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Himalayan fir growth in central Bhutan reflects variability in temperature and precipitation

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Abstract: Mountain ecosystems, especially those at the highest altitudes, are sensitive to current climate change. Proxy archives may provide an insightful tool to better understand ongoing changes and evaluate future scenarios. Trees have traditionally been used as such archives, as they often respond sensitively to environmental change. Thus, we studied tree-ring records of forest-line species *Abies densa* Griff. growing in the Eastern Himalayas, central Bhutan, to evaluate the effect of climate on the growth of this species. The annual chronologies were generated using standard dendrochronological methods and then compared with climatic data from the CRU TS database. The results demonstrate a negative effect of summer temperatures on the width of the annual rings, suggesting possible stress caused by higher temperatures during the monsoon season. On the other hand, a positive effect of temperatures on tree growth was observed during late winter months. The response to rainfall was mixed, with a positive effect on growth in November and a negative effect in May and January, suggesting a later onset of the vegetation season. To our knowledge, we present the first dendroclimatological study on this long-lived species in central Bhutan, portraying its potential for future climate and environmental research and applications.

Keywords: *Abies densa* Griff.; dendrochronology; dendroclimatology; Eastern Himalayas; tree rings

The Himalayas represent one of the natural systems most vulnerable to ongoing climate change. Climate change here, compared to the global average, is intense, with average temperatures in many areas rising by up to 1.2 °C per decade since the early 20th century (Singh et al. 2016). As temperatures rise, mountain vegetation migrates to higher elevations, potentially leading to species loss even before scientific description (Tewari et al. 2017). The most significant warming takes place in winter months and at higher altitudes (Dimri et al. 2018). Changes in temperature and precipitation regimes are manifested unevenly across the Himalayas. The central and eastern Himalayas show glacier

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retreat and an increase in average temperatures; in contrast, the northwestern parts show relative glacier stability and even local cooling during the summer months (Singh et al. 2016). Mountain ecosystems in the Himalaya represent a natural environment key to the ecological stability and socio-economic development of large areas of South Asia. They provide many essential ecosystem services, including fresh water supply, food, medicinal plants, energy and biodiversity (Tewari et al. 2017). Despite being such an important component of local livelihood stability, these ecosystems have not been robustly evaluated for their vulnerability to climate change. Where climate constraints allow, woody species are typically dominant in the most successionally developed ecosystems. At the same time, they provide the aforementioned ecosystem services, including timber for local consumption. Therefore, trees have played a pivotal role in community development and securing well-being. Understanding the impacts of climate change and the drivers of tree growth thus enables the evaluation of the future role of these dominant ecosystem species in ongoing environmental shifts, as well as the potential effects on community livelihood.

Abies densa Griff. is an evergreen tree with relatively small cones, growing 50 m to 60 m in height and inhabiting elevations between 2 450 m a.s.l. and 4 000 m a.s.l. (Christian 2021). Fir-dominated forest forms the most characteristic uppermost forest belt on ridges and mountains along an altitudinal gradient ranging from 3 200 m a.s.l. to 3 700 m a.s.l. in Bhutan. It accounts for 16.2% of the total forest cover, comprising 432 672 ha (FMID 2023). This mountain zone is typified by a unimodal precipitation pattern, with the highest precipitation during the monsoon period (May – September) and the lowest in the first quarter of the calendar year (Gratzer et al. 1999). The vegetation period is estimated to be up to 190 days, with an average annual temperature of 4.7 °C, with July as the warmest month of the year (11.1 °C monthly average temperature) and January as the coldest month (–3 °C monthly average temperature) (Rinchen et al. 1995). The fir forest is also characterised by strong solar radiation due to the generally south-facing slopes in Bhutan and its high-altitude occurrence.

Common associated species of the fir forest comprise deciduous broadleaf trees such as *Betula utilis* (D. Don), *Acer caudatum* (Wall.), *Acer pectinatum* (Wall ex D. Don), *Sorbus microphylla* (Wenz.), *Sorbus rufopilosa* (C.K. Schneid.), and *Prunus rufa* (Wall. ex Hook.f), as well as shrubs, mainly *Viburnum* spp., in the subcanopy layer. However, more than 45% of the fir forest stands in central Bhutan were reported to lack woody understory vegetation. Regeneration of fir mainly competes with an evergreen understory of *Rhododendron* shrubs at altitudes above 3 900 m a.s.l. and *Yushania microphylla* (Munro) R.B.Majumdar up to 3 700 m a.s.l. (Gratzer et al. 1999). The uses of *Abies densa* Griff. include timber for house building, particularly panels for roofing, although this traditional practice is now being abandoned.

This study aims to evaluate the relationship between the growth of the long-living, evergreen, mountain ecosystem species *Abies densa* Griff. (aka Bhutan fir or Himalayan fir) and climatic effects, with the main objective of providing new insights into the climate sensitivity at the forest-line. To our knowledge, this presents the first study of its kind from this region.

MATERIAL AND METHODS

We extracted 31 samples of *Abies densa* Griff. in central Bhutan at Thrumshing La pass at an elevation of 3 650–3 750 m a.s.l. (27°23'59''N, 90°59'53''E) after the end of the vegetation season in November 2024. This site is characterised by steep slopes covered mainly by primary forest dominated by monospecific stands of *Abies densa* Griff. at a canopy layer and *Rhododendron hodgsonii* and the bamboo species *Yushania microphylla* at an understory level (Gratzer et al. 1997). The local climate is strongly controlled by the summer monsoon, which brings oceanic moisture, while winters are defined by stable weather and little snow cover. Annual precipitation averages 1 809 mm, and the mean annual temperature is around 6.7 °C (Pelela meteorological station; Dorji et al. 2016).

All samples were cored at breast height in a perpendicular direction to the slope. A total of 20 trees were sampled, with two cores collected from most of them. Trees with largely rotten pith or visible injuries possibly influencing the climate signal were neglected; otherwise, we cored most of the dominant trees within the 500 m^2 designated site. Cores were glued to wooden holders, perpendicularly to the tracheids, in order to ease sanding and polishing the surface of the cores. One side of each wood

https://doi.org/10.17221/58/2025-JFS

core was sanded with a belt sander to improve the visibility of the tree rings and then scanned with an Epson Expression 12000XL scanner (Seiko Epson Corporation, Japan) at a resolution of 1 200 dpi. The scanned images were used to measure and visually crossdate the tree rings using the WinDENDRO (Version 2021b) and CDendro software (Version 9.6, 2020). The crossdating was verified using the COFECHA computer programme (Version 6.06P; Holmes 1983). Overall, the sampling and dendrochronological analyses were carried out according to Cook and Kairiukstis (1990). Excluding rotten, damaged or eccentrically shaped samples, we further processed 17 samples from 17 trees. Verification of the accuracy of the individual samples was performed using a statistical test of agreement of each tree-ring width series with the reference chronology using *t*-values. These *t*-values were obtained from a Student's *t*-test, which evaluates whether the correlation between a sample and the reference chronology is statistically significant, considering the length of their overlap (Bernabei 2022). They were calculated according to Equation (1):

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}} \tag{1}$$

where:

r – correlation coefficient between the normalised sample ring-width series and the normalised mean of the remaining series;

N – number of overlapping years (Baillie, Pilcher 1973).

The *t*-values were obtained using the CDendro software and ranged from 4.8 to 11.9. The average of these values was 8.1, which indicates a good level of agreement between samples and confirms the acceptability of the dating of most samples.

The analysis further included detrending of the tree-ring width series, with the aim of removing long-term, low-frequency growth trends that are naturally caused by ageing of trees or changing habitat conditions, while retaining the high-frequency climate signal (interannual fluctuations). Detrending was therefore performed using a spline curve, a commonly used method. In this way, the effect of varying series lengths on the standardisation result (ring-width index) is minimised. We selected a spline with a 30-year length for detrending, as most ring-width series showed irregular medium-term fluctuations (20–50 years) in addition to the age-related growth trend. These fluctuations likely reflect stand dynamics, such as competition between trees. The flexible 30-year spline removes such medium-term variability while preserving the high-frequency climate signal. The 'detrend' function from the 'dplR' package (Bunn 2008; Bunn et al. 2022) was used to perform this calculation in R (R Core Team 2024) with R Studio (Posit Team 2024).

The CRU TS v4.08 monthly precipitation and mean temperature data at 0.5° resolution were used (Harris et al. 2020). CRU TS (Climatic Research Unit gridded Time Series) is a widely used climate dataset developed by the Climatic Research Unit of the University of East Anglia. It is derived from the interpolation of monthly climate data from weather station observations (Harris et al. 2020). Version 4 of CRU TS begins in 1901 and is updated annually, with v4.08 covering 1901 to 2023. The data were accessed through the KNMI Climate Explorer (KNMI 2025).

A site chronology was constructed by calculating Tukey's biweight robust mean of the detrended tree-ring width series, and the mean interseries correlation (*Rbar*) and expressed population signal (*EPS*) were calculated. Correlation analysis was used to study how the climate influences tree growth by assessing the relationship between the ring-width index (*RWI*) and monthly temperature and precipitation data for the current and previous years (April of the year preceding ring formation to September of the year of ring formation). Pearson's correlations were calculated for the period 1902–2023. This was performed in R with the 'dcc' function from the 'treeclim' package (Zang, Biondi 2015).

RESULTS

The analysis of all the annual increments showed a relatively high age for all the trees studied. The average age of all trees sampled was 202 years; the oldest sample spanned back to the 17th century. The average width of the annual increment before detrending was 1.04 cm (Table 1).

The smallest ring width indices occurred in 1705–1707, 1745–1747, 1817–1819, and 1927–1928. Conversely, the largest increments are seen in 1714, 1757–1759, and 1987. A reasonable sample depth was achieved starting from the mid-19th century. The high rate of tree establishment

https://doi.org/10.17221/58/2025-JFS

in this period indicates a possible disturbance occurred around that time (Figure 1). The correlation between the chronology and individual samples was the highest in the mid-20th century: *Rbar* values remained around 0.3 for most of the time (50-year window), but *EPS* is high constantly from 1850 to 2024 – around 0.9 (Figure 2). Although the first half of the chronology is less reliable, this is not a concern for the climate–growth analysis, as correlations were calculated from 1902 onward (corresponding to the period covered by the climate data).

Table 1. Descriptive statistics of the tree-ring width chronology of *Abies densa* Griff. from Thrumshing La pass, central Bhutan

Parameter	Value
No. of trees/cores	17/17
Mean series length (years)	202
Mean ring width (mm)	1.04 ± 0.39
Rbar	0.31
EPS	0.89

Rbar – mean interseries correlation; *EPS* – expressed population signal

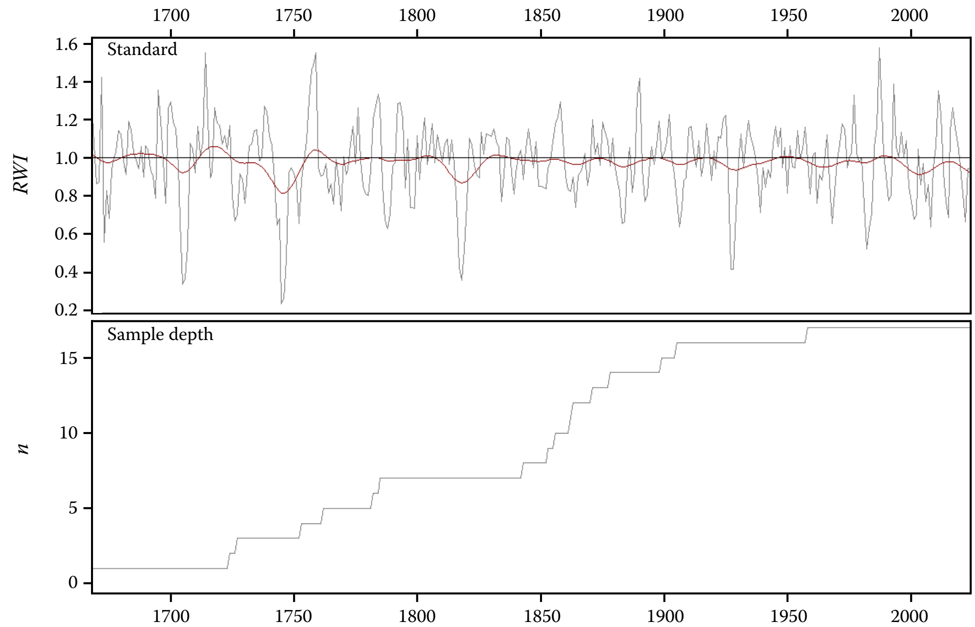

Figure 1. *Abies densa* Griff. from Thrumshing La pass, central Bhutan site chronology and 30-year spline (upper panel) and sample depth (lower panel)

RWI – ring-width index; *n* – number of ring-width measurements

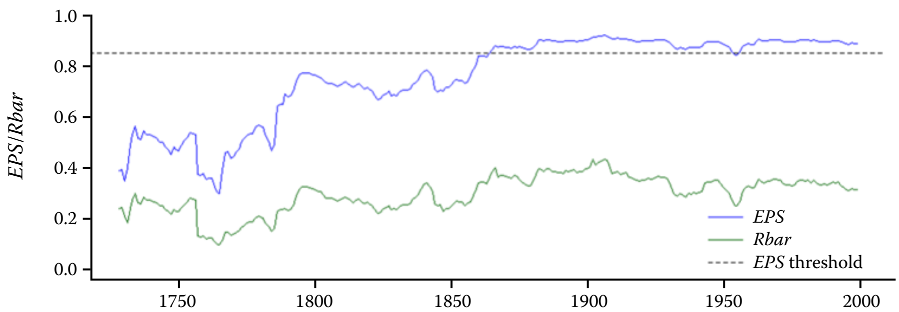

Figure 2. Running expressed population signal (*EPS*) and mean inter-series correlation (*Rbar*) for *Abies densa* Griff. from Thrumshing La pass, central Bhutan

Both metrics were calculated using a 50-year moving window with 1-year lags; the years on the x-axis correspond to the midpoints of each window; the dashed line indicates the commonly used *EPS* threshold of 0.85, above which the chronology is considered reliable

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The correlation analysis for the period 1902–2023 showed several significant correlations between detrended tree-ring width and climate variables. Temperatures in July (of both the current and previous years) and in October of the previous year showed a statistically significant negative correlation with tree growth. Temperatures in May and November of the previous year and in February of the current year were positively correlated with tree growth (Figure 3).

The effect of precipitation on tree growth was significant in May of the previous year, when high rainfall had a negative effect on the growth. Similarly, high precipitation in January of the current year had a negative effect. In contrast, the analysis showed a positive effect of the high previous year's November precipitation (Figure 4).

Climate-growth correlations were also calculated for the period 1996–2023, as weather station data from Bhutan are available from 1996 onward (NCHM Bhutan 2025). During this period, significant correlations were found only with current-year climate variables. June temperatures were positively correlated with tree-ring growth (Figure 5). Precipitation in May showed a negative correlation with growth, whereas precipitation in July was positively correlated (Figure 6). These correlations are stronger than those obtained for the full period.

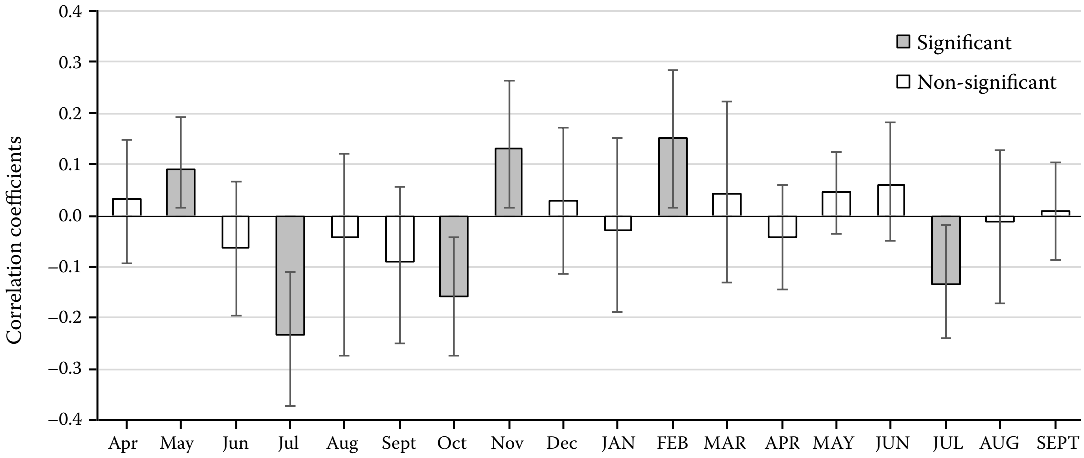

Figure 3. Relationship between ring width and mean monthly temperature from 1902 to 2023 (Pearson's correlation coefficients)

Lowercase text – months from the year preceding ring formation; uppercase text – current year

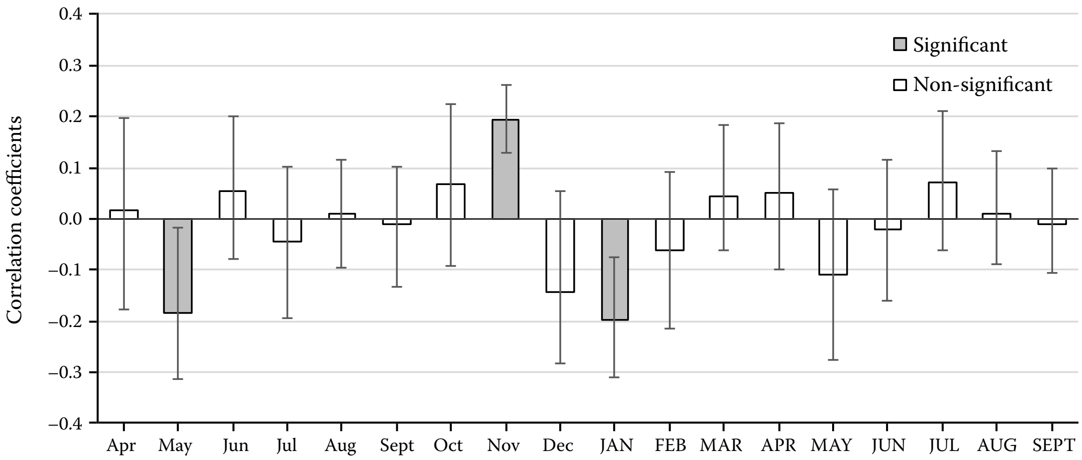

Figure 4. Relationship between ring width and mean monthly precipitation from 1902 to 2023 (Pearson's correlation coefficients)

Lowercase text – months from the year preceding ring formation; uppercase text – current year

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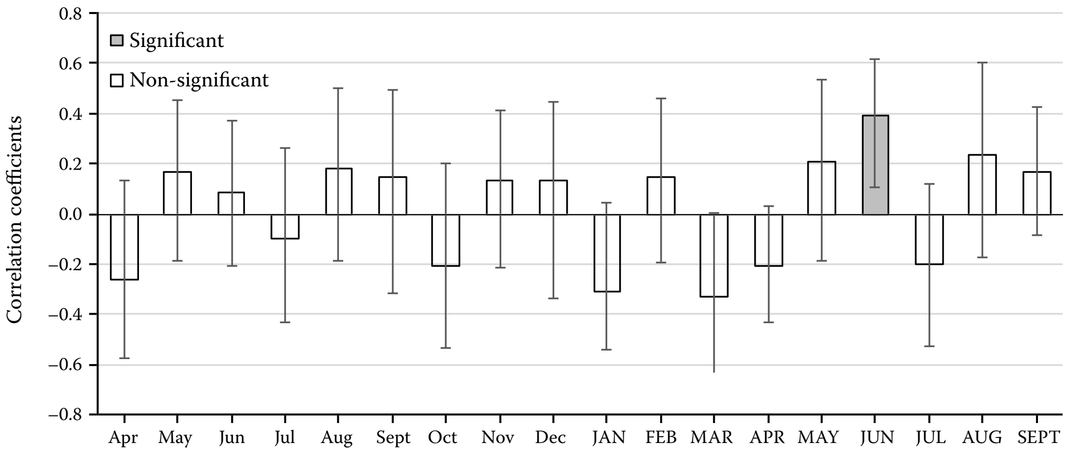

Figure 5. Relationship between ring width and mean monthly temperature from 1996 to 2023 (Pearson's correlation coefficients)

Lowercase text – months from the year preceding ring formation; uppercase text – current year

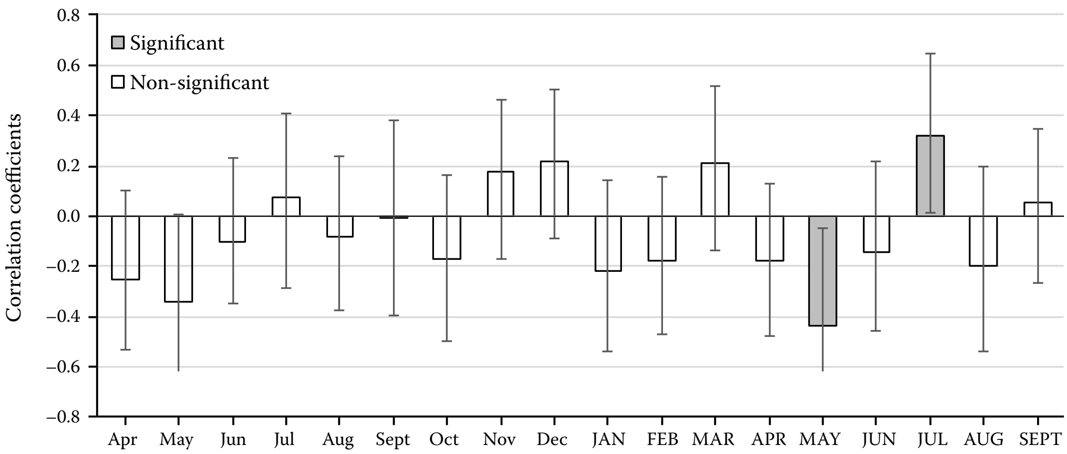

Figure 6. Relationship between ring width and mean monthly precipitation from 1996 to 2023 (Pearson's correlation coefficients)

Lowercase text – months from the year preceding ring formation; uppercase text – current year

DISCUSSION

Influence of climatic factors on the growth of Himalayan fir. The results of this study confirmed that in the study area in central Bhutan, Himalayan fir is significantly influenced by climatic conditions. There was a significant negative effect of July temperatures on growth, indicating that excessively high temperatures during peak growing season may reduce growth. As summer is the monsoon rainfall season in the Himalayas, it is unlikely that there is any effect of drought on tree growth, possibly rather an intensification of monsoon impacts (Bräuning, Mantwill 2004).

These observed growth patterns are consistent with general ecological knowledge about climatic influences on high-altitude coniferous trees, as well as other regional studies (Bhattacharyya, Chaudhary 2003; Khandu et al. 2022). In areas where rainfall is abundant, growth tends to be limited by temperature, whereas in drier areas, moisture availability is a key factor (Fan et al. 2009). Since the site of this study is located in the humid part of the Himalayas, which is influenced by the Indian monsoon, temperature is expected to be the main limiting factor, which is consistent with the data obtained. Nevertheless, correlations for temperature and precipitation are relatively weak in the studied

https://doi.org/10.17221/58/2025-JFS

period (1902–2023). The quality of the climate dataset might be part of the reason, as the oldest scholarly meteorological data from Bhutan only dates back to 1996 (NCHM Bhutan 2025). Climate-growth correlations from 1996–2023 are completely different (and stronger) as compared to the full period (Figures 5 and 6). However, this may also be attributed to climate change, as extreme climate conditions generally better imprint into the tree rings.

The negative effect of July temperatures on Himalayan fir growth in the Thrumshing La area can thus likely be explained by the effect of high temperatures and intensified monsoon impacts, typical for this part of the growing season (Luan, Zhai 2023). Warmer summer intensifies Asian monsoon due to pumping cooler high mountain air into mid-troposphere and forcing vertical uplift of air masses (Wu et al. 2012). Higher rainfall subsequently limits photosynthesis, while at the same time, waterlogging of the soil occurs, reducing oxygen availability to roots and negatively affecting cambium activity. These conditions can lead to plant stress, despite the fact that it is the growing season (Bhattacharyya, Chaudhary 2003). Warmer winter months in the mountains signalise an earlier onset of the vegetation season and thus an overall longer period for ring formation. The observed negative effect of higher January precipitation (which is typically in the form of snow) can be attributed to an unusually high snow cover and therefore a later vegetation season onset (Guan et al. 2022; Xu et al. 2022). In contrast, the positive effect of November precipitation in the previous year (typically still in the form of rain) on tree growth may result from higher moisture availability in the soil at the beginning of the growing season after the usually dry Himalayan winter (Huang et al. 2022; Ianbaev et al. 2025).

Climate sensitivity of other Himalayan *Abies* species. Sun et al. (2021) analysed *Abies georgei* in Haba Snow Mountain at two elevation zones, namely 3 000 m a.s.l. and 4 150 m a.s.l. Thus, they found significant differences in climatic sensitivity; while growth was limited by temperature at higher elevations, moisture deficit played a greater role at lower ones.

Similarly, Rai et al. (2020) in central Nepal for *Abies spectabilis* compared growth at three altitudinal sites and showed a trend where temperature increases in importance with increasing altitude and the influence of precipitation decreases. Nevertheless, our work presents an analysis of one site in a higher, wetter region, which shows limitations of growth due to temperature, but lacks the gradient comparison.

Ecological significance and implications for the future. Himalayan fir proved to serve as a potential climate archive in the region. Observed climate sensitivity of tree growth has important future implications; assuming summer temperatures continue to rise, it could lead to a decline in growth. Bhutan has not yet seen a significant decline in rainfall, but climate models indicate that there could be a variable monsoon regime in the future (Sanjay et al. 2020), meaning that the length and intensity of the rainy season could vary, and dry seasons may be more pronounced. Such a change could disrupt the growth rhythm not only of the Himalayan fir. We therefore provide a first step in understanding and portraying future scenarios of high mountain forest ecosystems which may have significant impacts on biodiversity and local communities.

CONCLUSION

We investigated the effect of climatic factors on the growth of *Abies densa* Griff. (Himalayan fir) in Thrumshing La pass, central Bhutan. The results showed that the growth of Himalayan fir is significantly negatively affected by July temperatures, which can be attributed to intensified monsoon impacts. Notably, a positive effect of November rainfall of the previous year could be related to the provision of water reserves for an earlier onset of the growing season. These findings are in line with previous studies of species from other regions or with other Himalayan fir species.

Himalayan fir from central Bhutan is a sensitive proxy archive that has the potential to contribute to the long-term monitoring of climate change in the region. In the context of expected alteration or intensification of monsoons in the region – which poses a threat to local ecosystems – Himalayan fir can also serve as a sensitive indicator of environmental shifts. Last but not least, a general understanding of how Bhutanese forests react to altered climate conditions has crucial importance to the livelihood of local communities.

Data availability statement: Analyses presented and data supporting the results in the paper are available on Mendeley Data (https://data.mendeley.com/datasets/334wbvg55z/1) or upon request to the corresponding author.

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