Tree-Ring Growth Response of *Juniperus excelsa* to Climate and Extreme Pointer Years in the Northwest of Iran

Vilma Bayramzadeh,[a] Samira Beiranvand,[b] and Pedram Attarod [b,*]

Northwestern Iran represents a significant data gap in the dendroclimatic network of West Asia, hindering a comprehensive understanding of regional hydroclimatic variability. This study aims to bridge this gap by constructing a robust tree-ring width chronology for *Juniperus excelsa* and evaluating its response to climatic extremes in the Hashtjin mountains of northwestern Iran. The authors analyzed 19 increment cores from 15 old-growth trees to develop a 110-year chronology (1898–2007). Statistical quality indicators confirmed a robust climatic signal. Analysis revealed that radial growth was primarily constrained by moisture availability, showing significant positive correlations with April and June precipitation and a significant negative correlation with April temperature, highlighting spring drought stress. Temporal instability in these climate-growth relationships was detected using moving window correlation. Four independent methods (IT, RGC, NW, zChron) identified major pointer years, with extreme droughts in 1907–1908 and 2001 consistently flagged. These extreme years show strong spatiotemporal coherence with historical drought records across West Asia and the Eastern Mediterranean, validating the chronology's climatic sensitivity and underscoring regional synchronicity in major hydroclimatic events. The findings underscore the vulnerability of juniper ecosystems to warming-induced drought and provide a crucial proxy for filling paleoclimatic gaps in the region.

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INTRODUCTION

There is broad consensus that the climate is changing, but the intensity and characteristics of its impacts vary significantly between regions. This is particularly true for Iran, where a complex topography, including the Alborz and Zagros mountains, and a wide latitudinal range result in highly distinct regional climates (Vaghefi *et al.* 2019). Understanding this regional climate evolution requires robust reconstructions of past climate patterns. This need is particularly critical in Iran, where instrumental climate records are scarce prior to 1950. While tree-ring networks offer a high-resolution solution to compensate for this lack of instrumental data (Briffa *et al.* 1998; Cook *et al.* 2004; Akkemik *et al.* 2005; Jones *et al.* 2009), large parts of Iran, Pakistan, and Afghanistan remain significant spatial gaps in the paleoclimatic archives of Western Asia (Hamzeh *et al.* 2021).

Among these under-studied areas, northwestern Iran remains a critical void in the dendroclimatic network. Few dendrochronological studies have been carried out in this region, and the only long-term *Juniperus excelsa* chronology (Liphschitz *et al.* 1979) is no longer accessible. This inaccessibility creates a gap that prevents robust assessment of long-term climate variability and limits our understanding of recent changes in this ecologically sensitive area. Currently, no reliable and accessible tree-ring chronology exists to support dendroclimatic reconstruction in northwestern Iran.

To address this gap, the present study focuses on developing a new tree-ring width chronology from *J. excelsa* in the Hashtjin Mountains. This species is well suited for such analysis, as *Juniperus* shows strong ecological and climatic sensitivity in high-elevation, semi-arid environments (Bräuning 2001). Moreover, this site lies within a climatically transitional zone, where interannual variability in moisture and temperature is pronounced and tree growth is expected to be especially climate-sensitive. Such transitional mountain zones often yield robust and interpretable climate signals in tree-ring variability (Touchan *et al.* 2005). Beyond gradual trends, it is often the occurrence of extreme events-such as severe droughts or anomalous wet years- that leaves the most profound ecological and social imprints in water-limited systems.

In Iranian dendrochronology, however, most research has centered on mean climate reconstruction rather than event detection. Initial studies focused on fundamental chronologies and ecological principles (Liphschitz *et al.* 1979; Pourtahmasi *et al.* 2007; Saderi *et al.* 2013), followed by research centered on climate reconstructions using traditional ring-width proxies (Arsalani *et al*. 2018; Bayramzadeh *et al.* 2018; Beiranvand *et al.* 2024). More recently, the field has advanced with the application of stable isotope dendroclimatology, which offers high-resolution insights into past hydroclimatic trends (Foroozan *et al*. 2019, 2020; Wang *et al*. 2025). While these studies have substantially improved our understanding of continuous climate variability, our knowledge of the frequency, magnitude, and timing of extreme events, such as severe droughts or unusually favorable years, remains limited. Pointer-year analysis directly addresses this gap by offering a systematic, high-resolution framework for identifying and interpreting extreme growth anomalies. In doing so, it provides critical insights into ecosystem responses to abrupt climatic events, responses that are largely inaccessible through conventional reconstruction approaches (Kienast *et al.* 1987; Schweingruber *et al.* 1990; Rolland *et al.* 2000; Genova 2012).

To ensure a robust identification of these events, multiple analytical methods are required. Several techniques are commonly employed, including Interval Trends (IT), Relative Growth Changes (RGC), Normalization in a Moving Window (NW), and Extreme Values of Chronology (zChron) (Cropper, 1979; Schweingruber *et al*. 1990; Neuwirth *et al*. 2007; Simon and Lena 2016; Jetschke *et al.* 2019). These methods differ fundamentally: some are qualitative (IT), others quantitative (zChron); some focus on individual trees (RGC, NW), while others assess the entire population (IT, zChron). Since no single method is a substitute for another, all four were applied in this work to gain a comprehensive and robust understanding of potential pointer years in our chronology.

The primary objectives of this study were: (1) to develop the first modern, accessible chronology for *J. excelsa* in the Hashtjin mountainous region of northwestern Iran; and (2) to identify the climatic factors influencing its tree-ring patterns, with a specific analysis of climatic responses associated with pointer years. By rigorously testing the temporal stability of these climate-growth relationships and evaluating the regional synchronicity of detected events, this study transcends local interest and contributes to a broader understanding of hydroclimatic variability in arid mountainous regions.

EXPERIMENTAL

Study Area

The study was conducted in the Hashtjin Mountains, which form part of the northern foothills of the Alborz mountain range in northwestern Iran, within the southern part of Ardabil Province (37°26′N, 48°24′E).

Sampling sites were located on mid- to upper slope positions at elevations ranging from 1,400 to 1,900 m a.s.l. (Fig. 1a). Soils are shallow lithic Entisols with a clay-loam to loam texture, typical of steep, mountainous terrain in this region (Roozitalab *et al.* 2018; Iranian Soil and Water Research Institute, 2020).

Tree ages, estimated from ring counts of increment cores, ranged from 70 to 120 years; this information is presented here for site context, while detailed sampling procedures are described later.

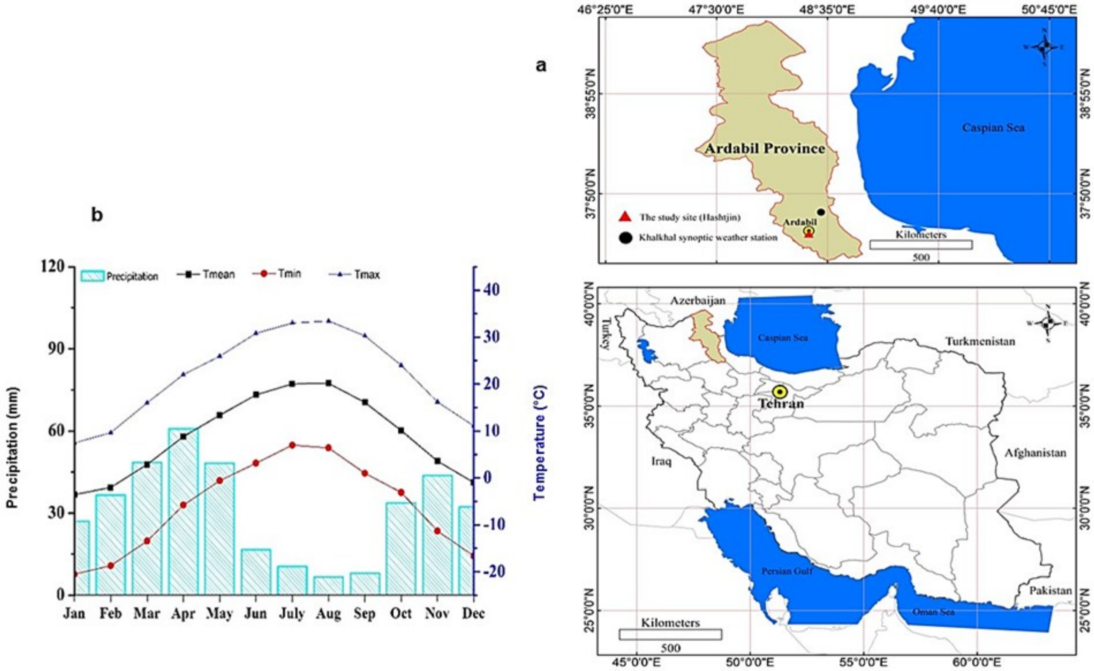

Fig. 1. (a) Location of the study area and sampling site (red dot) in the Hashtjin region, Ardabil Province, northwestern Iran. (b) Monthly climatic diagram for the Khalkhal synoptic station (1987–2017), showing mean, minimum, and maximum temperatures and total precipitation.

The natural vegetation consists of open, uneven-aged, mixed woodlands dominated by *J. excelsa*. Associated woody species include *Crataegus monogyna* (hawthorn), *Amygdalus scoparia* (wild almond), *Pistacia atlantica* subsp. *mutica* (wild pistachio), *Acer monspessulanum* (Montpellier maple), *Pyrus syriac*a (Syrian pear), *Rhamnus cathartica* (buckthorn), *Lonicera nummulariifolia* (honeysuckle), and *Berberis vulgaris* (barberry). This composition is characteristic of relict juniper woodlands on dry, rocky slopes of the Alborz (Sefidi *et al.* 2018).

Climate data (1987–2017) from the nearest synoptic station, Khalkhal (37°38′N, 48°31′E; 1,796 m a.s.l.; Islamic Republic of Iran Meteorological Organization, IRIMO), indicate a continental arid climate. Mean monthly minimum precipitation occurs in August (7 mm) and maximum in April (61 mm). The coldest month is January (mean −4 °C) and the warmest is August (mean 20.5 °C) (Fig. 1b). The de Martonne aridity index ($I = P / (T + 10)$, where P is annual precipitation in mm and T is mean annual temperature in °C) yields a value of 4.2, confirming the arid classification of the region (de Martonne 1926).

Sample Collection and Chronology Development

Increment cores were collected at breast height (1.3 m) from 15 mature *J. excelsa* trees at the study site. In total, 19 cores were obtained, with one or two cores extracted per tree depending on stem form. The sampled trees were healthy, dominant or co-dominant individuals, with no visible signs of mechanical damage or disturbance. Ring counts from the increment cores indicate that the sampled trees were approximately 70 to 120 years old. Tree-ring widths were measured to the nearest 0.01 mm using a high-precision scanner and the measurement tools in CooRecorder software (v7.3). Cross-dating was performed visually and statistically following standard dendrochronological procedures (Cook and Kairiukstis 2013) using the Cdendro software package. To remove age-related growth trends and enhance the common climate signal, raw ring-width series were detrended using a negative exponential curve (Cook and Peters 1981). All standardization procedures were carried out in R version 4.3.2 (R Core Team 2023), using the dpIR package (Bunn 2008).

Climate–Growth Relationships

Analyzing climate–growth relationships require long-term climate data from near the sampling site. The Khalkhal meteorological station, the closest station to the study area, provides only a limited record (1987 to 2017). Therefore, the Climate Research Unit (CRU) dataset was validated against station data for the overlapping period 1987 to 2017. This validation was carried out to determine whether the gridded CRU climate data can be used to extend the limited station record and accurately represent local climatic conditions.

The comparison showed a significant correlation between CRU and station data ($R^2 = 0.37$ for precipitation and $R^2 = 0.48$ for temperature; Fig. 2), indicating that the CRU dataset captures the main temporal variability of the local climate. Based on this validation, all climate–growth analyses were conducted using the CRU dataset (1901–2018), while station data were used only for validation purposes. Monthly precipitation, minimum, maximum, and mean temperature (T_{min}, T_{max}, T_{mean}), as well as the self-calibrating Palmer Drought Severity Index (sc-PDSI), were extracted at a spatial resolution of 0.5° × 0.5° for the grid cell containing the sampling site.

The sc-PDSI is a standardized soil moisture index ranging from approximately –10 (extremely dry) to +10 (extremely wet), with values below –3 indicating severe to extreme drought (Palmer 1965). This index is particularly valuable in dendroclimatic studies because it integrates temperature and precipitation effects on soil moisture availability, often explaining tree-growth variation more robustly than precipitation alone (Lebourgeois *et al*. 2005; Bista *et al*. 2021). In this study, monthly sc-PDSI values were examined as a drought-related indicator in the climate–growth analyses, beside precipitation and temperature. Correlation functions and moving-window analyses were applied to assess the relationships between tree-ring width and sc-PDSI over a 12-month period from October of the previous year to September of the current growing year (Fritts 1976).

Climate–growth relationships were quantified using the treeclim package (Zang and Biondi 2015) in R version 4.3.2 (R Core Team 2023). This package was used to compute correlation and response functions between the standardized tree-ring chronology and monthly climatic variables.

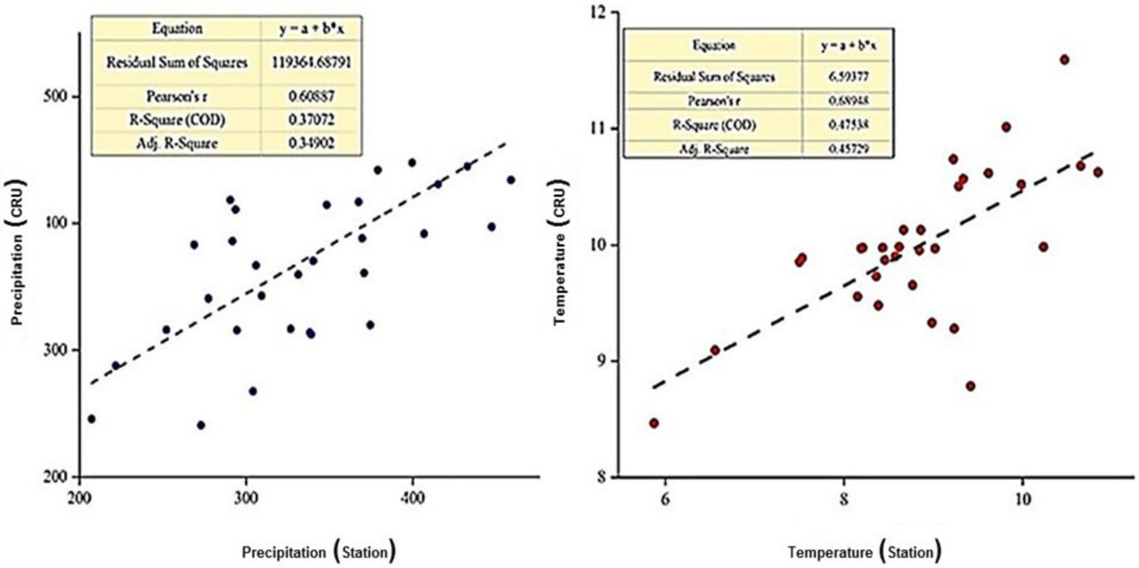

Fig. 2. Correlation between monthly precipitation and temperature records from the Khalkhal meteorological station and the CRU TS dataset for the overlapping period 1987–2017

Pointer Year Detection

In this study, pointer year detection was performed exclusively based on tree-ring growth variability, independent of instrumental or gridded climate data. Climatic datasets were used only to interpret the identified growth extremes. Pointer years were identified using four complementary methods: Interval Trend (IT), Relative Growth Change (RGC), Normalization in a Moving Window (NW), and Extreme Chronology Values (zChron). Although each method detects abrupt growth changes by analyzing individual tree-ring series, they employ distinct algorithms to define event years.

IT identifies years with synchronized growth changes across the population, with a year classified as a pointer year when at least 95% of trees show a consistent growth change in the same direction. RGC detects abrupt growth shifts relative to preceding years, with a pointer year defined when ≥60% of the sampled trees exhibit an abrupt growth change. NW normalizes growth within moving windows using an absolute Cropper index threshold of |C_Cropper| > 0.75, and zChron flags years with extreme values in the site chronology.

For each method, a year was classified as a pointer year if the proportion of trees exhibiting an event exceeded a predefined threshold. Only in the zChron method were statistical thresholds of 1.0, 1.28, and 1.645 standard deviations applied to distinguish between different strength classes of pointer years (Simon and Lena 2016; Jetschke *et al.* 2019). Because each method captures different aspects of pointer years, all four approaches were applied to obtain a comprehensive understanding of extreme growth responses, integrating individual-tree reactions, population-level coherence, and standardized growth anomalies. All analyses were performed using the pointRes package (van der Maaten-Theunissen *et al.* 2015) in R version 4.3.2 (R Core Team 2023).

RESULTS AND DISCUSSION

Tree-ring Chronology

To enable robust climate-growth modeling, the authors developed a statistically reliable tree-ring chronology. The final standardized ring-width chronology of *J. excelsa* spanned 110 years from 1898 to 2007 (Fig. 3a) and reflected the length of the available growth record. Its quality was evaluated using standard dendrochronological statistics (Table 1). Key metrics include an Expressed Population Signal (EPS) of 0.86 and a mean inter-series correlation (Rbar) of 0.37, confirming a robust common climatic signal. During cross-dating in Cdendro, missing rings, a common feature in arid environments, were identified and corrected in 9 of the 19 cores (47 %).

Table 1. Dendrochronological Statistics of the Tree-ring Width Chronology of *Juniperus excelsa* from the Hashtjin Mountains

Statistical Parameter	Value
Number of trees/ cores	15/ 19
Average series length (years)	88.2
Time span	110 (1898-2007)
Mean ring width (mm)	1.33 (SD=0.58)
Mean sensitivity (MS)	0.31
RWI standard deviation (SD)	0.2
Mean inter-series correlation (Rbar)	0.37 (SD=0.15)
Auto correlation (AR1)	0.47 (SD=0.13)
Signal-to-noise ratio (SNR)	5.59
Expressed population signal (EPS*)	0.86

* The EPS value of 0.86, exceeding the commonly accepted threshold of 0.85, indicates a robust common signal in the chronology, sufficient for reliable climate reconstruction.

Individual tree-ring series lengths ranged from 76 to 109 years, providing sufficient replication for reliable chronological development (Table 1). Overall dendrochronological statistics indicate high data quality and pronounced climatic sensitivity. In particular, the EPS exceeded the commonly accepted threshold, confirming a strong common climate signal, while mean sensitivity and first-order autocorrelation values suggest substantial inter-annual variability and a moderate carry-over effect of prior growing conditions on current-year growth.

Based on the standardized ring width index (RWI), year-to-year growth variability was evident (Fig. 3b). Periods of relatively higher growth were apparent in the late 1960s, whereas reduced growth characterizes the late 1910s. The mean (μ) and standard deviation (σ) of the RWI were 0.99 and 0.2, respectively. Years with values exceeding $\mu + 1\sigma$ indicate enhanced growth, while values below $\mu - 1\sigma$ correspond to suppressed growth (Fig. 3b), reflecting the sensitivity of *J. excelsa* growth to inter-annual climatic variability.

The 10-year moving average of the RWI showed multi-decadal fluctuations during recent decades (since the 2000s). Periods of low growth appeared more pronounced during the first half of the 20th century compared to the latter half and the early 21st century (Fig. 3b). These observations align with the findings of Bayramzadeh *et al.* (2018), who reported a long-term cooling trend in northern Iran from 1949 to 2006, with warming largely confined to the past two decades.

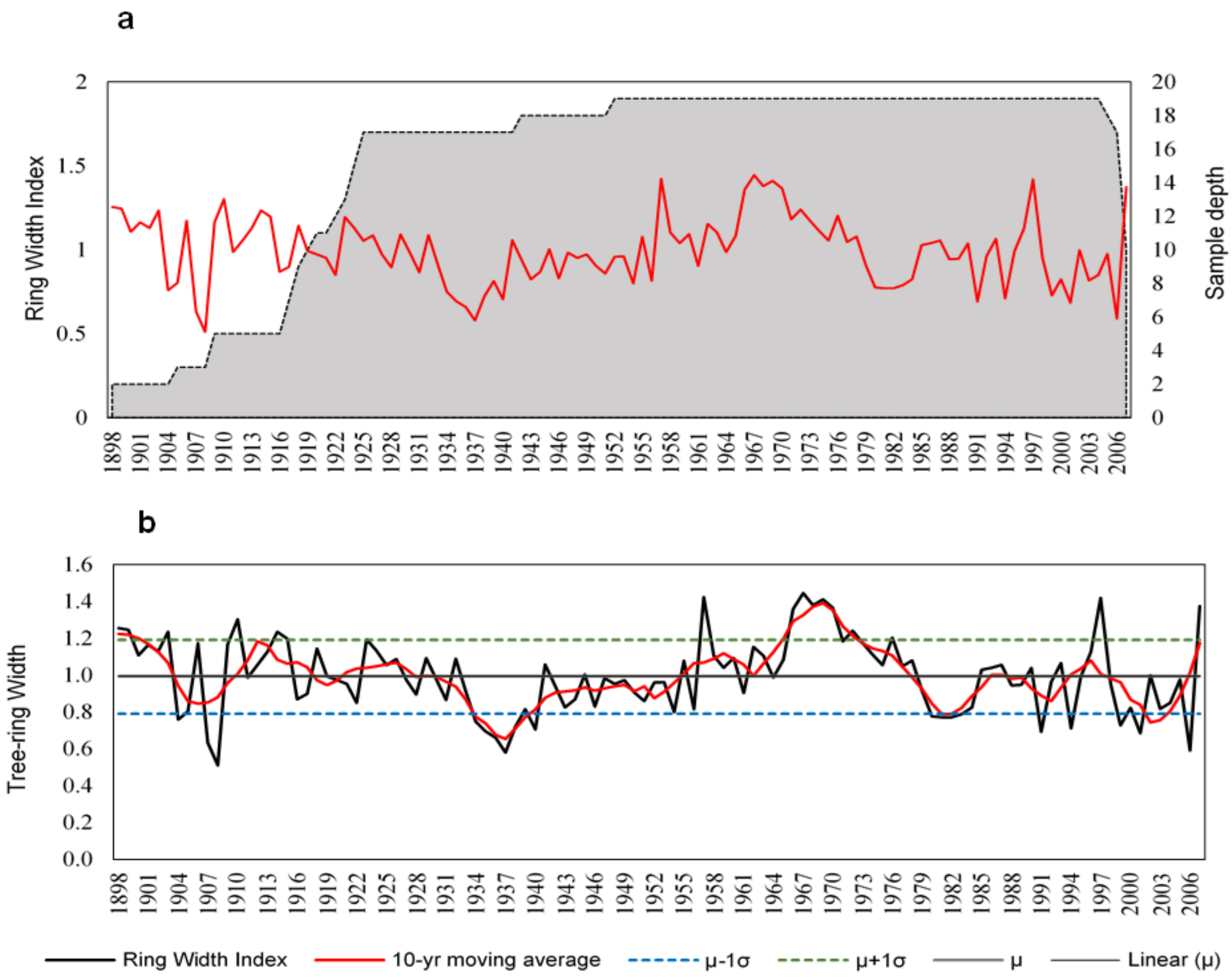

Fig. 3. (a) Raw and (b) standardized ring-width chronologies of *Juniperus excelsa* from the Hashtjin Mountains, Northwestern Iran (1898–2007). The shaded area represents sample depth. In (b), the ring-width index (black line), 10-year moving average (red line), mean (μ), and μ ± 1σ limits are shown.

Tree Growth-Climate Relationships

Climate-growth relationships for *J. excelsa* in the Hashtjin Mountains were studied to examine how climatic conditions affect its growth over time. Correlation functions were used to assess monthly relationships between tree-ring growth and climatic variables (precipitation, temperature, sc-PDSI) over a 12-month period from October of the previous year to September of the current year (Figs. 4a and 5a).

Significant positive correlations were found between ring-width and precipitation in April ($r = 0.26$, $p < 0.05$) and June ($r = 0.24$, $p < 0.05$) of the current growing year (Fig. 4a). This pattern reflects the importance of moisture availability during the early growing season for radial growth in this site and is consistent with observations from other juniper species in arid and semi-arid mountain environments, where sufficient moisture during cambial reactivation is critical for sustained annual growth (Zeng *et al.* 2020). Concurrently, a significant negative correlation was observed with April mean temperature ($r = -0.24$, $p < 0.05$), suggesting that warmer spring conditions exacerbate drought stress by increasing evapotranspiration demands (Lévesque *et al*. 2013).

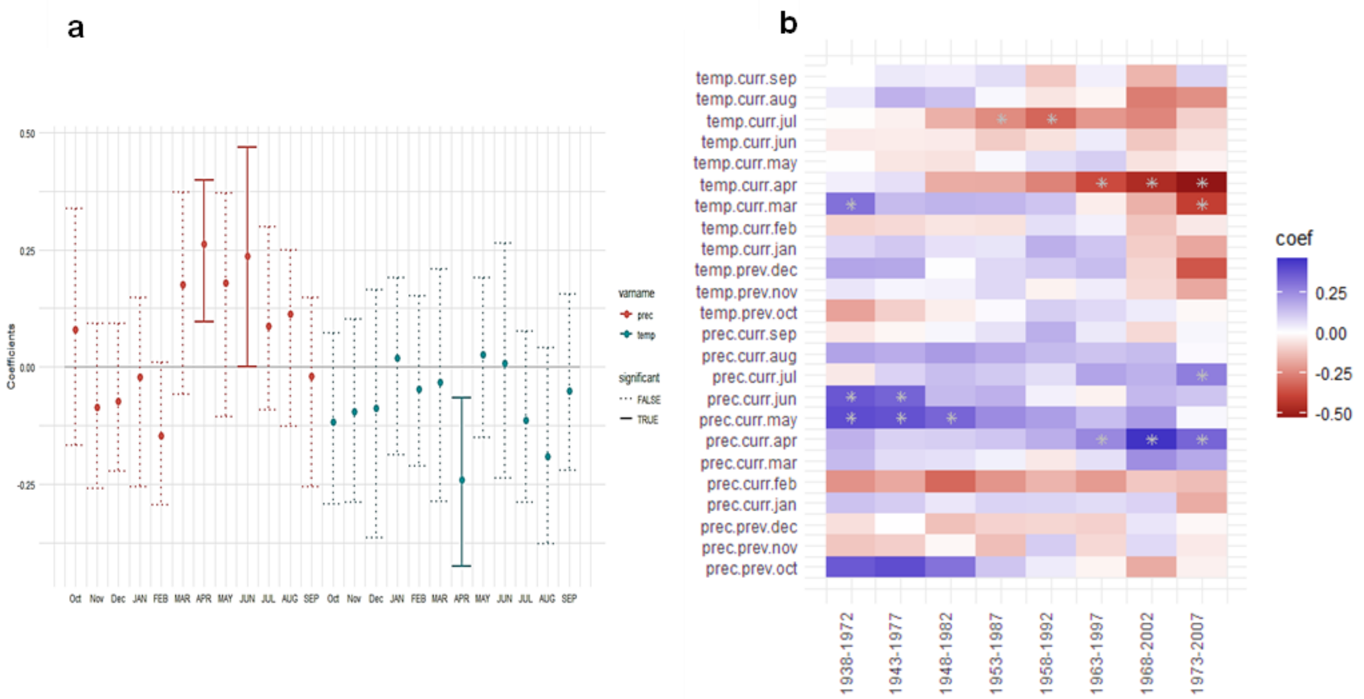

Fig. 4. Climate-growth relationships for *Juniperus excelsa* in the Hashtjin Mountains. (a) Monthly response function coefficients for the period 1930–2007. (b) Moving 35-year interval correlations between the tree-ring chronology and mean monthly climate variables. Solid lines and asterisks denote significant correlations ($p < 0.05$). Climate data were obtained from the CRU TS dataset, which provides continuous long-term coverage.

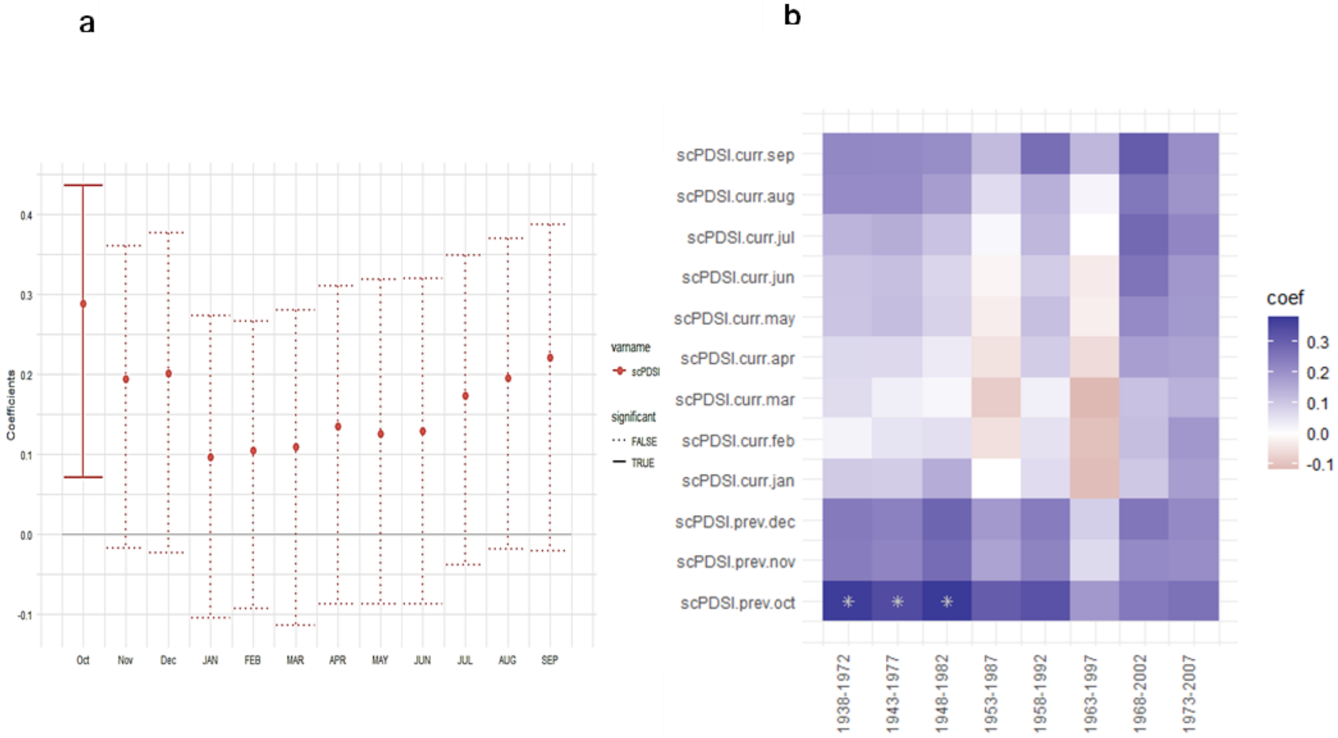

Fig. 5. Climate–growth relationships for *Juniperus excelsa* in the Hashtjin Mountains. (a) Monthly response function coefficients between the tree-ring index and sc-PDSI for the period 1930–2007. (b) Moving 35-year window correlations between the tree-ring chronology and mean monthly sc-PDSI. The color scale represents Pearson correlation coefficients, with red indicating positive and blue indicating negative relationships. Solid lines and asterisks denote statistically significant correlations ($p < 0.05$); significance indicates statistical robustness, not necessarily ecological or practical importance. Climate data were obtained from the CRU TS dataset, which provides continuous long-term coverage.

These findings align with the pioneering study by Liphschitz *et al*. (1979) on *J. polycarpos* in the Alborz Mountains. Of particular relevance is their Lake Rezaiyeh site (now Lake Urmia) in northwestern Iran, geographically closest to the present Hashtjin study area. At this site with annual precipitation greater than 450 mm, they reported significant positive correlations with summer temperatures (August–October, r=0.409 to 0.596), suggesting that in cooler environments, warmer summers may favor growth. In contrast, the present results from the Hashtjin site with annual precipitation near to 250 to 300 mm show stronger dependence on spring precipitation and negative responses to spring temperatures, indicating greater water stress.

Nearly five decades separate the two studies (1979 vs. 2026), a period during which Iran has experienced significant climate change. Long-term observations indicate that mean temperatures in Iran have increased by approximately 1.5 to 2.0 °C over the past 50 years, with the rate of warming accelerating in recent decades (Attarod *et al.* 2023; Fathian *et al.* 2022; Ghalhari *et al.* 2020). Specifically, Attarod *et al.* (2023) analyzed data from 104 synoptic stations across Iran over the 30-year period (1988 to 2017) and found that annual temperature significantly increased at about 61% of stations, while annual precipitation significantly decreased at 21% of stations, with the decline occurring mostly in dry and semi-dry regions. This warming has been accompanied by declining precipitation trends, particularly in northwestern Iran, where the frequency and intensity of drought events have increased substantially (Ghalhari *et al.* 2020). These climatic shifts may partially explain the differences in growth responses observed between the two study periods.

Moving-window correlation analysis revealed a persistently positive association between radial growth and May and June precipitation across several mid-20th-century windows (Fig. 4b). In contrast, a significant relationship with July precipitation emerged only in the most recent window, indicating a temporally variable climatic signal.

For temperature, a significant negative correlation with March mean temperature was evident across multiple windows (Fig. 4b). The negative correlation with April mean temperature was more pronounced in later periods, particularly from the mid-20th century onward, which is consistent with increased sensitivity of early-season growth to temperature-related moisture stress (Lévesque *et al.* 2013). Moreover, a significant positive correlation with July temperature was detected in some mid-century windows, which may relate to indirect effects on growing season length or cloud cover.

The observed temporal instability in climate–growth responses, particularly the time-dependent influence of July precipitation and variability in the strength of the April temperature signal, highlights the non-stationary nature of tree–climate relationships in this arid mountain environment (Carrer and Urbinati 2004; Babst *et al.* 2019). These findings underscore the importance of temporal context in dendroclimatic studies and the need to account for non-stationarity when interpreting tree–climate relationships.

Temporal Dynamics and Hydrological Constraints on Growth

To address the study objective concerning the seasonal and temporal stability of climate–growth relationships, the temporal dynamics of climate–growth relationships, the authors examined how moisture availability and temperature constrain radial growth across seasons and decades in *J. excelsa*. The moving window correlation analysis proved particularly valuable in revealing temporal shifts in climate–growth relationships that would be obscured by static correlation methods (Briffa *et al.* 1998; Shah *et al.* 2020). This approach confirmed that juniper growth in the Hashtjin mountains is predominantly constrained by moisture availability, a pattern consistent with semi-arid ecosystems globally (Meko 2006; Porter *et al.* 2013; Welsh *et al.* 2019).

The analysis highlighted a significant, sustained sensitivity to summer (July) precipitation alongside negative correlations with temperature (Fig. 4b), identifying drought stress as the primary limitation on summer growth. A clear statistical signal of summer moisture limitation is indicated by these correlations. These correlations are consistent with physiological mechanisms whereby higher temperatures can increase atmospheric water demand and exacerbate moisture limitation, as documented in previous studies (Williams *et al.* 2013; Young *et al.* 2017). During the arid late summer, elevated temperatures further exacerbate this hydraulic stress, potentially suppressing cambial activity (Feeley *et al.* 2007).

Growth was also strongly influenced by conditions in the preceding autumn and the following spring. Climate variables from the previous autumn were included to account for potential carry-over effects of soil moisture storage, which can influence cambial reactivation and early-season growth even when direct correlations are weak or temporally variable. In this context, a significant positive association with the October sc-PDSI from the previous year, together with persistent correlations across multiple moving windows (Fig. 5), underscores the critical role of autumn soil moisture recharge in supporting the subsequent growing season (Shi *et al.* 2018; Szeicz and MacDonald 1996). From a mechanistic viewpoint, warmer early-season temperatures intensify moisture stress. While mild March temperatures can stimulate growth initiation, they may also promote premature snowmelt, reducing water availability during critical early growth stages (Chen *et al.* 2015; Hannak and Eggertsson 2020). The consistent negative correlation with April temperatures reinforces this hydrological control.

At a wider regional scale, in the context of northwestern Iran, where June to August is the driest period (Fig. 1b), juniper growth has remained persistently sensitive to precipitation in these critical months across multiple decades. The more pronounced negative correlation with April temperature in recent windows suggests an increased sensitivity to early-season moisture stress under warmer conditions. Such climatic stress can directly manifest as reduced radial growth, missing rings, and increased tree mortality (Liu *et al.* 2013; Allen *et al.* 2015). Collectively, these findings indicate that Iran's juniper ecosystems may be sensitive to drought stress under warming conditions.

Pointer Years and Extreme Growth Events

To evaluate the temporal occurrence and methodological coherence of extreme growth events (Objective 2(ii)), pointer years were identified using four independent analytical methods: Normalization in a Moving Window (NW), Relative Growth Change (RGC), Extreme Chronology Values (zChron), and Interval Trend (IT). Each approach captures different expressions of markedly elevated or suppressed radial growth.

The NW method (threshold: |C_Cropper| > 0.75) identified 11 significant event years between 1898 and 2007, with a limited number of significant positive and negative pointer years primarily clustered in the early 20th century and the late 1990s (Table 2). The zChron method (threshold: |1.0| standard deviation) identified a broader range of positive and negative pointer years compared to the other approaches, reflecting its higher sensitivity to extreme deviations in the standardized chronology (Table 2).

The RGC method detected only one major positive event in 2007, with no significant negative event years. The IT method, which assesses synchronous growth changes across the tree population, highlighted several periods of widespread growth decline and increase, particularly during the early 20th century and in 2007 (Table 2).

Table 2. Comparison of Negative and Positive Pointer Years Identified by the IT, RGC, NW, and Zchron Methods

Method	**Negative event year**	**Positive event years**
NW (Cropper)	**1904**-1905, **1907-1908**, 1922, 1991, **2001**	**1906**, **1910**, **1914**, **1997**
RGC	-	**2007**
zChron	**1904**, **1907-1908**,1934-1938, 1940, 1980-1983, 1991, 1994, **2001**, 2006	1898,1899, 1903, **1910**, 1914, 1957, 1966-1970, 1972, 1976, **1997**, **2007**
IT	1899-1900, 1902, **1904**, **1907-1908**, 1915	1901, 1903, 1905-**1906**, 1909-**1910**, 1923, **2007**

Note: Years detected by multiple methods are highlighted in bold.

Across all methods, only a limited set of years was consistently identified, indicating robust extreme growth events within the chronology. Notably, the years 1907–1908 were consistently detected as negative pointer years by the NW, zChron, and IT methods, while 1910 and 1997 emerged as coherent positive pointer years across multiple approaches. Overall, despite differences in sensitivity among methods, convergence across multiple approaches highlights a small subset of years as robust benchmarks of extreme growth variability within the chronology.

Synthesis of Pointer Years and Regional Climatic Context

For regional synthesis, the integration of results from four independent detection methods through methodological triangulation revealed a limited set of robust pointer years, substantially enhancing confidence in the identified extreme growth events.

The years 1907–1908 emerged as the most pronounced negative pointer years, having been identified consistently by three independent methods. Other significant negative events confirmed by multiple approaches include 1904, 1922, and 2001. Conversely, the most reliable positive pointer years were 1910, 1914, and 2007, each showing convergence across multiple methods (Table 2). This multi-method convergence indicates that these years represent the most significant growth anomalies in chronology. From a climatic perspective, these anomalies were likely driven by major climatic extremes that overwhelmed tree-specific growth variations (Neuwirth *et al.* 2007; Jetschke *et al.* 2019).

To further contextualize the proposed use of pointer years, the authors digitized the master chronology for the Lake Urmia site (formerly Lake Rezaiyeh) from Fig. 4 of Liphschitz *et al.* (1979) using Web PlotDigitizer software. This site, located in northwestern Iran (45°15′E, 38°15′N), is geographically closest to our Hashtjin study area. Although the digitized data are approximate and contain gaps, they provide the only available long-term juniper chronology from the region for qualitative comparison.

A qualitative comparison between the presently determined pointer years (Table 2) and extreme growth years in the Liphschitz *et al.* (1979) chronology reveals both. The positive pointer year 1910 identified in the present study corresponds to a high growth value (index = 1.218) in the Lake Urmia record, and the negative pointer year 1936 aligns with a very low growth value (index = 0.540). These agreements suggest that some extreme events, such as the 1936 drought, had regional impacts detectable across different sites and climatic contexts. This finding is consistent with historical agricultural archives from the Ardabil and Khalkhal regions, which document favorable growing conditions and increased tax revenues during the early 1910s, reflecting above-average spring precipitation in northwestern Iran (National Archives of Iran 1911).

The negative pointer year 1936 aligns with a very low growth value (index = 0.540) in the Lake Urmia record, corroborating extensive historical documentation of severe drought across Iran during 1935 to 1937. Contemporary government reports and foreign diplomatic dispatches describe this period as one of acute water shortage, crop failure, and rural distress throughout Azerbaijan, including areas adjacent to the present study site (Ambraseys and Melville 1982; National Archives USA 1936). The partial agreement between current study with *Liphschitz et al.* (1979), and convergence of tree-ring evidence with multiple independent historical sources underscore the value of expanding dendrochronological networks across environmental gradients to better understand species responses to climate variability.

The chronology shows remarkable spatial coherence with documented historical climatic events across West Asia and the Eastern Mediterranean. For example, the negative pointer year 1899 aligns with recorded dry conditions in Turkey and Cyprus (D'Arrigo and Cullen 2001; Griggs *et al.* 2014). The 1904 drought corresponds to historical accounts of famine and ecological stress in Anatolia and neighboring regions (Akkemik and Aras 2005; Akkemik *et al.* 2005). The strong negative signal observed for 1907–1908 has been similarly identified in dendroclimatic studies across Iran, Turkey, and the Caucasus (Arsalani *et al.* 2018; Touchan *et al.* 2005; Solomina *et al.* 2005), suggesting a widespread climatic anomaly. Likewise, the 1922 drought aligns with severe historical drought conditions documented in Iran (De Planhol 2012) and supported by multiple Asian-scale reconstructions (Fan *et al.* 2008; Nadi *et al.* 2017; Cook *et al.* 2010). Finally, the 1935–1936 negative pointer years correspond to drought signals reconstructed from juniper in Turkey (Touchan *et al.* 2005) and oak in Greece (Klippel *et al.* 2018).

More recently, the negative pointer year 1999 matches documented drought conditions in southeastern Europe (Levanic *et al.* 2009) and the Levant (Touchan *et al.* 2008), while the positive year 2007 aligns with favorable growth conditions reported for Turkey (Akkemik and Aras 2005). This spatiotemporal coherence validates the climatic sensitivity of the *J. excelsa* chronology and highlights the regional synchronicity of major hydroclimatic events. The consistency of growth anomalies across political and geographical boundaries underscores the influence of large-scale atmospheric circulation patterns, likely associated with North Atlantic and Mediterranean dynamics (Touchan *et al.* 2005; Luterbacher *et al.* 2004), which can synchronize tree-growth responses across this climatically sensitive region.

Methodological Insights into Pointer Year Detection

The variation in pointer years identified by different methods reflects their distinct analytical sensitivities, with each approach emphasizing a different type of growth anomaly. Some methods are more responsive to extreme departures from long-term mean conditions, while others capture highly synchronous population-wide signals or highlight abrupt, tree-level fluctuations in growth relative to recent trends. These differences naturally lead to variation in the set of years identified as pointer years.

Methodologically, this explains why severe, widespread events such as 1907–1908 are consistently detected across methods, whereas other years are method-specific, reflecting different facets of tree-growth response. This multi-method approach, supported by established dendrochronological practice (Schweingruber *et al.* 1990; Neuwirth *et al.* 2007), enables a more robust and nuanced identification of pointer years by integrating population-level synchrony with individual-tree sensitivity, thereby providing a sound methodological basis for subsequent growth–climate analyses presented elsewhere in the study.

To achieve a more comprehensive understanding of long-term climate dynamics in northwestern Iran, future research should prioritize expanding the dendrochronological network. Extending chronologies to greater lengths and increasing spatial coverage across different elevations and exposures will be essential for developing robust paleoclimatic reconstructions and improving predictions of forest responses to future climate change.

CONCLUSIONS

1. This study developed a 110-year tree-ring width chronology of *J. excelsa* from the Hashtjin Mountains in northwestern Iran. Despite its relatively limited temporal extent, the chronology demonstrates strong analytical quality, as reflected by robust statistical characteristics, and shows moderate to high mean sensitivity, indicating a pronounced responsiveness of radial growth to interannual climatic variability.
2. Growth–climate relationship analyses reveal that juniper growth at this high-elevation, semi-arid site is predominantly controlled by moisture availability. Significant positive correlations with current-year precipitation in late spring and early summer (April and June), together with a significant negative response to April temperatures, emphasize the importance of early-season water stress as a key limiting factor for radial growth.
3. The identification of pointer years using multiple independent approaches (IT, RGC, NW, and zChron) resulted in a coherent set of extreme growth years that are consistent across methods. Major drought events, particularly those recorded during 1907–1908 and 2001, were robustly detected and show strong agreement with independent historical drought evidence. This methodological convergence confirms the reliability of the climatic signal preserved in chronology and supports the interpretation of these years as regionally significant hydroclimatic extremes, consistent with large-scale atmospheric influences affecting West Asia.
4. To achieve a more comprehensive understanding of long-term climate dynamics in northwestern Iran, future research should prioritize expanding the dendrochronological network. Extending chronologies to greater lengths and increasing spatial coverage across different elevations and exposures will be essential for developing robust paleoclimatic reconstructions and improving predictions of forest responses to future climate change.

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