as driver of growth responsiveness to drought severity was indirectly inferred.

5. Conclusions

Under forecasted warmer and drier summer conditions, such as those observed from the 1980s onwards in western Romania, interactions between past forest management and current climate-growth relationships must be investigated. The studied very old unmanaged stand, which corresponds to unique remnants of old-growth sessile oak forests in temperate Europe, was less responsive to summer drought than old and young managed stands. The higher growth coherence and temporal variability observed in young managed stands concurred with their strongest coupling with summer drought, whereas the lower coherence of the very old stand suggested a more individual growth behavior and less coupling with regional climate. In the future, it would be worthy investigating how growth rates and responsiveness to drought are related to root-to-shoot ratios in historically managed oak forests.

CRedit authorship contribution statement

Dragos Postolache: Writing – review & editing, Resources, Investigation, Conceptualization. **Any Mary Petritan:** Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **J. Julio Camarero:** Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Virgil Scarlatescu:** Writing – review & editing. **Ion Catalin Petritan:** Writing – review & editing, Formal analysis.

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Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2025.126371.

Data availability

Data will be made available on request.

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