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Spatial Distribution and Climatic Sensitivity of Juniper Forests in the Cold-Arid Ladakh, North-western Himalaya, India

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Abstract: The cold arid Ladakh region in the north-western Himalaya represents one of the most extreme environments, where low precipitation, harsh temperatures, and a short growing season constrain vegetation growth. *Juniperus polycarpos* C. Koch is a main conifer species in this region, forming sparse woodlands and isolated stands between 3,200 and 4,400 m asl. Its longevity, slow growth, and sensitivity to environmental stress make it well-suited for dendroclimatic studies. In this study, we examined the distribution, ecological traits, and climatic growth response of *J. polycarpos* in Ladakh. Tree-ring samples were collected from climatically stressed sites in Kargil and Leh districts of Ladakh, and standard dendrochronological techniques were applied to develop robust ring-width chronologies. Tree-growth-climate analysis indicates that radial growth is primarily influenced by moisture availability, showing positive correlations with May precipitation and negative responses to May temperature. High mean sensitivity and strong inter-series correlation demonstrate the suitability of *J. polycarpos* for high-resolution climatic studies. These findings emphasize its value as a dendroclimatic archive in the data-scarce cold deserts of the Himalaya and provide insights into forest responses to ongoing climate change.

Key words: Tree-rings, high-altitude, precipitation, climate change, hydroclimate variability, Ladakh, India.

The Ladakh region, extending between 32°15′-36°N and 75°15′-80°15′E, lies on the western flank of the Himalaya. The area is traversed by four major mountain ranges: the Greater Himalaya, Zanskar, Ladakh, and Karakoram. Characterized by a cold desert climate, Ladakh spans a wide altitudinal range from ~3000 to 7680 m above msl (Kala and Mathur, 2002). This pronounced elevational gradient exerts a strong control over key environmental parameters, including temperature regimes, precipitation patterns, solar (UV) radiation intensity, wind dynamics, atmospheric pressure, and duration of snow cover (Körner, 2007). The Ladakh region receives extremely low annual precipitation, generally less than 100 mm in the form of snowfall or rainfall, and experiences severe winters with temperatures frequently dropping to ~ -30°C to -40°C (Dvorskŷ *et al.*, 2011; Kala and Mathur, 2002). The environment is further characterized by very low relative humidity (<30%), reduced oxygen availability, reduced atmospheric pressure, and intense solar irradiance, all of which make the region highly inhospitable to life (Murugan *et al.*, 2010). Despite these extreme climatic constraints, Ladakh supports a remarkable diversity of vascular plant species, reflecting the resilience of its flora (Kala, 2011; Klimeš and Dickoré, 2006; Shukla and Srivastava, 2020). Survival in such environments is enabled by a suite of adaptive strategies, in which plants undergo significant morphological, physiological, and genetic modifications that enhance tolerance to cold, drought, and high radiation stress (Liu *et al.*, 2014; Qi *et al.*, 2020).

The Himalayan pencil cedar (*Juniperus polycarpos*) is a slow-growing evergreen conifer distributed across the dry, high-altitude regions of Afghanistan, Baluchistan, the Kagan Valley, Kashmir, Lahaul-Spiti, and parts of western Tibet (Sahni, 1990). In the western Himalaya, the species commonly occurs on exposed slopes and valley bottoms where moisture availability is low and climatic conditions are harsh. Trees usually grow in open and scattered stands, reflecting limited interspecific competition and adaptation to nutrient-poor environments. The species is characterized by irregular stem growth, often showing lobed trunks that produce wedged or incomplete growth rings (Sahni, 1990). This growth pattern is associated with strong climatic control on radial growth, particularly under drought-dominated conditions. Due to its exceptional tolerance to environmental stress and very slow growth rate, *J. polycarpos* is regarded as the longest-living tree species in India (Yadav, 2012). Its longevity and clear climatic sensitivity make it especially valuable for dendrochronological and paleoclimatic investigations in the western Himalaya.

Previous dendrochronological research on Juniper species in Central Asia and the western Himalaya has shown that tree growth is closely linked to hydroclimatic factors, particularly precipitation and temperature (Esper *et al.*, 2002; Sheppard *et al.*, 2004; Yadav, 2012; Yadav *et al.*, 2006, 2011; Managave *et al.*, 2020; Misra *et al.*, 2020). Despite this, comprehensive, region-specific studies on the distribution and climatic sensitivity of *J. polycarpos* in Ladakh remain lacking. Understanding the environmental controls on tree growth in this region is especially important in view of ongoing climate change, glacier retreat, and concerns over water resources in the Himalaya. In this context, the present study aims to: (i) document the spatial distribution and ecological characteristics of *J. polycarpos* across the Ladakh Himalaya, (ii) develop reliable tree-ring chronologies from climatically sensitive sites, and (iii) examine growth-climate relationships to identify the key climatic drivers for radial growth of trees. Besides the climatic sensitivity, *J. polycarpos* is widely used by local communities for fuel, ritual incense, and traditional medicine, reflecting its strong cultural importance, especially in Buddhist practices.

Materials and Methods

Study Area and Tree-Ring Sampling

The Ladakh region of the north-western Himalaya is characterized by a cold-arid climate, rugged topography, sparse vegetation, and shallow coarse-textured soils with low organic matter content (Gupta and Arora, 2017). Natural vegetation is dominated by alpine steppe communities, xerophytic shrubs, and scattered woodland patches. *Juniperus polycarpos* occurs mainly between ~3,200 and 4,400 m above sea level, often on exposed slopes and valley bottoms under moisture-limited environmental conditions. The species is commonly associated with drought-tolerant taxa such as *Caragana versicolor*, *Artemisia brevifolia*, *Hippophae rhamnoides*, and *Acantholimon lycopodioides* (Kumar *et al.*, 2016; Shah, 2014; Hussain *et al.*, 2024; Dolma and Uniyal, 2025; Angmo *et al.*, 2025).

Extensive field surveys were conducted in different parts of Ladakh, including the Akchamal, Hunderman, and Ganasok regions of Kargil district and the Hemis Shukpachan region of Leh district (Fig. 1). Sampling sites were selected from climatically stressed habitats where tree growth is likely to be strongly influenced by hydroclimatic variability. Mature and dominant trees of *J. polycarpos* showing healthy stems and minimal visible disturbance were selected for sampling (Fig. 2).

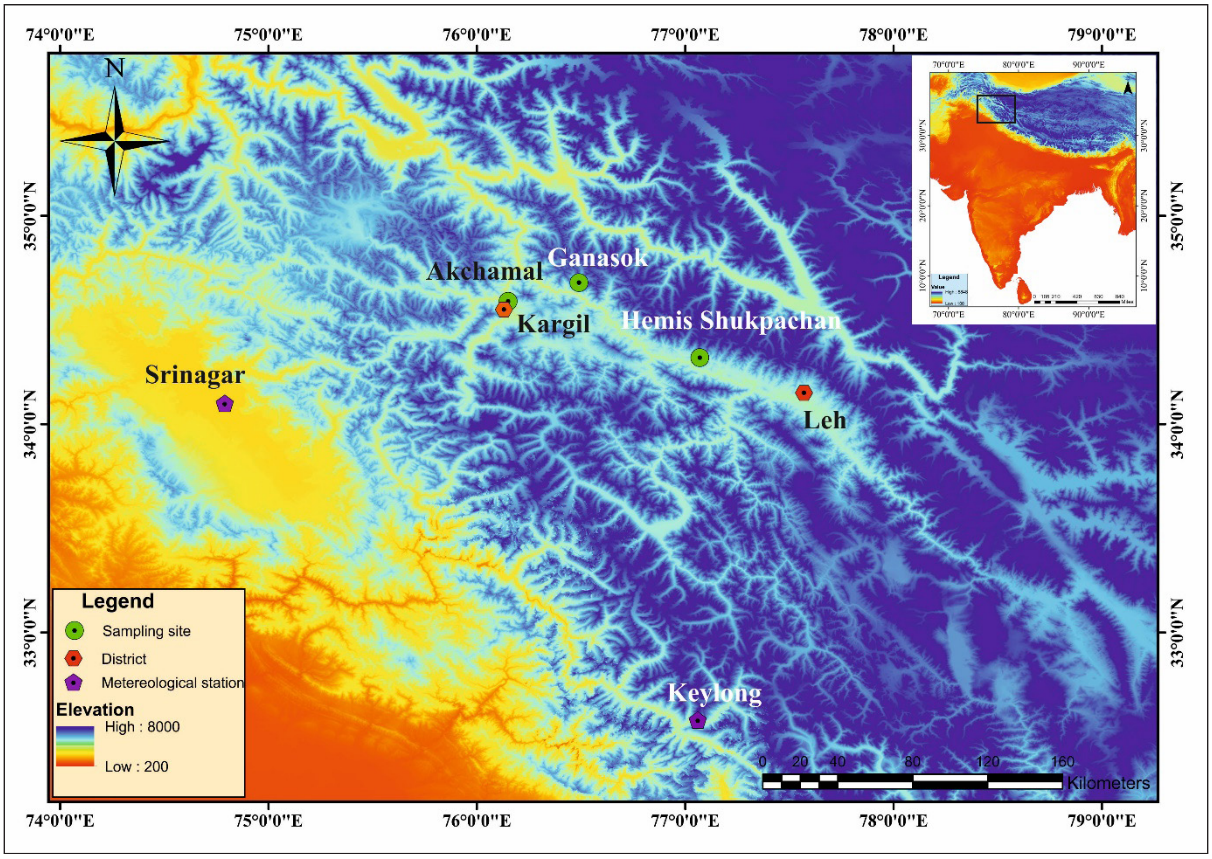

Fig. 1. Map showing the location of tree-ring sampling sites and meteorological stations used in the present study, along with major locations in Ladakh.

Increment cores were extracted at breast height (~1.4 m above ground level) using standard increment borers. In cases where coring was not feasible because of stem irregularities or deadwood availability, cross-sections/discs were collected from naturally fallen or anthropogenically cut trees. All sampling procedures followed standard dendrochronological protocols to minimize damage to living trees.

A total of 121 samples, including increment cores and discs, were collected during the study. Of these, 34 samples representing 25 trees were obtained from Akchamal, 64 samples

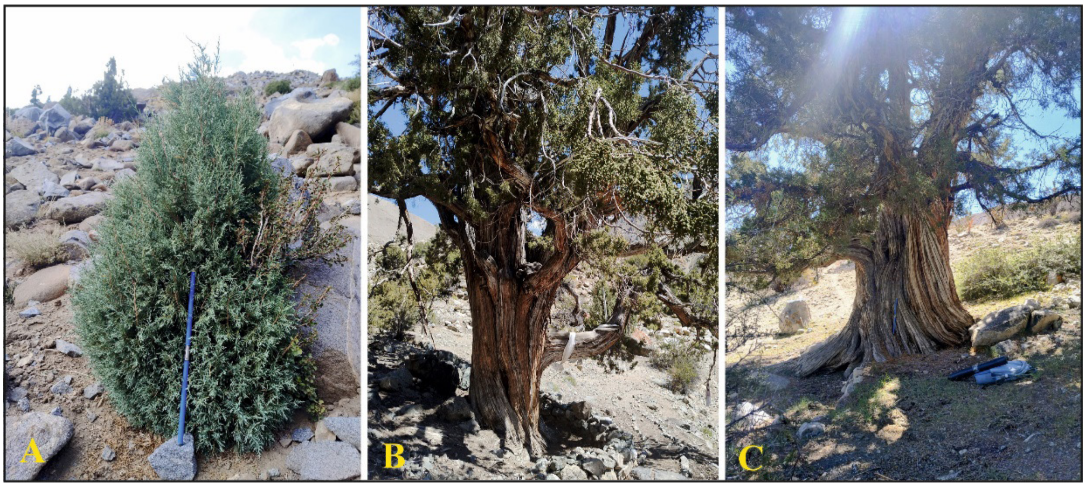

Fig. 2. Age structure of sampled trees across sites, showing (A) juvenile-dominated stands at Akchamal and (B and C) comparatively older, mature trees at Hemis Shukpachan and Ganasok.

from 30 trees from Ganasok, and 23 samples from 15 trees from Hemis Shukpachan. Trees sampled at Akchamal were generally younger and represented juvenile stands, whereas those from Ganasok and Hemis Shukpachan were comparatively older and more mature (Fig. 2). Additional occurrences of *J. polycarpos* were observed in the Baru and Hunderman regions, indicating the wider distribution of the species across high-altitude cold-arid environments of Ladakh.

Sample preparation and ring-width measurement

Collected increment cores and cross-sections were air-dried, mounted on wooden supports with the transverse surface exposed, and progressively sanded using increasingly finer grades of sandpaper (220-400 grit) until annual growth rings became clearly distinguishable. Ring widths were measured along selected radii using a computer-assisted measuring system with a precision of 0.01 mm.

Cross-dating was initially performed visually by identifying and matching characteristic narrow and wide ring patterns among individual samples and by detecting common pointer years (Stokes and Smiley, 1968; Fritts, 1976). The visual dating was subsequently verified statistically using the COFECHA program (Holmes, 1983) and TSAP software (Rinn, 1996). Samples showing poor correlations or dating inconsistencies were carefully re-examined and corrected, and only accurately dated series were retained for chronology development.

Chronology development

To isolate the climatic signal from age-related and non-climatic growth trends, tree-ring series were standardized using the ARSTAN program. Prior to detrending, an adaptive power transformation was applied to stabilize variance across individual series. Detrending was then carried out using a cubic smoothing spline with a 50% frequency response cutoff at two-thirds of the series length. This procedure removed long-term biological growth trends while preserving high-frequency interannual variability associated with climate.

Standardized ring-width series were averaged using a biweight robust mean to minimize the influence of outliers and to develop representative site chronologies suitable for dendroclimatic analysis. Chronology statistics, including mean sensitivity and inter-series correlation, were calculated to evaluate the strength of the common climatic signal and the year-to-year variability in radial growth.

Climate data and tree-growth analysis

To assess the climatic sensitivity of *Juniperus polycarpos*, tree-growth-climate relationships were examined using bootstrap correlation analyses implemented in the DENDROCLIM2002 program (Biondi and Waikul, 2004). Monthly temperature and precipitation data from the nearest long-term meteorological stations at Srinagar (34°08′N, 74°48′E) and Keylong (32°58′N, 77°06′E), respectively, were used for the analysis.

Climate-growth relationships were evaluated over a 12-month window extending from October of the previous year to September of the current growth year in order to capture both carry-over effects from the preceding winter season and climatic influences during the active growing period. Bootstrap correlation analysis was used to identify statistically significant relationships between radial growth and monthly climatic variables. Particular emphasis was placed on evaluating the influence of spring temperature and precipitation on cambial activity and early-season growth in the cold-arid environment of Ladakh.

Results and Discussion

Distribution and stand characteristics

Juniperus polycarpos exhibits an irregular and patchy distribution across the cold-arid landscapes of Ladakh, where its occurrence is largely confined to microsites with relatively higher moisture availability. The species typically occurs either as sparse open woodlands or as scattered isolated individuals on exposed slopes and valley margins. Such discontinuous distribution patterns reflect the severe environmental constraints operating in the region, including extremely low precipitation, prolonged winter freezing, strong winds, shallow soils, and a short growing season. These harsh conditions considerably restrict seed germination, seedling establishment, and stand expansion.

The sampled trees are characteristically slow-growing, as indicated by narrow annual rings,

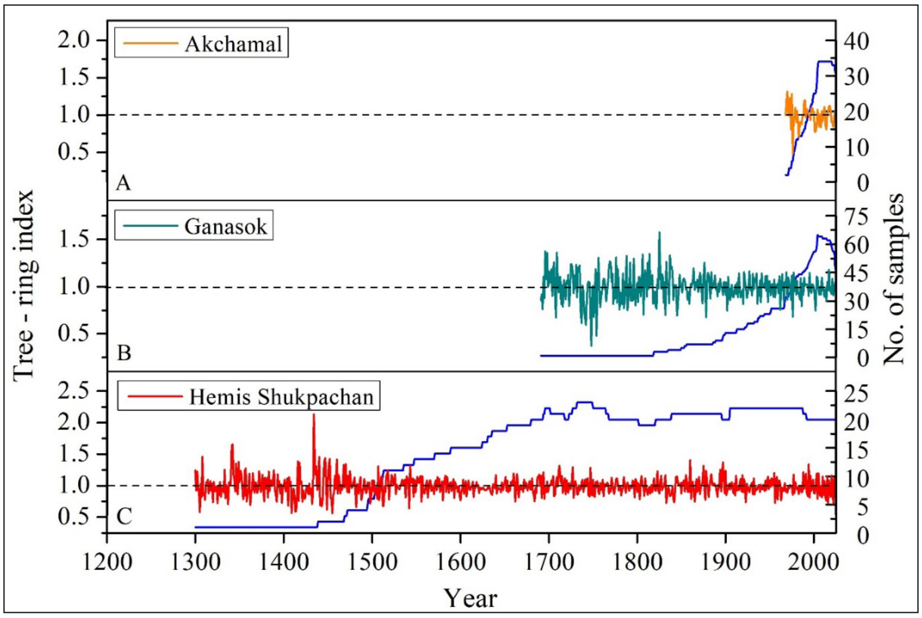

Fig. 3. J. polycarpos tree-ring chronologies from the different sampling sites, along with the number of samples used in the study (A) Akchamal (AD 1968-2024), (B) Ganasok (AD 1691-2024), and (C) Hemis Shukpachan (AD 1300-2024).

irregular stem morphology, and lobed trunk structures. Such growth features are typical of trees growing under persistent climatic stress and moisture limitation. The dominance of older trees and the comparatively poor representation of younger individuals at several sites further suggest limited regeneration under the present climatic regime. Similar observations have been reported for high-altitude juniper populations from other parts of the western Himalaya and Central Asia, where growth and regeneration are strongly constrained by hydroclimatic stress and low-temperature conditions. The observed stand characteristics therefore indicate that even small changes in local moisture availability and temperature may substantially influence the long-term survival and regeneration dynamics of *J. polycarpos* populations in Ladakh.

Chronology Characteristics and Growth Variability

Tree-ring chronologies of *J. polycarpos* were successfully developed from three high-elevation sites in Ladakh to investigate long-term growth variability and climatic sensitivity (Fig. 3). The chronologies differ considerably in temporal coverage, reflecting differences in stand age structure and tree longevity among sites.

The Akchamal chronology extends from AD 1968 to 2024 and mainly represents recent growth variability under contemporary climatic conditions. In contrast, the Ganasok chronology spans 334 years (AD 1691-2024), providing information on multi-decadal to centennial-scale growth variability. The Hemis Shukpachan chronology is the longest, extending over 725 years (AD 1300-2024), and constitutes one of the longest dendrochronological records presently available from the cold-arid north-western Himalaya.

The long temporal coverage of the Ganasok and Hemis Shukpachan chronologies highlights the exceptional longevity and climatic sensitivity of *J. polycarpos* under high-altitude arid conditions. These long-lived chronologies provide an important archive for examining long-term hydroclimatic variability, extreme climatic events, and environmental changes over several centuries.

The chronology statistics further demonstrate the suitability of *J. polycarpos* for dendroclimatic investigations. Mean sensitivity values are relatively high for all three chronologies (Akchamal: 0.181; Ganasok: 0.171; Hemis Shukpachan: 0.169), indicating pronounced year-to-year variability in radial growth and a strong response to interannual climatic fluctuations. Moderate inter-series correlation values (Akchamal: 0.401; Ganasok: 0.403; Hemis Shukpachan: 0.412) indicate the presence of a coherent common growth signal among individual trees within each site, suggesting that regional climatic forcing exerts a strong control on radial growth patterns.

The comparatively higher mean sensitivity observed at Akchamal may reflect the greater responsiveness of younger trees to short-term climatic variability, whereas the slightly lower values at Ganasok and Hemis Shukpachan probably indicate greater growth stability in older and mature trees. Nevertheless, all chronologies retain a sufficiently strong climatic signal for assessing tree-growth-climate relationships in the cold-arid environment of Ladakh.

Tree-Growth-Climate Relationships

Analyses revealed that radial growth of *J. polycarpos* is strongly controlled by hydroclimatic conditions during the early growing season. Tree growth shows a positive relationship with precipitation, particularly during May, whereas higher temperatures during the same period exert a negative influence on radial growth (Fig. 4). These relationships indicate that moisture availability at the onset of the growing season is a major limiting factor for cambial activity and wood formation in the cold-arid environment of Ladakh.

In high-altitude cold deserts, winter snowfall and spring precipitation constitute the principal sources of soil moisture available for early-season growth. Increased precipitation during May likely enhances snowmelt and improves soil water availability, thereby promoting cambial reactivation and earlywood formation. Conversely, elevated temperatures during spring may increase evapotranspiration rates and accelerate soil moisture depletion, resulting in enhanced drought stress during a physiologically sensitive period of growth initiation.

Bootstrap correlation analysis further indicates that precipitation exerts a generally positive influence on radial growth during most months, although negative or weak relationships occur during October of the previous year and February and August of the current growth year. Among all climatic variables, May precipitation shows the strongest positive influence on tree growth. In contrast, temperature displays predominantly negative correlations during March, April, May, June, and September, with May temperature showing a statistically significant negative effect on radial growth.

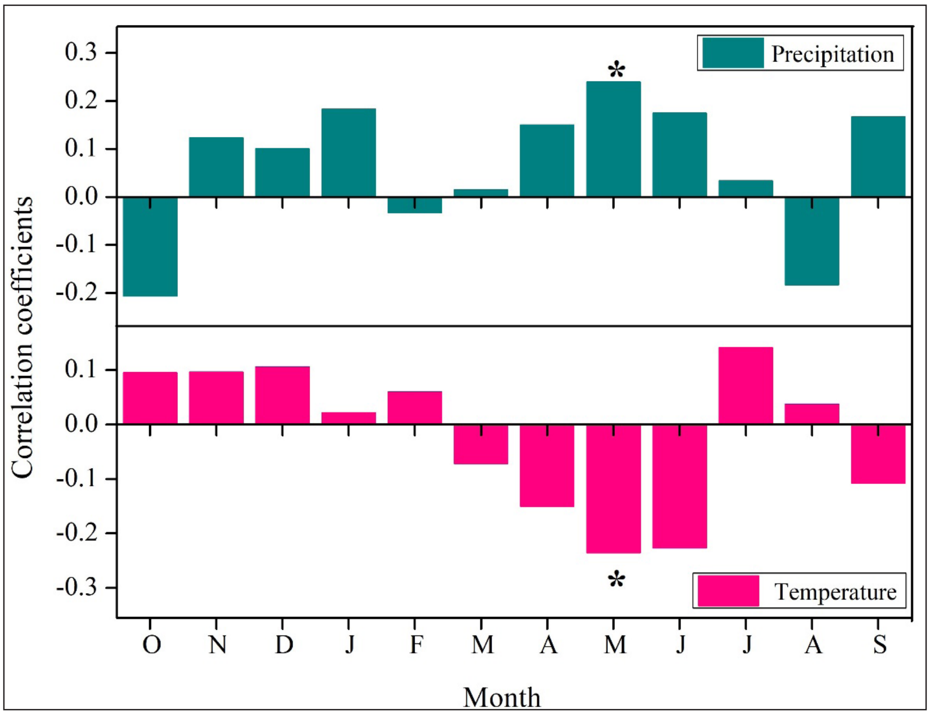

Fig. 4. Bootstrap correlation analysis between the tree-ring chronology and climate variables, including monthly precipitation from Keylong and temperature from Srinagar. Asterisks indicate significance at the 95% confidence level.

These results collectively suggest that cool and moist conditions during spring are essential for sustaining radial growth of *J. polycarpos* in Ladakh. The observed climatic sensitivity is likely associated with snowmelt-driven moisture dynamics, where increased spring precipitation and lower temperatures enhance soil moisture availability and nutrient mobilization, thereby supporting cambial activity and early-season xylem development. Similar growth responses have been reported for juniper species from other moisture-limited regions of the Himalaya and Central Asia, where tree growth is primarily regulated by the balance between spring temperature and moisture availability.

The strong dependence of *J. polycarpos* growth on spring hydroclimatic conditions also indicates its vulnerability to future climatic warming in the Himalaya. Rising temperatures accompanied by reduced snow accumulation or accelerated snowmelt may intensify moisture stress during the growing season, potentially affecting growth, regeneration, and long-term stand persistence in these fragile cold-arid ecosystems.

Conclusions

The study demonstrates that the tree growth of *J. polycarpos* in the cold arid region of Ladakh is strongly controlled by moisture availability at the beginning of the growing season. The developed chronologies, ranging from 57 years at Akchamal (AD 1968-2024) to 334 years at Ganasok (AD 1691-2024) and 725 years at Hemis Shukpachan (AD 1300-2024), collectively capture growth responses across multiple temporal scales. Bootstrap correlation analyses reveal a consistent positive relationship between radial growth and May precipitation, while higher May temperatures exert a negative influence on growth. These findings highlight the critical importance of early-season moisture supply, likely mediated through snowmelt and soil moisture availability, in regulating cambial activity and earlywood formation. In contrast, elevated temperatures during May appear to intensify evapotranspiration and moisture stress, thereby constraining growth during a sensitive phase of the growing season. Overall, the long-term chronologies provide valuable insights into climate-growth relationships in this climatically sensitive Himalayan region and underscore the vulnerability of high-altitude juniper forests to ongoing and future climatic warming. Such findings can contribute to better climate adaptation strategies, informed conservation practices, and the long-term management of cold-arid forests.

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Competing Interests

The authors declare no competing interests.

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