

Original Article

How do tree-ring records of *Acer hyrcanum* Fisch. & C. A. Mey. reflect climate sensitivity at the high-elevation forest edge of the Alborz Mountains?

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Abstract: High-elevation forests are among the most climate-sensitive ecosystems, and understanding their growth responses is crucial for predicting ecological consequences under future climate change. The climate sensitivity of tree species in the Hyrcanian forests in the Alborz Mountains of northern Iran, one of the southernmost temperate deciduous forests in the Northern Hemisphere, remains largely unexplored. In particular, *Acer hyrcanum* Fisch. & C. A. Mey., growing mainly at high elevations, has not yet been studied in detail in dendroclimatology. Here, we present the first tree-ring chronology of *Acer hyrcanum* spanning 1814–2022 and analyze its growth–climate relationships to assess how this species reflects climatic sensitivity at the upper forest limit. The results reveal significant positive correlations between tree-ring width and temperature, particularly from May to September, suggesting that warmer growing-season temperatures enhance tree growth. In contrast, tree-ring width showed negative correlations with precipitation and standardized precipitation–evapotranspiration index, especially from January to May, and with cloud cover from March to May. These findings suggest that moisture availability does not limit radial growth in *Acer hyrcanum* and that the precipitation and water

surplus signals may instead reflect the influence of cloud cover, which reduces sunlight availability during critical early-season months. This study contributes to the growing body of dendroclimatic research in the Alborz Mountains and, more broadly, on *Acer* species, particularly in high-elevation ecosystems where such studies are scarce. It also provides valuable insights into how *Acer hyrcanum* may respond to future climate change.

Keywords: Alborz Mountains; Climate change; Climate-growth relationships; Climate reconstruction; Dendroclimatology; High-elevation forest edge

1 Introduction

Temperature and precipitation are widely recognized as the primary factors regulating plant growth and development. Their influence is particularly pronounced at high elevations, where they significantly limit the establishment, growth, and survival of trees at the upper limits of their distribution (Schweingruber 1996; Jobbágy and Jackson 2000; Grace et al. 2002; Körner 2012, 2020). These extreme environments offer a unique opportunity to study how climate shapes tree growth under challenging

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conditions. High-elevation ecosystems are especially sensitive to climate change, serving as early indicators of shifting environmental conditions and providing critical insights into the impacts of global warming on forest dynamics (Schwab et al. 2018; Schickhoff et al. 2023). While temperature and precipitation are the most studied factors, other parameters, such as sunshine duration (Björkman et al. 1972) and cloud cover (Young and Smith 1983), may also influence growth rates but remain understudied. Understanding these complexities is essential for predicting how tree species will respond to ongoing climate change, particularly in vulnerable high-elevation ecosystems that are changing on all continents at an unprecedented rate (Schickhoff et al. 2022).

The Alborz Mountains in northern Iran provide an ideal setting for investigating tree growth-climate relationships due to their diverse climate and topography which create steep environmental gradients in elevation, temperature, precipitation, and vegetation composition over relatively short distances (Zohary 1973). The Hyrcanian (Caspian) forests, located on the northern slopes of the Alborz, are among the southernmost closed-canopy deciduous forests in the Northern Hemisphere (Zohary 1973). These forests, composed of Euro-Siberian species, span a wide elevational gradient, ranging from lowland to submontane, montane, and upper montane (subalpine) zones, extending from the Caspian Sea to the high-elevation forest boundary at approximately 2,850 meters above sea level (Zohary 1963; Gholizadeh et al. 2020).

Acer hyrcanum Fisch. & C. A. Mey., an Euxino-Hyrcanian species distributed across the Balkans, the Caucasus, Anatolia, and Syria, Lebanon, and northern Iran (Browicz 1982), is abundant in certain parts of the Alborz Mountains in northern Iran. Yet it has been largely overlooked in dendrochronological research. Previous studies in the region mainly focused on more widely distributed species, such as *Fagus orientalis* and *Quercus macranthera* (e.g., Pourtahmasi et al. 2009; Oladi and Pourtahmasi 2012; Oladi et al. 2017; Opala-Owczarek et al. 2021; Moradi et al. 2025a, b). While a recent contribution from Azerbaijan (Agamalieva et al. 2025) examined growth patterns of *Acer hyrcanum* but did not explore the species' climate-growth relationships in detail. As a result, knowledge of the climatic sensitivity of this species remains very limited, particularly at higher elevations.

This study aims to address this gap by

investigating the climate-growth relationships of *Acer hyrcanum* in the high-elevation forests of the Alborz Mountains. To the best of our knowledge, this is the first study to evaluate the climatic sensitivity of this species using dendroclimatological methods. Specifically, we seek to answer the following questions: 1) Which climatic variables are most strongly correlated with the radial growth of *Acer hyrcanum*? 2) During which months do significant correlations between climate and radial growth occur? Finally, we place our results in context by comparing them with earlier studies on *Fagus orientalis* and *Quercus macranthera* from the same sites. This research contributes to a broader understanding of how high-elevation tree species respond to climate change and provides insights relevant for forest management strategies and climate change adaptation efforts in mountainous regions, particularly in the context of rapidly changing environmental conditions.

2 Material and Methods

2.1 Study area and sampling site

The study was conducted at the high-elevation forest edge of the central Alborz Mountains, on the northeastern slope. The northern lowland-facing slopes of the region receive relatively consistent rainfall year-round (Raziei 2018), with an average annual precipitation of 1,073.2 mm and a mean temperature of 18.6°C (Najafi and Alizadeh 2023). In contrast, higher elevations experience less precipitation than the lowlands, with substantial snowfall occurring from late autumn through early spring, resulting in cold and snow-covered conditions (Noroozi and Körner 2018). Analysis of the Climatic Research Unit (CRU) Time-Series (TS) 4.07 dataset (Harris et al. 2020; University of East Anglia Climatic Research Unit et al. 2023) from 1901 to 2022 for the studied site shows that July and August are the warmest months, while the coldest temperatures occur in December, January, and February. Summer and autumn droughts are common, and overall, annual precipitation is relatively low, with April typically receiving the highest monthly rainfall (see Moradi et al. 2025a for details).

Within this climatic context, *Acer hyrcanum* thrives in submontane, montane, and subalpine forests (Sabeti 1976) and is known for its drought tolerance

and preference for open, sunlit environments (Mohtashamian et al. 2017). It typically grows at elevations between 1,500 and 2,800 meters, where annual precipitation ranges from 500 to 800 mm and mean annual temperatures vary between 11°C and 17°C (Mohtashamian et al. 2017). *Acer hyrcanum* is often found alongside species such as *Quercus macranthera*, *Acer monspessulanum*, *Acer campestre*, and *Sorbus torminalis* (Gholizadeh et al. 2020; Moradi et al. 2024).

Our sampling site is located along the ridge of the Kuhe-Golijan Peak in the Alam-Kuh region, at an elevation between 2,600 and 2,660 meters above sea level and is locally known as Kule-Chal (Fig. 1). This area is characterized by a mixed forest, predominantly consisting of *Acer hyrcanum* and *Quercus macranthera* (Fig. 2). Tree-ring cores were collected using standard methods described by Cook and Kairiukstis (1990) and Speer (2010). Sampling focused on healthy, upright *Acer hyrcanum* trees, avoiding those growing on steep slopes or affected by otherwise extreme site conditions. At the study site, the sampled *Acer hyrcanum* trees had an average height of 9.6 m, an average diameter at breast height of 33.4 cm, and an average crown length of 6.3 m. For each tree, one or two cores were extracted at breast height (approximately 1.3 m above ground) using a 5-mm increment borer, depending on tree size, tree condition, and accessibility of suitable sampling points. For

example, some trees had defects, rot, or cracks that prevented collection of a second core, while others were growing in harsh, high-elevation conditions in which collecting a single core was sufficient to avoid harming the tree. In total, 35 radii were collected from 28 trees during June 2023. After quality control and cross-dating, the final dataset comprised 33 radii.

The collected samples were scanned under controlled darkroom conditions using an Epson Perfection V850 flatbed scanner at 2400 dpi resolution in RGB mode. TRW were measured using CooRecorder 9.6 software (Cybis Elektronik and Data AB, Saltsjöbaden, Sweden). To ensure accuracy, the measurements were visually cross dated using CDendro 9.6 software (Cybis Elektronik and Data AB, Saltsjöbaden, Sweden) according to protocols described by Maxwell and Larsson (2021). Statistical verification was performed using the *dplR* package in R (Bunn 2008; Bunn et al. 2023).

To analyze the relationship between TRW and climate, we used the CRU data mentioned above. This dataset provides gridded data of monthly minimum, mean and maximum temperature, precipitation (monthly sums) and cloud cover (in percent) from 1901 to 2022 at a spatial resolution of 0.5°. The data were obtained from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) Climate Explorer (Trouet et al. 2013).

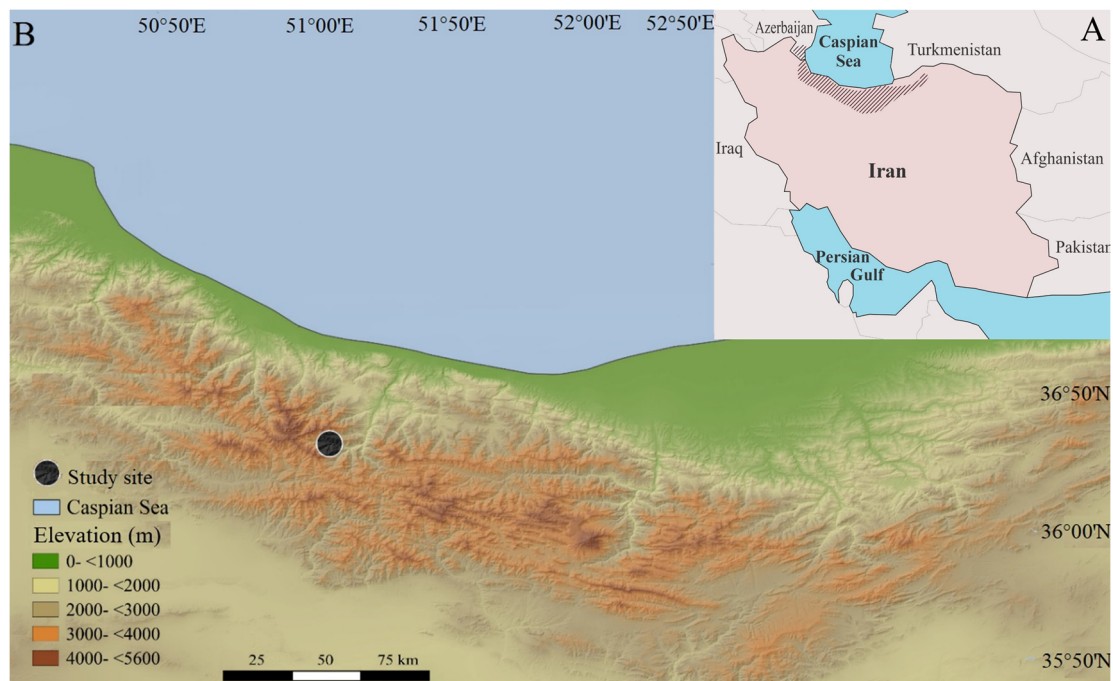


Fig. 1 Map of the study area: (A) Location of Iran and surrounding countries, with the Alborz Mountains in the northern part of Iran marked by crosshatching; (B) The Alborz Mountains south of the Caspian Sea, with the study area marked by a black filled circle.

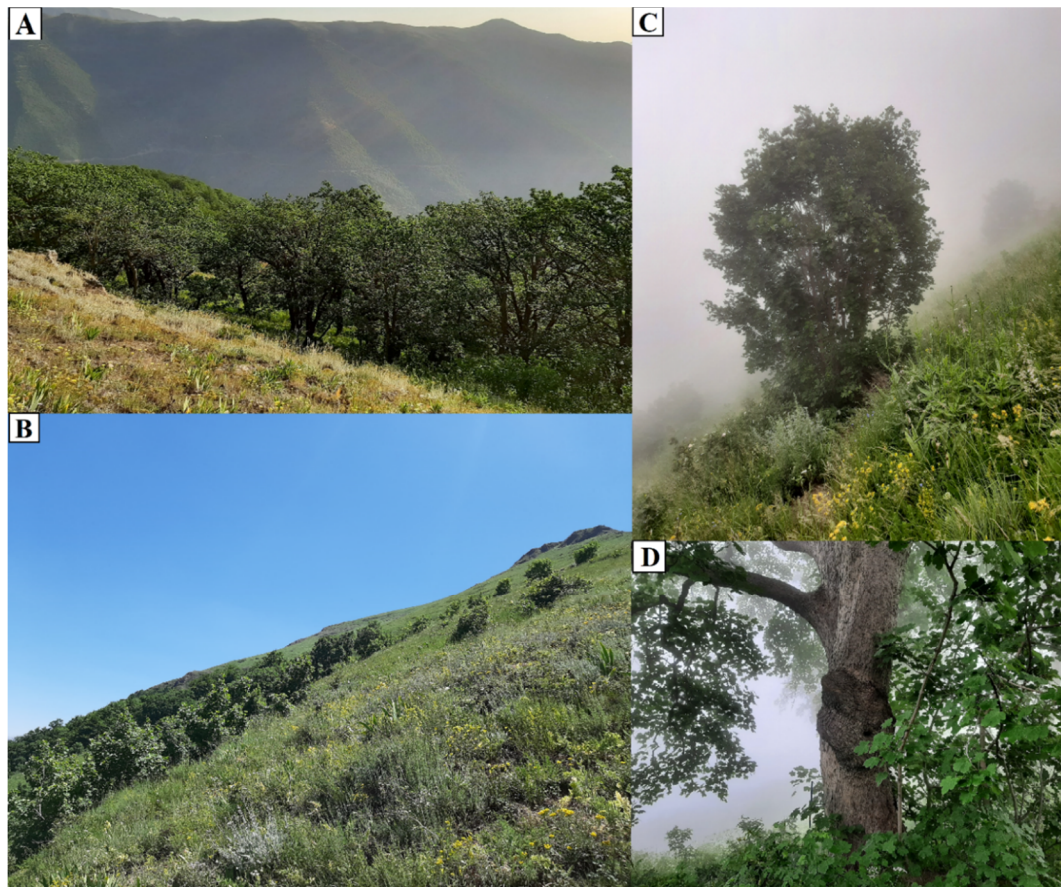


Fig. 2 Study sites: (A) Location of the sampled cores in Kule-Chal, situated at the edge of the high-elevation forest in the Alborz along the ridge of Kuhe-Golijan Peak; (B) Young *Acer hyrcanum* individuals growing above the sampled core locations, with the core locations visible in the background; (C) A young *Acer hyrcanum* tree in foggy conditions; (D) An old *Acer hyrcanum* tree observed during the survey at Kule-Chal. All photos were taken by H.M. in July 2023.

2.2 Data analyses

All tree-ring series were standardised using a 100-year cubic smoothing spline with a wavelength cut-off of 0.1, using the *dplR* package in R (Cook 1985; Bunn 2008; Bunn et al. 2023). This approach was chosen to isolate short-term climate variability (interannual to decadal variability), effectively removing long-term and non-climatic trends such as those related to tree age and size while emphasizing the climatic signals most relevant to the study period (Fritts 1976; Cook 1985).

The strength of the common signal in the chronology was assessed using the Subsample Signal Strength (SSS), which indicates how well the subsample represents the full dataset; and the Expressed Population Signal (EPS) statistic, both applied with 30-year long, 15-years overlapping time windows. An EPS value above 0.84 (Wigley et al. 1984) was considered sufficient to indicate a strong common signal within the dataset. Additional statistical

measures were used to assess chronology quality, including: Mean first-order autocorrelation, which reflects the influence of past growth on current growth; Mean inter-core correlation ($r_{bar_{bt}}$), which measures coherence between samples; Signal-to-noise ratio (SNR), based on the average number of trees sampled (Bunn 2010; Vicente-Serrano et al. 2010; Cook and Pederson 2011; Buras 2017).

To explore climate-growth relationships, we used the trend-adjusted standard chronology to assess correlations with aforementioned climate parameters. In addition, we used the Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010) for 1-month scale derived from CRU data. It was computed using the R package *SPEI* (Beguería et al. 2014) to assess periods of water deficit, as SPEI accounts for both precipitation and temperature-driven evapotranspiration. This allowed us to determine whether the observed negative correlations between tree-ring width and precipitation were due to true moisture limitation or instead reflected the indirect

effects of cloud cover reducing sunlight during critical early-season months. Pearson's correlation coefficients and confidence intervals were calculated using a stationary bootstrap approach with optimal block length selection, as described by Politis and Romano (1994) and Politis and White (2004). Since temperature and precipitation in the previous summer and autumn can influence tree growth (e.g., Gillner et al. 2014, for *Acer saccharum*), the analysis period spanned from May of the previous year to December of the current year. Statistical significance was set at $p < 0.05$.

All analyses were performed with R version 4.4.2 (R Development Core Team 2024).

3 Results

3.1 Chronological features

The tree-ring series of *Acer hyrcanum* was successfully cross-dated, resulting in a chronology from 1814 to 2022 (Fig. 3). The EPS values exceeded the threshold, reaching 0.86, indicating a sufficiently replicated chronology. The current EPS exceeded this threshold from 1948 onwards, marking the beginning of the most reliable part of the chronology (1948-2022) (Fig. 3), and therefore became the focus of the analyses in this study. However, additional analyses were carried out for the period 1902–2022 to assess the stability of the TRW-climate correlations over the whole period. The mean correlation between trees was $r = 0.35$ (SD = 0.15), while the first order autocorrelation had a mean value of 0.68 (SD = 0.14). The $r_{bar_{bt}}$ value was 0.16, with running $r_{bar_{bt}}$ values ranging from 0.18 at the beginning of the chronology (centered on 1857) to 0.33 at the end (centered on 2007) (Fig. 3). The signal-to-noise ratio was 5.93 and the mean sensitivity, reflecting the annual variability in the TRW, was 0.33.

3.2 Dendroclimatic response of *Acer hyrcanum*

Tree growth showed strong statistically significant

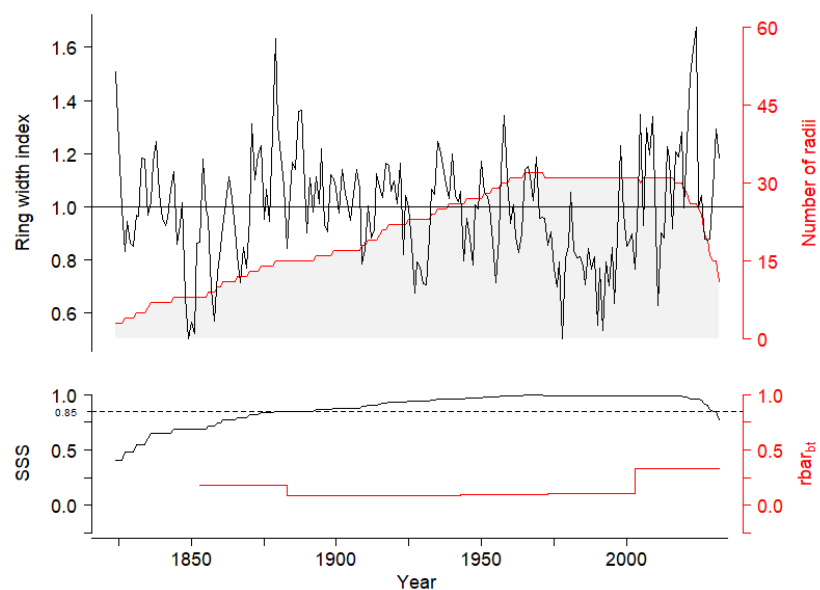


Fig. 3 Standard TRW chronology (black curve) and sample depth (red curve) for the study site. The corresponding values for subsample signal strength (SSS) and mean interseries correlation ($r_{bar_{bt}}$) are also shown. The dotted line at 0.85 indicates the threshold above which SSS is considered reliable.

correlations with precipitation, temperature and cloud cover across several months and seasons (Fig. 4). Specifically, TRW was positively correlated with minimum temperature in May ($r = 0.272$), June ($r = 0.361$), July ($r = 0.256$), August ($r = 0.324$) and October ($r = 0.219$) of the previous year. Similar positive correlations were observed for May ($r = 0.343$), June ($r = 0.391$), July ($r = 0.325$), August ($r = 0.425$) and September ($r = 0.334$) of the current year. On a seasonal scale, tree growth was significantly associated with mean minimum temperature from March to May ($r = 0.247$) and from May to September ($r = 0.440$).

The influence of mean temperature followed a similar pattern. Higher mean temperatures in May ($r = 0.269$), June ($r = 0.331$) and August ($r = 0.281$) of the previous year were associated with increased tree growth. Similarly, significant positive correlations were found for May ($r = 0.349$), June ($r = 0.357$), July ($r = 0.279$) and August ($r = 0.408$) of the current year. Seasonal correlations were also found, especially for March to May ($r = 0.283$) and May to September ($r = 0.418$) mean temperatures.

Tree growth also showed strong relationships with maximum temperature. TRW was positively correlated with May ($r = 0.238$), June ($r = 0.299$) and August ($r = 0.192$) of the previous year and with May ($r = 0.342$), June ($r = 0.348$), July ($r = 0.265$), and August ($r = 0.396$) of the current year. At the seasonal level, significant correlations were found for January to

March ($r = 0.211$), March to May ($r = 0.272$) and May to September ($r = 0.408$).

Interestingly, TRW was negatively correlated with precipitation totals, especially in the previous May ($r = -0.235$), the current May ($r = -0.295$) and October ($r = -0.229$). Seasonal trends also showed negative correlations with precipitation during January to March ($r = -0.263$) and March to May ($r = -0.215$). Negatively correlated with one-month SPEI, TRW decreased with higher water availability in the previous May ($r = -0.250$), previous June ($r = -0.216$), current March ($r = -0.186$), current May ($r = -0.335$), current June ($r = -0.231$), current August ($r = -0.263$), January to March ($r = -0.275$), March to May ($r = -0.290$) and May to September ($r = -0.311$).

In addition, tree growth was significantly influenced by cloud cover, with negative correlations found in the previous May ($r = -0.343$) and June ($r = -0.398$), as well as in the current March ($r = -0.287$), April ($r = -0.557$) and May ($r = -0.482$). Seasonal cloud

cover also had a negative influence, especially from January to March ($r = -0.243$), March to May ($r = -0.533$) and May to September ($r = -0.274$).

The climate-growth relationships found for the longer period (1814–2022) resembled those observed for the more recent period (1948–2022). In particular, the relationship between tree growth and temperature remained positive across multiple months, with higher temperatures in May, June, and August of both the previous and current year associated with increased growth. Similarly, the negative correlations with total precipitation during this period mirrored those found for 1948–2022, particularly in the previous May, current May, and the seasonal periods of current January to March, March to May, and May to September, all of which showed a negative association with tree growth. Analysis of one-month SPEI for the longer period (1902–2022) supported the patterns observed for 1948–2022, with significant negative correlations in previous May, current May, current August, January to

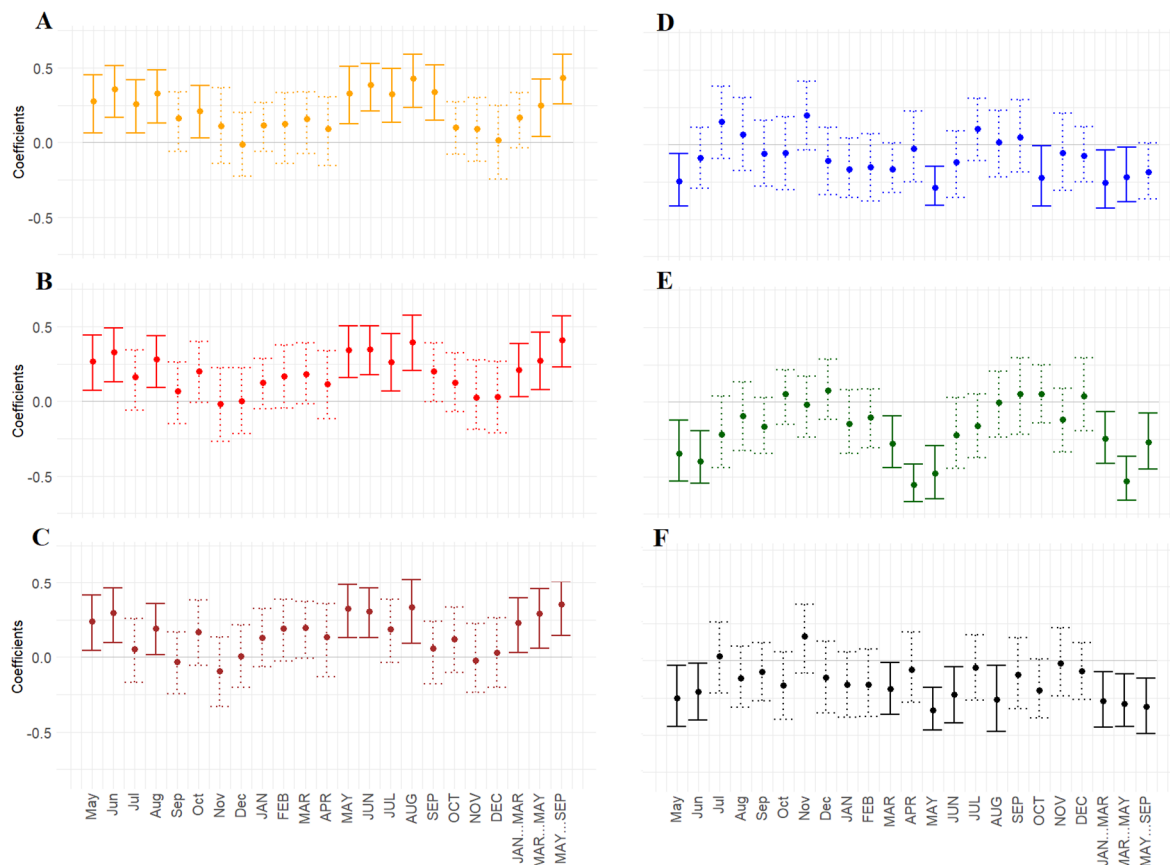


Fig. 4 Static correlations between TRW chronology and (A) minimum temperature (orange bars), (B) mean temperature (red bars), (C) maximum temperature (brown bars), (D) total precipitation (blue bars), (E) percentage of cloud cover (green bars), based on CRU data, and (F) the Standardised Precipitation-Evapotranspiration Index (SPEI) drought indices (black bars) from 1948 to 2022 for the previous and current year. Solid bars indicate significant correlations ($p < 0.05$). Error bars represent the bootstrapped 95% confidence intervals of the correlation coefficients. Months in lowercase letters represent the previous year, while months in uppercase letters correspond to the current year.

March, March to May, and May to September.

In addition, similar correlations were observed between cloud cover and TRW, with negative correlations found for the previous June, as well as the current March, April, and May. Seasonal correlations also followed the same pattern, with negative relationships identified for the periods of January to March, March to May, and April to September. Detailed results for this period are given in Fig. 5.

Despite minor differences between the TRW-climate correlations of the two periods (1902–2022 and 1948–2022), these results highlight the consistent influence of temperature, precipitation, and cloud cover on tree growth patterns over time.

4 Discussion

This study demonstrates the feasibility of

accurately cross-dating a hitherto neglected and poorly studied species in high-elevation forests in the Alborz Mountains of northern Iran. The establishment of a reliable chronology for *Acer hyrcanum* from 1814 to 2022 allows us to contribute valuable information on its growth-climate relationships over the past centuries. The EPS values combined with other chronological features such as high correlation between trees and a reasonable signal-to-noise ratio, suggest that the tree-ring series from this period provide a robust record of environmental conditions, which is crucial for understanding the response of the species to climate variability.

The positive correlations between TRW and temperature, particularly from May to September, suggest that warmer temperatures during the growing season promote tree growth by enhancing photosynthesis (Zhou et al. 2021) and stimulate root processes that improve water and nutrient uptake,

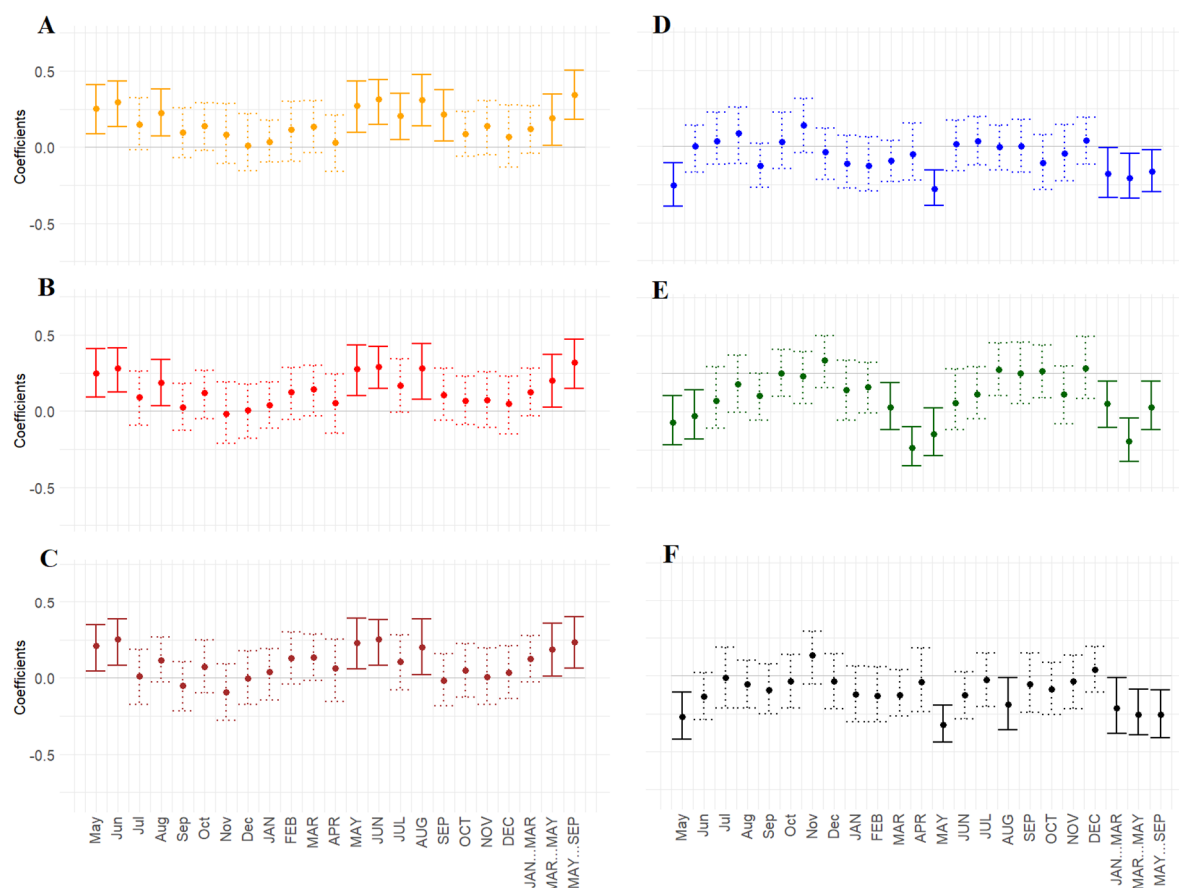


Fig. 5 Static correlations between TRW chronology and (A) minimum temperature (orange bars), (B) mean temperature (red bars), (C) maximum temperature (brown bars), (D) total precipitation (blue bars), (E) percentage of cloud cover (green bars), based on CRU data, and (F) the Standardised Precipitation-Evapotranspiration Index (SPEI) drought indices (black bars) from 1902 to 2022 for the previous and current year. Solid bars indicate significant correlations ($p < 0.05$). Error bars represent the bootstrapped 95% confidence intervals of the correlation coefficients. Months in lowercase letters represent the previous year, while months in uppercase letters correspond to the current year.

thereby facilitating radial growth (Lyu et al. 2017). In cold regions, annual tree growth is closely linked to growing season air temperatures (Mikola 1962; Kay 1978; Jacoby and Ulan 1981; Körner and Paulsen 2004; Allen et al. 2012; St. George 2014). At higher elevations, rising temperatures are thought to support tree growth by alleviating thermal limitations associated with altitude (Di Filippo et al. 2007; Dittmar and Elling 2007; Martin-Benito et al. 2018). The consistent positive correlations with temperature in both the previous and current years highlight temperature as a key factor limiting *Acer hyrcanum* growth in this high-elevation environment.

The influence of climatic conditions in the previous growing season on tree growth is consistent with findings from other *Acer* species, such as *Acer saccharum*. This effect is likely due to carry-over processes related to carbohydrate storage and allocation (McLaughlin et al. 1991; Lane et al. 1993). Additionally, the seasonal trends observed in the early growing season, particularly from March to May, align with the known phenological patterns of temperate tree species. Temperature conditions during this period can significantly impact the timing and rate of early-season growth (Perry 1971; Linkosalo et al. 2006; Oladi et al. 2017).

Interestingly, precipitation showed a negative correlation with TRW, especially during the months of January to May, a pattern mirrored by one-month SPEI during the same period. This suggests that early-season wetness may reduce growth through indirect effects, such as increased cloud cover and lower light availability, rather than reflecting water limitation. Excess rainfall can also negatively affect growth by reducing oxygen availability in the root zone and restricting water and nutrient transport (Rood et al. 2010; Canham et al. 2012). The negative correlation with SPEI further indicates that moisture stress is unlikely to limit *Acer hyrcanum* radial growth, reinforcing the interpretation that the precipitation signal acts as a proxy for cloud cover. During the growing season, particularly in late spring, growth appears constrained by cloudiness, which reduces solar radiation and photosynthetic activity (Oladi and Pourtahmasi 2012). Together, these results highlight that wet periods in early spring are more likely to inhibit growth by reducing light availability than by limiting soil moisture.

The negative correlation with cloud cover, particularly during March to May, provides direct

evidence for this interpretation, as increased cloud cover during these months would reduce the amount of solar radiation reaching trees, potentially limiting photosynthetic activity (Deo et al. 2022). In addition to reducing photosynthetically active radiation, cloud cover and aerosol loading typically lead to reduced photosynthetic photon flux density and changes in microclimatic parameters such as temperature and vapour pressure deficit (Gu et al. 2002). Our finding that cloud cover negatively affects growth of *Acer hyrcanum* throughout much of the year, particularly in the spring and early summer, emphasizes the complex interactions between temperature, moisture, and light availability, that are critical for optimal tree growth in these ecosystems. When considered together with the negative correlations observed with precipitation and SPEI, these results strongly suggest that light limitation from persistent cloudiness rather than soil moisture deficit, is a central factor shaping radial growth patterns in this species.

As climate change continues to alter temperature and precipitation patterns (Hansen et al. 2012; IPCC 2023), particularly in mountain regions, understanding species' climate responses will be critical for predicting future growth patterns and forest dynamics (Schwab et al. 2018). Research in similar study areas at the high-elevation forest in the Alborz has highlighted that other tree species, such as *Fagus orientalis* and *Quercus macranthera*, are showing signs of stress due to dry conditions and high temperatures during the growing season (Moradi et al., 2025a, b). Interestingly, *Acer hyrcanum*, classified as "Near Threatened" (Mohtashamian et al. 2017), which occurs in the same habitats but has a more restricted distribution, seems to benefit from higher temperatures. This suggests that while some species may struggle with rising temperatures, *Acer hyrcanum* might be better adapted to these new conditions, at least in the short term. However, this research focuses on a single site, and this species may show site-specific climatic signals similar to other broad-leaved species of the respective genus, such as *Acer saccharum* (Copenheaver et al. 2020; Gillner et al. 2014) or *Fagus* species (Pourtahmasi et al. 2024; Moradi et al. 2025a). Expanding dendroclimatological research on this species is therefore crucial to understanding its long-term response to climate change in different locations with different local conditions, as well as its potential for reconstructing past climates. Despite these promising insights, data on the growth-climate

relationships of tree species in the Alborz Mountains remain limited. Further research is needed to better understand how these species will respond to future climate scenarios. Such studies could provide invaluable information for similar poorly studied mountain systems, such as the Caucasus, or other regions with comparable vegetation and climate dynamics.

Finally, due to strong climatic signals of *Acer hyrcanum* at its high-elevation growing area, it is suggested as a potential species for high-resolution climate reconstructions, particularly for reconstructing temperature at high elevations.

Traditionally, species from open-canopy forests, such as *Acer hyrcanum*, which are poor competitors, tend to have stronger climate signals and are easier to cross-date accurately (Fritts 1976; Copenheaver et al. 2020). Despite exhibiting clearer climatic signals than other tree species in the high-elevation forests of the Alborz (e.g., Moradi et al. 2025a, 2025b), *Acer hyrcanum* remains understudied. In contrast, better-studied species such as *Fagus orientalis* (e.g., Oladi et al. 2017) and *Quercus macranthera* (e.g., Opala-Owczarek et al. 2021), which are distributed across western Asia, including northern Iran, Turkey, and the Caucasus region (Rechinger 1971), show weaker climatic signals (Moradi et al. 2025a, b). The limited attention given to *Acer hyrcanum* in dendrochronological studies may stem from biased sampling, particularly against species that predominantly grow at high elevations, or from perceived difficulties in cross-dating. However, our study demonstrates not only the feasibility of developing a reliable chronology for this species, but also its strong potential for capturing high-resolution climatic signals. The reasons behind the scarcity of studies on *Acer hyrcanum* remain unclear, but may in part reflect the general preference in dendroclimatology for conifers, which are often considered more reliable for capturing long-term climate signals due to their clearer ring structure and greater longevity (e.g., Schweingruber 1996; Schweingruber et al. 1979). We encourage further research to explore the dendroclimatic potential of *Acer hyrcanum* and other underrepresented broadleaf species.

5 Conclusions

This study provides valuable insights into the dendroclimatic response of *Acer hyrcanum* at a high-elevation forest edge in the Alborz Mountains, northern Iran. By establishing a robust chronology

from 1814 to 2022, we were able to assess the influence of climatic variables, including temperature, precipitation, Standardized Precipitation-Evapotranspiration Index (SPEI) and cloud cover, on tree growth. The results highlight the strong sensitivity of the species to temperature, with positive correlations between TRW and temperature over several months, particularly during the growing season. In contrast, precipitation, SPEI and cloud cover were found to negatively affect tree growth, probably due to their influence on light availability and photosynthesis rather than water limitation alone. This underscores the importance of considering interactions among multiple climatic factors, as wet and cloudy periods in early spring may reduce growth despite adequate moisture, while warmer, sunnier conditions enhance radial growth. The results suggest that *Acer hyrcanum* is rather well adapted to climate change-induced warmer temperatures, particularly at the high-elevation forest edge, where it benefits from increased solar radiation. This contrasts with other species in the region, such as *Quercus macranthera* and *Fagus orientalis*, which have shown signs of stress due to rising temperatures causing dry conditions. Overall, our findings highlight the need to account for the combined and sometimes counterintuitive effects of temperature, moisture, and light when predicting the responses of high-elevation species to ongoing climate change. This study is particularly timely in the context of ongoing climate change, and contributes to our understanding of how high-elevation species may respond to changing environmental conditions.

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Author Contributions

MORADI Halime: Investigation, Conceptualization, Methodology, Data curation, Funding, Formal analysis, Writing-original draft, Writing-review & editing. SCHWAB Niels: Methodology, Visualization, Writing-review & editing. SCHICKHOFF Udo: Conceptualization,

Visualization, Writing-review & editing, Supervision.

Ethics Declaration

Availability of Data/Materials: The datasets used during the current study are available from the corresponding author on reasonable request.

Conflict of Interest: The second author, Niels SCHWAB, is a scientific editor of Journal of Mountain Science, and the third author, Udo SCHICKHOFF, is an Editorial Board member of this journal. They were not involved in the journal's review of, or decisions related to, this manuscript.

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