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Topography- and age-driven growth response of Himalayan birch to climate in Trans-Himalayan Manang valley, Nepal

Achyut TIWARI[1]* ORCID-0000-0001-9095-4067, Aashish BIDARI[1] ORCID-0009-0002-4087-2084, Devi LAL[2] ORCID-0009-0008-7118-9468 and Giri Prasad JOSHI[1] ORCID-0000-0001-9166-3974

[1] Central Department of Botany, Tribhuvan University, Kirtipur, Post Box: 26429 Kathmandu, Nepal
[2] Department of Geography, School of Environment and Earth Sciences, Central University of Punjab, Bathinda, India-151401

***corresponding author:** achyut.tiwari@cdb.tu.edu.np

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Abstract: This study aims to evaluate how climate variability influences both the long-term radial growth dynamics and regeneration patterns of Himalayan birch (*Betula utilis*) across contrasting slope aspects in the Trans-Himalayan region of central Nepal. We investigated radial growth responses and regeneration status of *B. utilis* using tree-ring width and stand regeneration consensus. We produced tree ring-width chronologies of *B. utilis;* 304 years (1720–2023) from the north facing moist slope of Milarepa, and 58 years (1966–2023) from the south facing dry slope of Ngawal. Results indicate that warming temperatures in moist Himalayan forests negatively affect the growth of *B. utilis*, particularly through increasing minimum (night-time) temperatures. Radial growth at Ngawal is negatively affected by higher late- and early-growing season temperatures but benefits from winter precipitation, whereas growth is more strongly limited by both minimum and mean temperatures across seasons at Milarepa. The declining basal area increment and ring-width indices

from the late twentieth century, especially in the moist forest, further indicated higher growth sensitivity. Also, growth sensitivity to climate strengthened from young stands toward old-growth forests, suggesting that stand development stage modulates climate–growth relationships. Further, *B. utilis* shows stable regeneration overall, with stronger recruitment at Milarepa, but more limited regeneration at Ngawal due to environmental and anthropogenic constraints. These findings highlight that warming in moist Himalayan forests may suppress birch growth and increase vulnerability of late-successional forests to climate change.

Keywords: Third Pole, Himalayas, *Betula utilis*, tree-ring, climate, temperature, climate sensitivity.

Introduction

Climate change has become one of the most pressing global challenges, profoundly influencing ecosystems and landscapes worldwide. Rising temperatures, shifting precipitation regimes, and an increasing frequency of extreme weather events are already altering environmental conditions, and these impacts are projected to intensify in the coming decades (IPCC 2022). The warming rate of Himalayas is higher than the global average (Wester *et al.* 2019), which could alter terrestrial ecosystems and species interactions (Wang *et al.* 2023; Sigdel *et al.* 2024) in multiple ways (Gray and Brady 2016; Román-Palacios and Wiens 2020). In addition, climate change is associated with increased tree mortality and reduced forest growth, particularly in warm and dry regions (Tiwari *et al.* 2017; McDowell *et al.* 2020).

Himalayan birch (*Betula utilis* D. Don) is a medium-sized broadleaved pioneer tree species, usually < 20 m tall, that dominates extensive subalpine forests up to *ca.* 4500 m elevation, often occurring close to glaciers on the northern slopes of the inner Himalayas (Stainton 1972; Zobel and Singh 1997; TISC 2002; Schickhoff 2005; Miehe *et al.* 2015). Its distribution shows considerable local variation, likely influenced by microclimatic variability and topographic sheltering effects. *Betula utilis* is also a common treeline forming species across many parts of the Himalayas (Miehe *et al.* 2015), yet its growth sensitivity across the diverse climatic zones and complex topography of central Nepal remain insufficiently explored. Treeline is generally defined as the highest elevation at which a single upright tree exceeding 2 m in height occurs across the landscape (Hofgaard 1997; Körner 2003), whereas alpine

timberline represents the upper limit of closed mountain forest with a tree density (trees > 5 m tall) covering at least 30% of the area (Wardle 1974; Holtmeier 2003). Tree species including *B. utilis* often exhibit contrasting growth responses to warming temperatures at their upper and lower distribution limits (Peñuelas *et al.* 2008; Cavin and Jump 2016). Various studies indicated the higher moisture sensitivity of *B. utilis* especially at upper elevational limits where temperature driven moisture availability controls tree growth across Himalayas (Dawadi *et al.* 2013; Liang *et al.* 2014; Tiwari *et al.* 2017). Although warming trends in the Himalayas are widely documented (Shrestha *et al.* 2012; Wester *et al.* 2019), responses of tree growth vary depending on local moisture conditions. Usually, in moist sites, warming may enhance growth by extending the growing season, whereas in dry forests higher temperatures can increase evapotranspiration, soil moisture deficits, and physiological stress.

Tree radial growth responses to climate are primarily controlled by factors such as species, provenance, and site condition including soil characteristics and local climate (Camarero *et al.* 2015; Sánchez-Salguero *et al.* 2018). However, stand- and tree-level characteristics, such as size, age, structure, and competition, also influence climate–growth relationships, though their effects are less clear due to strong interactions among variables (Fritts 1976; Rossi *et al.* 2008; Sánchez-Salguero *et al.* 2015). Young forests often respond primarily to stand dynamics and competition, while older forests tend to show stronger climate signals due to reduced structural plasticity and increased hydraulic limitation (Carrer and Urbinati 2004; Trouillier *et al.* 2019). Competition is a fundamental driver of forest growth, as it constrains access to essential resources such as soil water, nutrients, and light (Orwig and Abrams 1997; Weiner 1990). Similarly, tree growth is also influenced by slope exposure and microhabitat conditions particularly in mountain landscapes (Körner 2003; Bidari *et al.* 2026). This study therefore aims to (*i*) analyze the regional climate pattern and assess the influence of temperature and moisture on radial growth between younger and older forest stands of *Betula utilis*, (*ii*) examine long-term growth trends, and (*iii*) the stand characteristics and regeneration potential of *B. utilis* in north and south facing slopes of Trans-Himalayan zone of Manang in central Nepal.

Study area

The study area lies in the central Himalayas of Nepal (Fig. 1), within the so-called “Third Pole”, which contains the largest ice reserves outside the polar regions and plays a vital role in regional

climate and Asian water resources (Yao *et al.* 2012). The study sites along the Marsyangdi River Valley in upper Manang span high elevations of *ca.* 3400 to 3550 m a.s.l., characterized by low temperatures, strong seasonality, and short growing seasons with summer monsoon precipitation and cold winters. The vegetation shows clear altitudinal zonation from subalpine forests to alpine and nival zones.

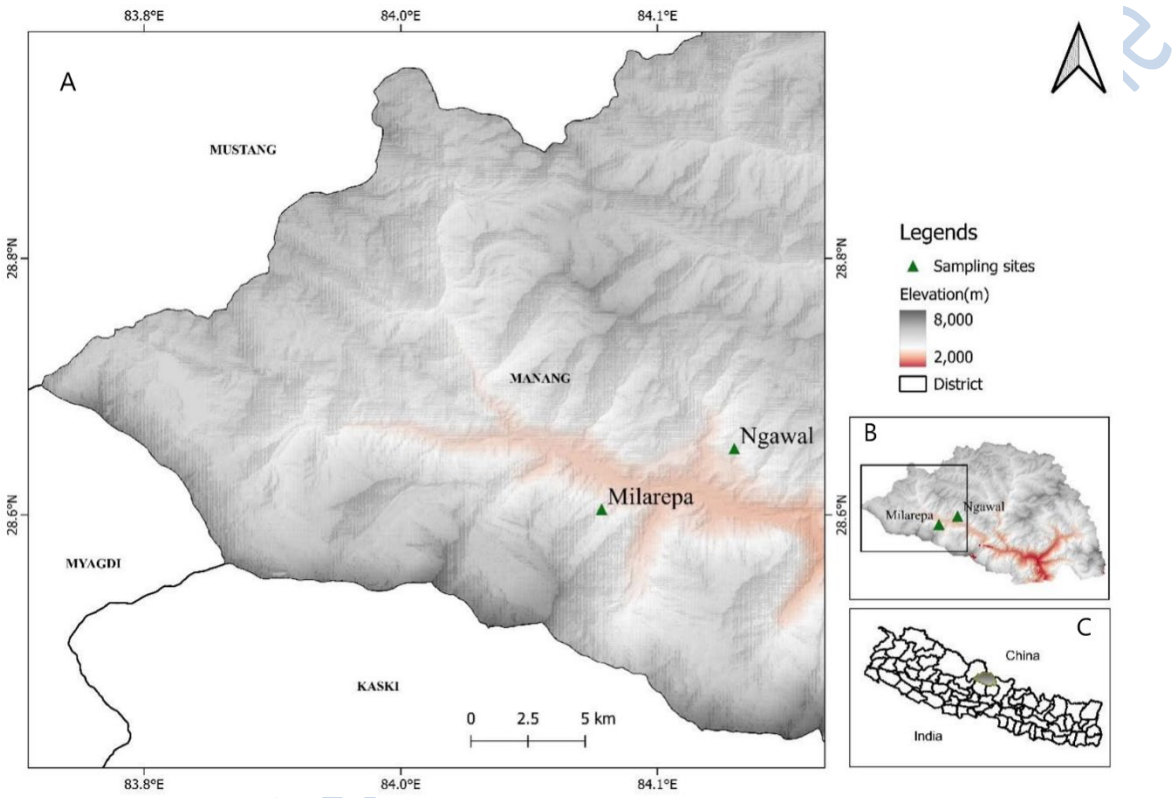

Fig. 1. Location map of the sampling sites showing the two slopes of Manang valley; the north facing slope represented by Milarepa (4100 m a.s.l.) and the south facing slope represented by Ngawal (3775 m a.s.l.) in Manang, central Nepal (**A**), map of Manang district showing study sites (**B**) and map of Nepal showing Manang district (**C**).

The climate of the study area is the typical monsoon climate, with the marked annual variation of temperature and precipitation as indicated by Climatic Research Unit Time Series (CRU TS) (Harris *et al.* 2020). The temperatures rise steadily from winter to peak in early summer, rising up to 18°C in June and then gradually decline toward winter, with minimum temperatures dropping below 0°C. Precipitation varies throughout the year, reaching its highest levels in mid-summer, especially July (139.62 mm), and lowest levels in late autumn to early

winter, lowest in the month of November with only 10.51 mm rainfall. Overall, climate is a temperate continental type characterized by cold winters, mild summers, with a maximum rainfall in summer.

Climate of the study area in 1970–2025 was relatively dry due to low annual precipitation (700.6 mm yr^{-1}). The annual maximum and minimum temperature of the region over the past 50 years were 13.05°C and 0.52°C respectively, with the maximum temperature recorded in the month of June, while the minimum temperature was recorded in the month of January. Similarly, the maximum rainfall (139.48 mm) occurred in July while the lowest rainfall (10.47 mm) occurred during November (Fig. 2).

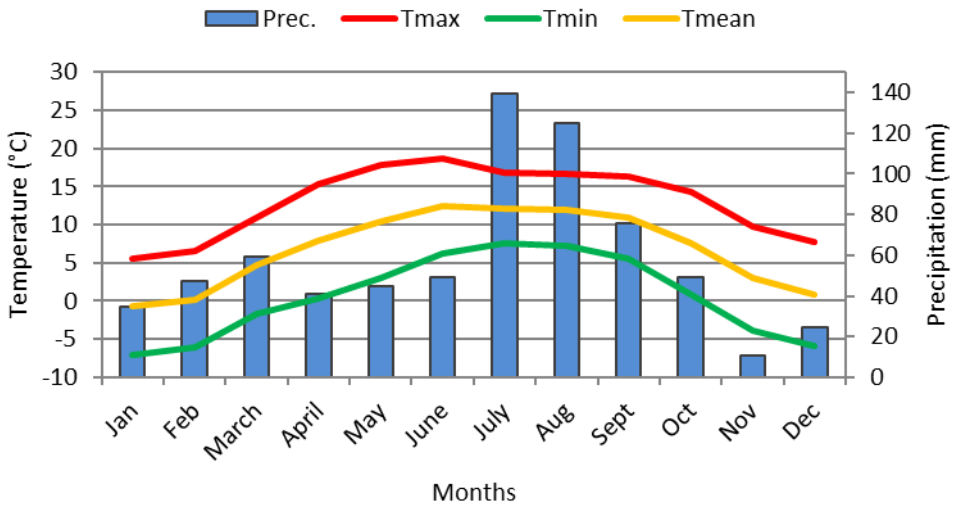

Fig. 2. Climatic summary (1970–2025) of the study area, following Climatic Research Unit gridded Time Series (CRU TS) climatic data of Harris *et al.* (2020).

Materials and methods

Sampling sites

The sampling locations are bounded by the dry alpine deserts of Mustang and Tibet (China) in the north. The study sites were selected as two different slopes, *i.e.*, north facing slope (Milarepa Cave area: 28.6375° N, 84.04° E, 4100 m a.s.l.) and south facing slope (Ngawal: 28.6647° N, 84.0994° E, 3775 m a.s.l.) in the Trans-Himalayan Manang valley. The two study sites were selected to represent contrasting slope aspects under similar regional climatic conditions. Although located on different mountains, both sites fall within comparable elevational ranges

and support *Betula utilis*-dominated treeline forests. Site selection aimed to minimize major environmental differences (*e.g.*, geology, slope angle, and vegetation type), allowing for a focused assessment of age and aspect-related variability in growth and regeneration (Fig. 1).

CRU TS climatic data (Harris *et al.* 2020) were used to characterize the study sites as the nearest meteorological station at Chame (28.5518° N, 84.2409° E, 2705 m a.s.l.), characterized by a completely different physiographic and climatic conditions, lies at *ca.* 18 km distance from the study site. We used climate data from the valley below the treeline, with both sampling sites located within a *ca.* 3 km aerial distance from the reference point, ensuring that they fall within the same local climatic domain.

Tree-ring sampling and chronology development

Sampling was conducted during September–October 2024 along north and south facing transects established in mountain forest area of Milarepa and Ngawal. Tree cores were collected from dominant and co-dominant *B. utilis* tree individuals; one to three cores were extracted from each tree using a 5.5 mm increment borer (Fig. 3). We employed standard dendrochronological methods to measure annual rings and to develop ring-width chronologies. The collected cores were air-dried, mounted on wooden holders, and progressively sanded with increasingly finer grades of sandpaper following standard dendrochronological procedures (Fritts 1976). Ring widths were measured to a precision of 0.01 mm using a LINTAB measuring system (Rinntech, Germany) and cross-dated. We used COFECHA software program to check the accuracy of cross-dating and measurement (Holmes 1983; Grissino-Mayer 2001). Statistical analyses were conducted using the software R (R Core Team 2015). Ring-width indices and basal area increment (BAI) chronologies were constructed to evaluate both relative and absolute growth trends (Cook 1985). Each ring-width series was detrended using a negative exponential, linear, or cubic spline curve as appropriate. To remove autocorrelation, the detrended series were pre-whitened using autoregressive modeling, and standard chronology was then developed by averaging individual series with a bi-weight robust mean (Cook 1985). Chronology quality was assessed using statistics including mean ring width, mean sensitivity, standard deviation, autocorrelation, within- and between-tree correlation, mean series correlation, signal-to-noise ratio, and expressed population signal (Briffa 1995; Wigley *et al.* 1984).

Fig. 3. *Betula utilis* old growth forest stand at Milarepa at 4100 m a.s.l. (**A**) and sampled tree at Ngawal at 3750 m a.s.l. (**B**) in Manang.

For each series, a negative exponential, linear or cubic spline curve was chosen as needed. Then, in order to eliminate any auto correlation effects, the detrended ring-width index series were pre-whitened by fitting an autoregressive modeling (Cook 1987). Standard and residual chronologies were created by averaging individual time series using a bi-weight robust mean function (Cook 1985), following detrending. To evaluate the quality of site chronologies, various statistics such as mean ring width, mean sensitivity, standard deviation, auto correlation, within-tree correlation, between-tree correlation, mean series correlation, signal-to-noise ratio, expressed population signal were used (Wigley *et al.* 1984; Briffa 1995). Further, we produced basal area increment (BAI) chronology for *B. utilis* from both north and south facing as BAI is widely used to assess tree and stand productivity (Rubino and McCarthy 2000). Ring-widths were directly converted to BAI using the dplR package (Bunn 2008) following formula:

$$BAI = \pi (R_n^2 - R_{n-1}^2)$$

where ‘R’ is tree radius of the tree and ‘n’ is the year of ring formation (Biondi and Qeadan 2008). This method assumes uniform radial growth and converts ring-widths into annual basal area increments (Biondi and Qeadan 2008; Panthi *et al.* 2020).

Growth-climate relationship

Correlation analysis between tree-ring width indices and climatic variables (temperature and precipitation) was conducted to identify the climatic factors limiting tree growth in the study area. Pearson’s correlation coefficients were calculated using monthly climate data from June of the year preceding ring formation to December of the growth year, capturing the previous growing season, the intervening winter and spring, and the current growing season. This framework enables the assessment of potential lagged (preconditioning) climate effects on growth (Biondi and Waikul 2004). Correlation coefficients between climatic variables and ring-width indices were computed for both study sites, and significance was tested at the 95% confidence level using the R package bootRes (Zang and Biondi 2015). Data processing and visualization were performed in R using the packages dplr and Origin.

Population structure and regeneration potential

We carried out random-purposive sampling at the upper distribution range edge of each tree species in order to examine the regeneration potential of selected tree species. We laid down sampling at least ten square quadrats of 10 m × 10 m size, and made a consensus of trees, saplings and seedling density for each tree species at each sampling location. We estimated the regeneration potential by evaluating seedling sapling ration following Deb and Sundriyal (2008). Samples were categorized as seedlings (height < 20 cm), saplings (diameter at breast height < 10 cm and height > 20 cm), or mature trees (diameter at breast height >10 cm). The regeneration status of tree species was determined based on the population sizes of seedlings, saplings, and adults, according to Khan *et al.* (1987) and Khumbongmayum *et al.* (2006). Regeneration was categorized as good (seedlings > saplings > adults), fair (seedlings > saplings ≤ adults), poor (saplings but no seedlings), none (only adults with no seedlings or saplings) and new (only saplings and/or seedlings are present with no adults).

Results and interpretation

Climatic trends based on archive meteorological data

The trend of annual means, maximum and minimum temperatures as well as annual precipitation rates of the study area are given in Fig. 4. The trend in the climatic data of the

study area showed an increasing trend in the maximum, minimum and mean temperature with significant differences, while there was no significant trend in the total precipitation patterns over the past 50 years (Fig. 4).

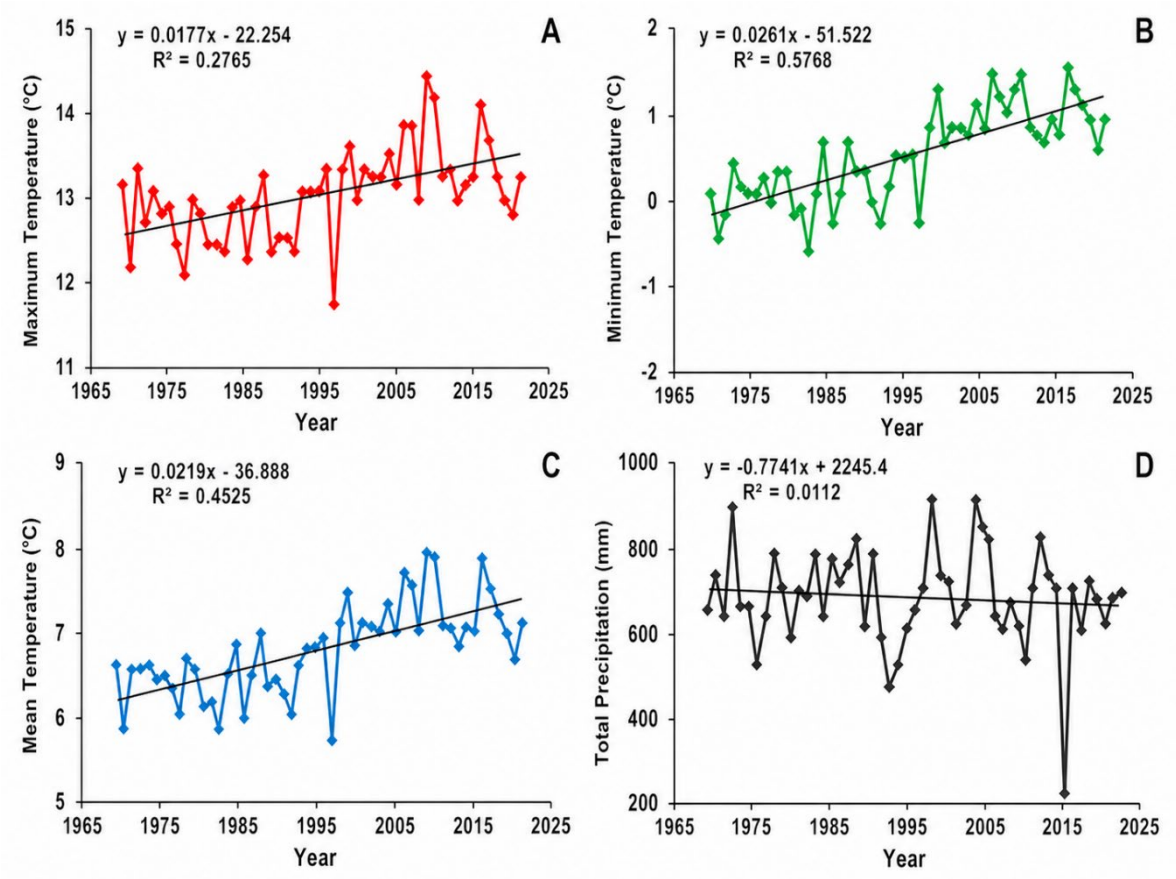

Fig. 4. Annual climatic trend of the study area between the years 1970–2023; maximum (**A**), minimum (**B**) and mean temperature (**C**) as well as total precipitation (**D**).

The climatic analysis showed a significant increasing trend in minimum and mean temperatures at the study site, while there is not any trend for precipitation. This is a similar warming pattern reported across the Hindu Kush Himalayan region (Shrestha *et al.* 1999; Shrestha and Aryal 2011). Comparable results have been documented by DHM (2017), Khand *et al.* (2020) and Bajracharya *et al.* (2011), who also highlighted stronger warming in high-altitude regions. However, some studies reported contrasting patterns for minimum temperature, showing a decreasing trend in mountain and hill regions (Bajracharya *et al.* 2011; DHM 2017; Adhikari and Mathema 2023).

Annual precipitation at the study site does not exhibit a significant long-term trend, that clearly showed that the Trans-Himalayan zone of Manang is getting drier in the recent years, and similar results were shown by Adhikari and Mathema (2023) in Manang. This contrasts with findings of increasing precipitation trends in parts of the Himalayan region reported by DHM (2017) and Sigdel *et al.* (2022) for the Gandaki Basin. In this study, climate trends were derived from CRU gridded datasets, which may not capture a fine-scale climatic variability in complex Himalayan terrain and potentially underestimate short-term or aspect-driven microclimates influencing tree growth.

Growth-Climate Relationship

We produced tree ring-width chronologies of *B. utilis* from the north facing slope of Milarepa 304 years (1720–2023), and from the south facing slope of Ngwal 58 years (1966–2023) (Fig. 5). The mean series length was much longer at Milarepa (184.7 years) than at Ngawal (36.6 years), reflecting the presence of older trees at Milarepa. Both chronologies show reliable chronology characteristics for growth-climate relationships (Table 1).

Table 1. Tree ring-width chronologies of *Betula utilis* at Milarepa and Ngawal sampling sites.

Parameters	**Milarepa**	**Ngawal**
No. of series (trees) used	55 (38)	49 (25)
Chronology span (years)	1720–2023 (304)	1966–2023 (58)
Average mean sensitivity	0.353	0.389
Series intercorrelation	0.364	0.473
Signal to noise ratio	7.135	7.535
Expressed population signal	0.877	0.883
Mean length of series	184.7	36.6

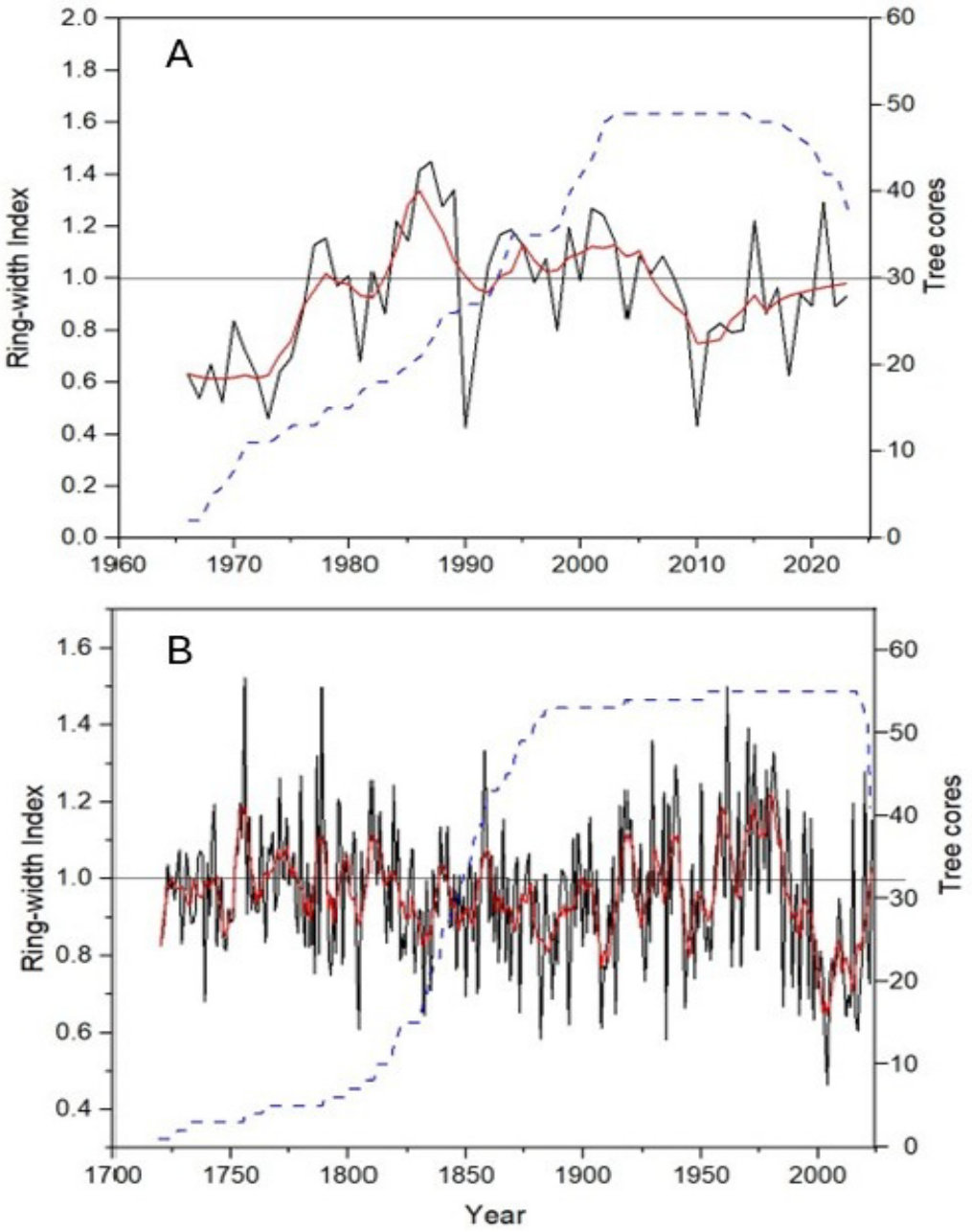

Fig. 5. Tree ring-width chronology of *Betula utilis* from Ngawal (**A**) and Milarepa (**B**); black line refers to ring-width indices, red line shows a 10-year moving average and dashed line is the number of tree cores.

The Pearson's correlation analysis between ring-width indices and monthly climatic variables at Milarepa showed stronger and more widespread significant negative correlations, particularly with temperature variables. Maximum temperature showed significant negative correlations across parts of the previous winter and several months of the current growing season, while minimum temperature exhibited widespread and consistent negative relationships

spanning the previous growing season and most periods of the current year. Similarly, both mean and minimum temperatures were negatively correlated with growth across multiple seasons. Precipitation displayed limited negative correlations during parts of the previous monsoon season (Fig. 6).

In contrast, Ngawal showed fewer but distinct relationships, with negative correlations primarily linked to temperatures during the previous monsoon and early current growing season, while precipitation had a limited but positive influence only during the winter period (Fig. 6). Overall, these results suggest that radial growth at Ngawal is negatively influenced by higher temperatures during the late previous growing season and early growing season, while winter precipitation positively supports growth. These findings indicate that radial growth at Milarepa is strongly constrained by both minimum and mean temperatures across multiple seasons, highlighting a pronounced temperature limitation compared to Ngawal.

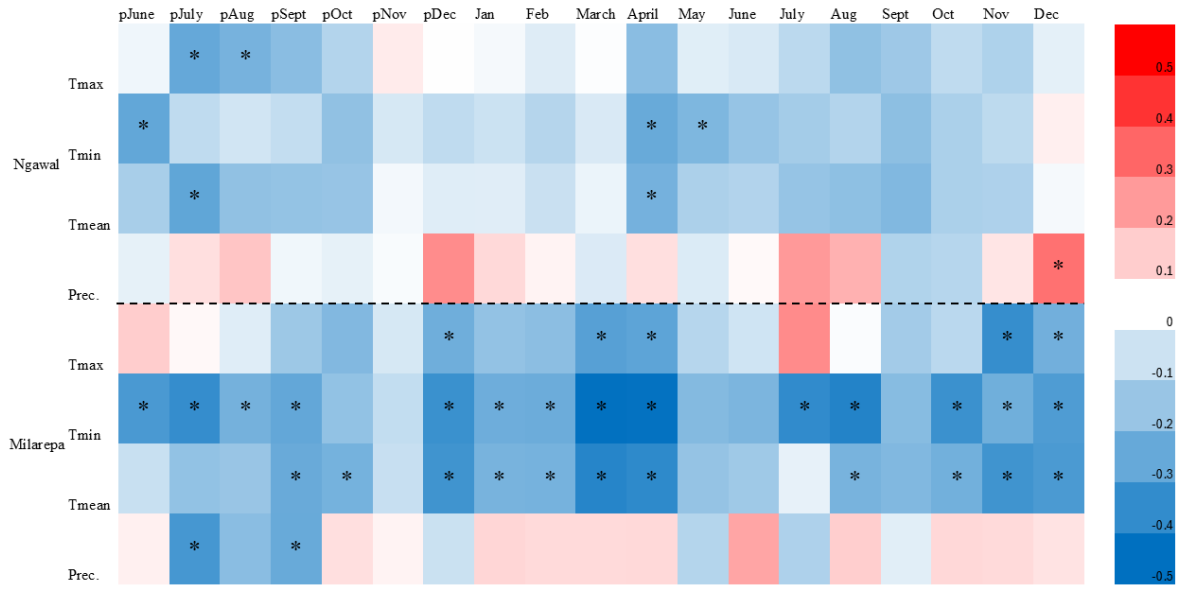

Fig. 6. Correlation coefficients between radial growth with temperature and precipitation and; X-axis showing months (previous year's June to Current year's December), Y-axis showing correlation coefficient, the color code indicated correlation strength. Significant correlation at 95 % confidence limit is given * (r = 0.28) for a two tailed test.

Treeline-forming *B. utilis* in the Manang valley shows strong sensitivity of radial growth to pre-monsoon moisture availability, indicating that spring moisture is a key limiting factor in

the dry Trans-Himalayan environment. Further, the radial growth showed higher sensitivity to warming climate at moist slope with the dominance of old growth trees than at the dry slope dominated by young trees. Such age-dependent growth trends have already been documented in a variety of tree species (Carrer and Urbinati 2004; Trouillier *et al.* 2019; Tiwari 2020). Spring season moisture sensitivity has been reported for both high mountain conifers and broadleaved trees in Nepal Himalayas (Dawadi *et al.* 2013; Liang *et al.* 2014; Tiwari *et al.* 2017; Sigdel *et al.* 2018). On the other hand, spring warming, combined with increased solar radiation, promotes early snowmelt and elevates atmospheric evaporative demand. This intensifies drought stress in the ecotone prior to the onset of summer precipitation (Fritts 1976; Cook 1985; Winkler *et al.* 2018). The frequent occurrence of narrow and missing growth rings was reported in birch across the central Himalayas, which further indicated that drought conditions constrain radial growth (Liang *et al.* 2014). Climate–growth relationships differ markedly between sites with contrasting slope aspects and moisture regimes. At the dry, south-facing Ngawal site, growth responses are largely consistent with moisture limitation, where winter precipitation, especially snowfall, supports early-season growth and moderate warming can enhance cambial activity by extending the growing season. In contrast, the moist north-facing Milarepa site exhibits stronger negative correlations between temperature and ring-width, suggesting that higher temperatures increase atmospheric evaporative demand and physiological stress, reducing tree growth, such slope mediated growth-climate response was also reported for blue pine from Manang (Bidari *et al.* 2026).

Basal area increment

The basal area increment (BAI) chronology from the Ngawal (dry) site (1966–2023), representing a young *B. utilis* population on a dry south-facing slope, shows a pronounced long-term increasing trend. BAI values rise gradually during the early decades and accelerate after the 1990s, exceeding *ca.* 1000 mm² in recent years, indicating strong radial growth as trees mature and expand their stem diameter (Fig. 7A). In contrast, the Milarepa chronology (1720–2023), derived from a moist north-facing old-growth forest, exhibits relatively stable BAI values that generally remain below *ca.* 400 mm² and fluctuate around a consistent level without a strong long-term increasing trend, reflecting the mature developmental stage of trees in this stand (Fig. 7B). Moreover, the decreased BAI since *ca.* 1975 indicates that the increased temperatures were high enough to hamper the further growth rate of the forest stand.

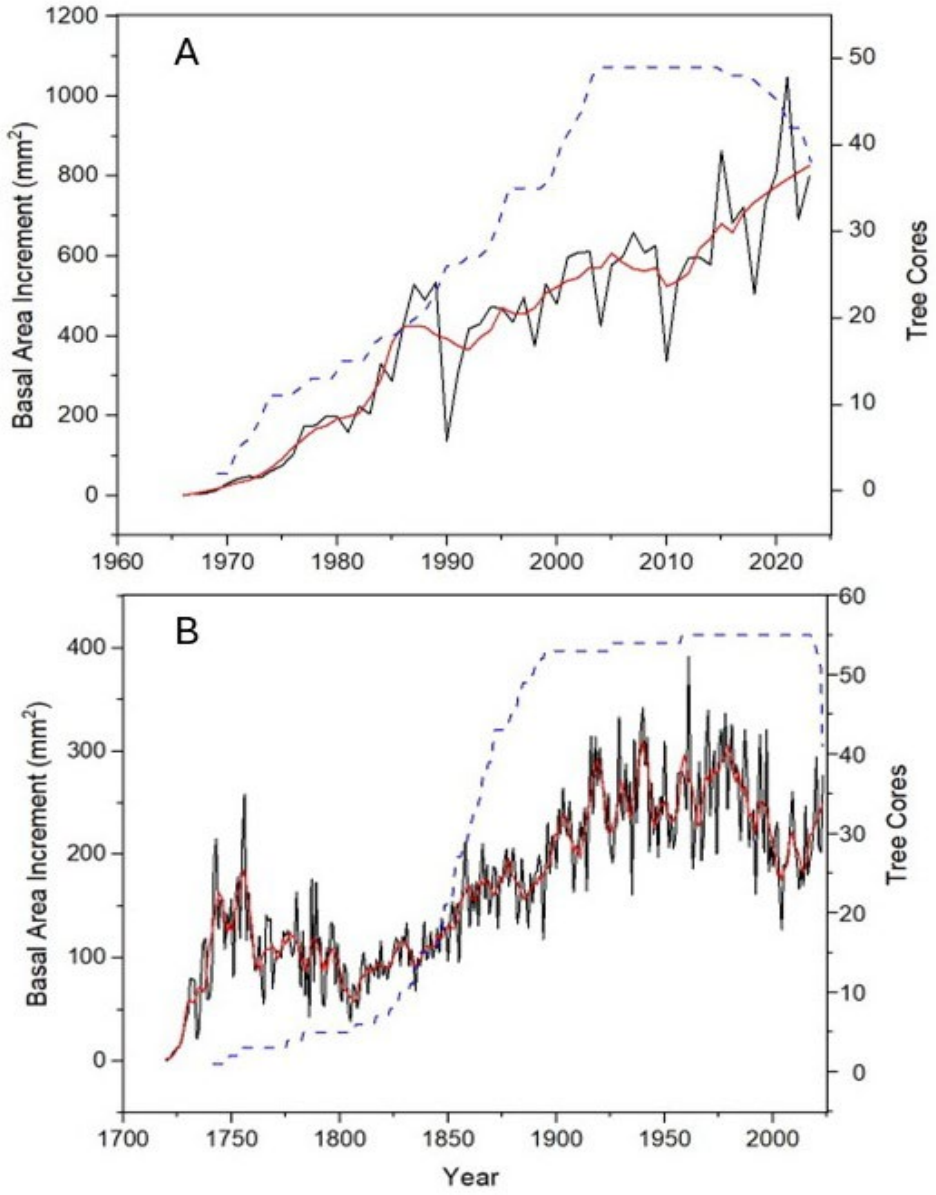

Fig. 7. Basal area increment of *B. utilis* from Ngawal (**A**) and Milarepa (**B**) in Manang; black line refers to basal area increment, red line shows a 10-year moving average and dashed line is the number of tree cores.

The contrasting BAI patterns primarily reflect differences in stand age structure, slope aspect, and site moisture conditions. The increasing BAI trend at Ngawal is characteristic of young developing stands where growth accelerates as crown size and photosynthetic capacity expand, following the typical sigmoidal growth trajectory described in forest development studies (Spiecker *et al.* 1996; Weiner and Thomas 2001). In contrast, the relatively stable BAI at Milarepa reflects the dynamics of mature trees in an old-growth forest, where basal area

increment tends to stabilize after trees reach physiological maturity and canopy structure becomes relatively constant (Fritts 1976; Cook and Kairiukstis 1990). Topographic influences may further reinforce these differences, as north-facing slopes generally maintain higher soil moisture and lower atmospheric evaporative demand, supporting stable long-term growth, whereas south-facing slopes experience warmer and drier conditions that may initially limit establishment but allow rapid growth once trees become established. Overall, these results demonstrate that stand structure, ontogenetic development, and topographic controls strongly influence long-term growth trends, emphasizing the importance of considering stand age and site conditions when interpreting growth–climate relationships in Himalayan dendroecological studies.

Population structure and regeneration

The regeneration pattern of *B. utilis* varied between the two study sites and across elevations. Milarepa site showed considerably higher regeneration densities. Tree density ranged from about 300 to 1100 individuals ha^{-1}, whereas sapling and seedling densities were markedly higher, reaching up to 3360 and 5140 individuals ha^{-1}, respectively. The highest seedling and sapling densities occurred near the upper elevation limit (3950 m).

In contrast, tree density at Ngawal ranged from *ca.* 320 to 660 individuals ha^{-1}, with the highest density at 3950 m. Sapling density varied between *ca.* 140 and 500 individuals ha^{-1}, while seedling density ranged from roughly 300 to 460 individuals ha^{-1} (Table 2). In most elevation bands, seedling density slightly exceeded sapling density, suggesting ongoing recruitment but relatively moderate progression from seedlings to saplings. These patterns indicate that *B. utilis* maintains active regeneration at both sites, although regeneration intensity differs substantially. The moderate densities at Ngawal (Table 2) suggest stable but limited recruitment, potentially reflecting environmental constraints such as moisture availability, grazing pressure, or microsite limitations affecting seedling survival and transition to the sapling stage. In contrast, the very high seedling and sapling densities at Milarepa indicate strong regeneration potential and favorable establishment conditions, possibly associated with suitable canopy gaps and reduced disturbance pressure as the site is far away from the settlement area.

Table 2. Density (trees, saplings and seedlings) and regeneration status of *B. utilis* at Ngawal and Milarepa

Ngawal							
Elevation (m a.s.l.)	No. of trees	Density per ha	No. of saplings	Density per ha	No. of seedlings	Density per ha	Regeneration status
3950	33	660	25	500	18	360	fair
3890	18	360	14	280	21	420	good
3856	16	320	10	200	23	460	good
3786	21	420	7	140	15	300	fair
Milarepa							
Elevation (m a.s.l.)	No. of trees	Density per ha	No. of saplings	Density per ha	No. of seedlings	Density per ha	
3950	15	300	168	3360	257	5140	good
3815	36	720	16	320	59	1180	good
3770	50	1000	7	140	62	1240	good
3676	55	1100	28	560	207	4140	good

The dominance of juvenile individuals at Milarepa, particularly near the upper elevational range, may also suggest a potential upward expansion of *Betula utilis*, consistent with observations from Himalayan treeline ecosystems under changing climatic conditions (Tiwari *et al.* 2023). A higher density of seedlings relative to larger size classes suggests frequent recruitment but low survival rates. The size-class distribution of a species, therefore, provides a useful indication of its regeneration status (Lv and Zhang 2012). However, increased canopy cover, leading to reduced light availability, can contribute to higher seedling mortality (Marchand and Chabot 1978; Castro *et al.* 2004; Shrestha *et al.* 2007). Additionally, at higher elevations, seedling mortality is often associated with low temperatures and winter drought stress, particularly in open habitats, further limiting survival (Marchand and Chabot 1978; Coates 2002; Castro *et al.* 2004). Overall, the population structure observed in this study reflects a generally stable regeneration status of this key treeline species, although site-specific environmental factors appear to influence recruitment dynamics.

Conclusion

This study shows that warming temperatures in moist Himalayan forests negatively affect the growth of *Betula utilis*, particularly increased minimum (night-time) temperatures showing negative response to *B. utilis* growth in moist habitat, with site-specific responses showing

temperature- and moisture-driven limitations on the southern slope at Ngawal and stronger multi-season temperature limitation on the northern slope at Milarepa. The negative relationship between temperature and growth is evident in declining basal area increment and ring-width indices from the late twentieth century, especially in the moist north-facing forest. Climate sensitivity also increased with forest stand age, with mature and old-growth stands showing stronger responses to temperature variability than young stands, where growth patterns may still be influenced by juvenile effects rather than climate alone. *Betula utilis* exhibits overall stable regeneration across sites, with markedly stronger recruitment and potential upward expansion at Milarepa, while more moderate and constrained regeneration at Ngawal reflects site-specific environmental limitations influencing seedling survival and transition dynamics as well as different level of anthropogenic disturbance. These findings highlight that forest developmental stage and slope-controlled microclimate must be considered when predicting climate change impacts on Himalayan treeline ecosystems, and they provide important insights into how continued warming may alter forest structure, productivity, and ecosystem functioning in the central Himalayas.

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