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Growth and Climate Sensitivity of *Pinus roxburghii* (Chir pine) from Melamchi Region of Nepal Himalaya: Research through Education

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Abstract

Climate change is affecting multiple sectors in Nepal including its diverse forests. Tree-rings data have many applications including the growth of species, and climate change impacts on tree species, among others. The Melamchi region has witnessed rapid climate change and extreme events and associated environmental hazards in recent years. In this context, a dendrochronological educational research field work was carried out in the Melamchi region of Nepal with the objective to assess the growth and regeneration of trees in different forests including the climatic response of chir pine (*Pinus roxburghii* Sarg.). Tree-core samples were collected and analyzed by following the standard dendrochronological method. The average diameter at breast height (DBH) of pine was 29.62 cm while the average annual radial growth was 2.71 mm per year and the average basal area increment was 1153.92 mm^2 per year. We observed many false ring bands in tree rings likely due to intra-annual climatic variability and or due to anthropogenic disturbances in the studied forest stands. An 83 years long tree-ring width site chronology of chir pine spanning from 1941 to 2023 AD was developed which shows long-term growth variability. The study found a significant positive relationship (based on correlation coefficient) between the pine chronology and precipitation in current year February, negative relationship with May month precipitation and February month temperature (average and maximum). The study also highlights that growth climate response of the chir pine is stable to changing over time i.e. the response to the February and May month precipitation and February month temperature is persistent over time while response with May month temperature is positively intensified but response to June and previous year October precipitation is weakening during recent years. The study also indicated that pine trees are sensitive and responsive not only to the climate change but also to the prevailing disturbances events, and growth of which can be affected by both of the phenomena. Educational research field studies are effective means in transferring theoretical knowledge to practical research aspects.

Keywords: Climate change, tree-ring, dbh, basal area, dendrochronology, forest growth

1. Growth and Climate Sensitivity of the *Pinus roxburghii* (Chir pine) from Melamchi Region of Nepal Himalaya: Research through Education

Dendrochronology, the science of tree-ring dating, has several applications in ecology, forestry, climatology, among others (Speer, 2010). Annual tree-ring can be used not only to study the climatic sensitivity and response but also to assess the impacts of climate change in the forests (Gaire et al., 2023a; Speer, 2010). Similarly, tree-ring data have been widely used to study past centennial to millennial-scale local, regional to hemispheric scale temperature, precipitation, drought conditions and streamflow (Cook et al., 2003; Gaire et al., 2022, 2024; PAGES 2k Consortium, 2013; Rao et al., 2020; Shah et al., 2014, 2019). Nepal Himalaya is experiencing rapid climate change with diverse impacts on multiple sectors (Chaudhary et al., 2023; ICIMOD 2023; IPCC 2022; MOFE 2021). Knowing the climatic sensitivity of the forest species is very essential to understand the possible fate of the different forest species in response to climate change as forests respond to climate change in diverse ways (IPCC, 2022; MOFE, 2021).

Located in the central part of the Himalaya, Nepal holds multiple tree species that can be used to assess the climate change impacts in the forests and biodiversity sectors using a dendrochronological approach (Gaire et al., 2023a; Gautam et al., 2020). Dendroecological studies already revealed the impacts of climate change on treeline ecotone of Nepal which indicated stable to changing treeline position in response to climate change (Chhetri & Cairns, 2015; Gaire et al., 2023a; Sigdel et al., 2024; Tiwari et al., 2023). Diverse tree species found in the country may respond to and adapt to the changing climate in their own ways. Growth-climate response analysis indicated that there is species- and site-specific climatic sensitivity and response of the tree species (Baral et al., 2022; Dawadi et al., 2013; Gaire et al., 2023a; Panthi et al., 2020). Therefore, it is very essential to know how the growth of tree species is controlled by different climatic factors. Are there any changes in the growth-limiting climatic factors over time? How are diverse tree species adapting in changing climate? Answering these questions enables us to assess how the ecosystem services provided by forest can be change in future.

Pine forests occupy sub-tropical to temperate regions of Nepal (DFRS, 2015; Stainton, 1972). Pine forest is very important socio-economically and ecologically (DFRS, 2015). They provide different ecosystem services to the people, and hence pine forests are under human pressure in most of the accessible areas of the country. A study from the Koshi River Basin of Eastern Nepal found that disturbance events evident in pine ring-width data are largely asynchronous, indicating these forests have been historically perturbed by human influences rather than large-scale climatic or ecological influences (Thapa & George, 2019). Pine trees are widely used in dendroclimatic study across Himalaya (Ahmed et al., 2009; Bhattacharya et al., 1992; Shah & Bhattacharyya, 2012). *Pinus wallichiana* and *Pinus roxburghii* are the two major native pine tree species distributed across the Himalaya including Nepal (FRTC 2015). These pine species produce annual rings that can be used to analyze quantitative growth, their climatic sensitivity and response to climate change (Aryal et al., 2023, 2024; Bhattacharya et al., 1992; Gaire et al., 2019; Gautam et al., 2022). Considering the significance of *Pinus roxburghii* (chir pine), some tree-ring studies have been conducted from Nepal using their annual tree-rings and associated features. Previous studies on chir pine have covered different aspects like wood anatomy (Joshi & Chalise, 2022), growth and plantation history (Bhuju & Gaire, 2012; Tiwari et al., 2020), growth-climate response (Aryal et al., 2018; Bhandari et al., 2024; Sigdel et al., 2018; Verma et al., 2018), forest health (Speer et al., 2017; Thapa & George, 2019), impacts of resin tapping (Bhattarai et al., 2025), impacts of invasive species in growth (Dyola et al., 2020), intra-annual growth dynamics (Aryal et al., 2023) and tree-ring stable isotopes (Aryal et al., 2024). Studies have been carried out from far-east to far-west of Nepal. Pine forest occupies large fraction of the forest in the Sindhupalchok district, however previous tree-ring studies have not covered the Melamchi watershed of the district which is experiencing rapid climate change, extremes and climate induced disasters (Adhikari et al., 2023; Baniya et al., 2024). Realizing this research gap and considering the importance of dendro-study, an educational research field visit was carried out in the Melamchi region in Nepal with the aim to understand the climate change situation, the growth of chir pine, and the climatic sensitivity of the pine growth.

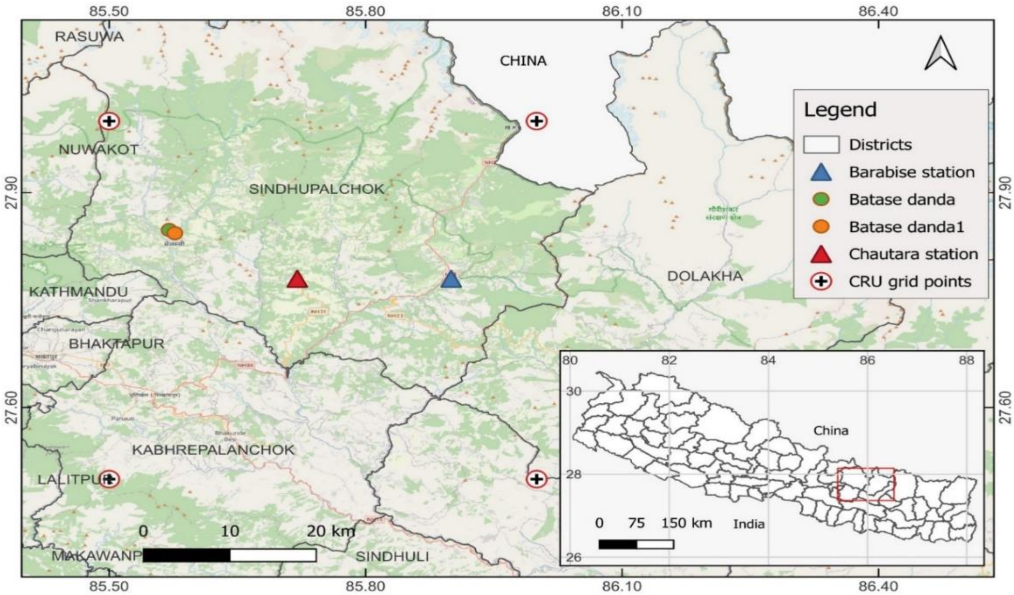
2. Materials and Methods

Study Area and Climate

Melamchi Municipality was selected as the study area (Figure 1). Melamchi Municipality is situated in Sindhupalchok District in the Bagmati Province of central Nepal. Of the total 160.04 km^2 area of the municipality, 37.4% was covered by forest in 2017 (DFRS, 2018; GGGI, 2018). Most of the area's forests are community forests, being sal, asna, khayar, katus, chilaune, gobre salla, thingre salla and gurans major tree species (GGGI, 2018).

Figure 1

Location of two Sampling Sites (circle) in Batase Danda of Melamchi Municipality and Local Climatological Stations (triangle) and CRU Grid (crossed circle) Used in This Study



The Melamchi watershed region is monsoon-dominated with majority of annual precipitation being received during the summer monsoon season (Figure 2). According to the Köppen–Geiger classification (Karki et al., 2016) it falls in Cwa (Temperate climate with dry winter and hot summer) and Cwb (Temperate climate with dry winter and warm summer). The lower part of Melamchi valley has a sub-tropical climate, while the upper part has a cool temperate climate (GGGI, 2018). The upper part of the valley receives more rainfall than in the lower part. According to the CRU gridded climate data (Harris et al., 2020), the average annual temperature was 16.2 °C while annual total precipitation was 2041 mm during the period of 1950 to 2022. Autumn and winter season are relatively dry (Figure 2). There is a significant increasing trend in the annual minimum (slope = 0.015), maximum (slope = 0.01) and average (0.013) temperature while no significant trend observed in the annual CRU and local station (Barabise) rainfall data (Figure 3). Previous studies also indicated that Sindhupalchok district is experiencing a non-significant decreasing trend in the annual and seasonal precipitation but a significant positive trend in the maximum seasonal and annual temperature and monsoon season minimum temperature (DHM 2017). The district is experiencing significant changes in climatic extreme events like Extremely wet days, Warm days, Cool days, Warm spell duration and Warm nights (DHM, 2017). But, no long-term trend in the scPDSI data (van der Schrier et al., 2013) was observed though extreme drought events have been increasing in recent years. The scPDSI data analysis revealed that years 2015, 2014, 1995, 1921, 1994, 1908, 1992, 1958, and 1993 experienced severe to extreme droughts while years 2011, 1945, 1949, 1987, 1913, 1946 and 1986 were very wet (Figure 3b).

Figure 2

Walter-Leith Climograph of the Melamchi area based on CRU grid climate data. In the X-axis, Abbreviations of the Month are Presented Starting from January (J) to December (D)

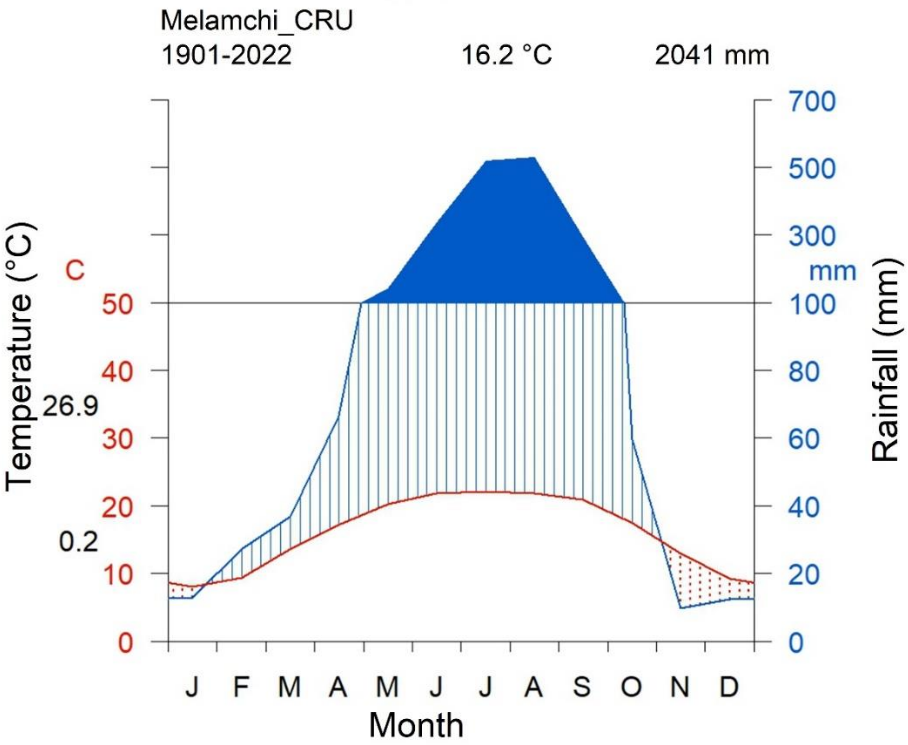
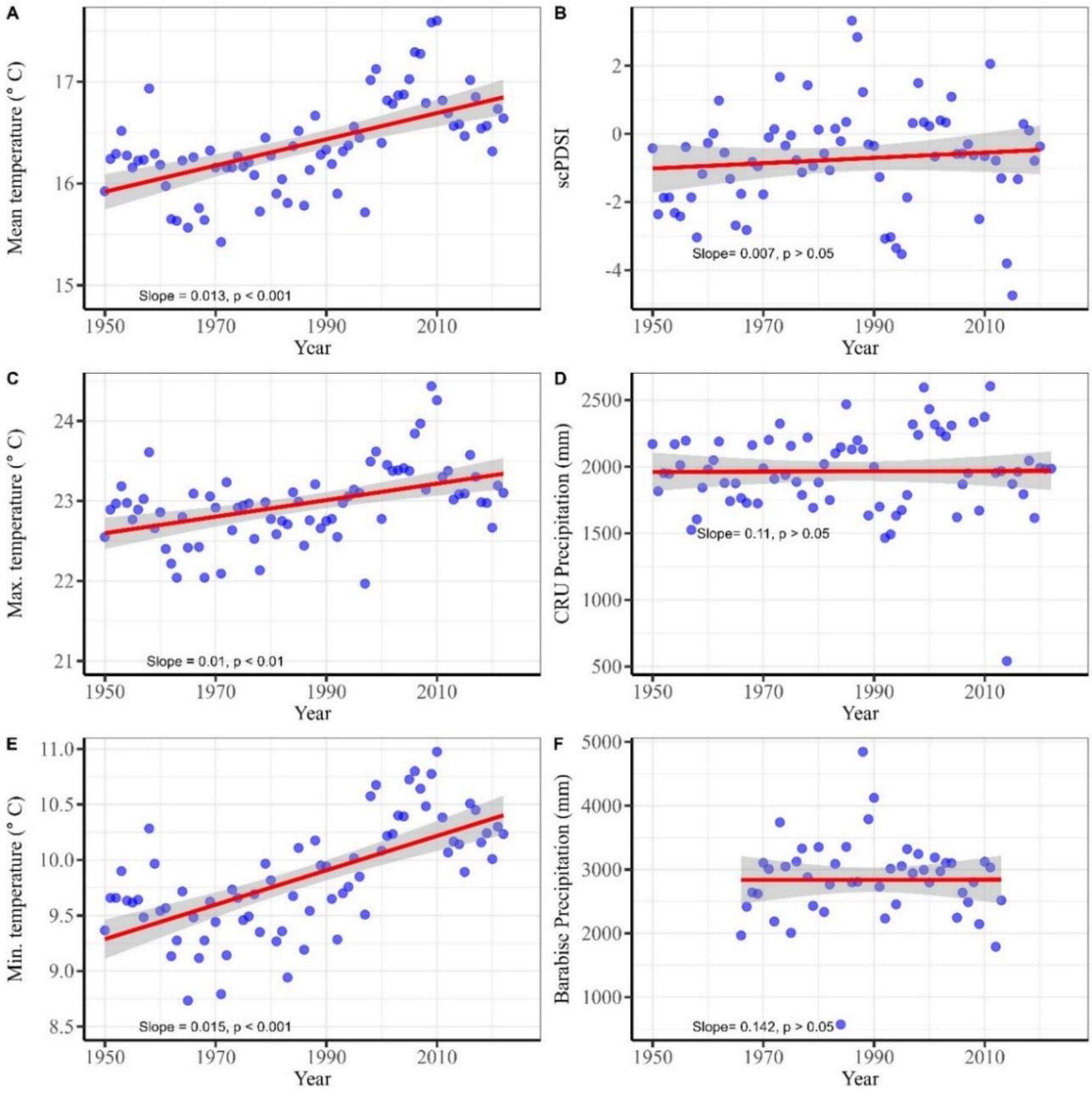


Figure 3

Trend in the Annual Maximum, Minimum, Average Temperature, Annual Total Precipitation and scPDSI Based on CRU and Barabise Station Data



Field Visit, Data and Sample Collection and Analysis

An educational field visit was carried out in the Melamchi Municipality during March-April month of 2024. We carried out forest surveys in the different locations of the Melamchi for educational research field study purposes targeting species richness of the area and growth of pine trees. During the visit students also learned different aspects of dendrochronological research including how to collect tree cores for different study purposes, and how to analyze samples to estimate their age and growth. Pine forest of Batasedanda of Melamchi Municipality was selected for the study site. Tree cores were collected using an increment borer following standard sampling procedures (Fritts, 1976; Speer, 2010). One to two cores per tree were collected from the breast height of the selected healthy appearing trees. Sampling location was recorded using the GPS. Collected tree cores were carefully packed in the plastic straw with proper labelling and brought to the laboratory for further analysis.

In the laboratory, tree cores were left for a few days for the air dry and then mounted in the wooden frame with the transverse surface facing up (Speer, 2010). Then they were again left for a week to air dry of the glue. The air-dried core samples were sanded and polished using different grits of sandpaper until the cellular levels' visibility of the tree-rings under the microscope. Then, each ring in the cores was counted and dated to their calendar year. As the sampling year's growth was just started with incomplete growth rings, its width was not measured and measurements were done until 2023 AD's rings. After counting and dating of each ring, measurement of the ring width was carried out by using the LINTAB measuring system attached to the computer having TSAP-win software (Rinn, 2010). Crossdating was carried out in the TSAP-win program by using different crossdating statistics (Rinn, 2010). Crossdating was challenging due to the presence of asynchronous false ring bands within tree rings; however, we were able to accomplish it by careful re-checking of samples. Further error in the crossdating was corrected using the quality control program COFECHA (Holmes, 1983).

Crossdated samples were proceeded for standardization and chronology development. Standardization was carried out in the dplR package (Bunn, 2008). Detrending was done by using modified negative exponential growth curve or spline curve or using both. Finally, a different version of the chronologies was developed. The quality of the chronology was assessed by using commonly used chronology statistics like R-bar, EPS, etc. (Wigley et al, 1984). The running R-bar and EPS value were calculated in the RCSSigFree program (http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software). To assess the long-term growth of trees, a BAI chronology was developed by using dplR package (Bunn, 2008).

The climate data of meteorological stations closer to the sampling site were collected from the Department of Hydrology and Meteorology. Since, stations data covers only short time span with many missing values, CRU gridded climate data (0.5 X 0.5° resolutions) was extracted by using KNMI climate explorer (Harris et al., 2020; Trouet & Oldenborgh, 2013) for further analysis as majority of the previous dendrochronological studies from Nepal have also used them in growth-climate response analysis. The CRU data used in the study includes monthly minimum, maximum and average temperature, monthly precipitation and monthly scPDSI. To assess the growth-climate relationship, simple and bootstrapped correlation was carried out by using the "treeclim" R package (Zang & Biondi, 2015). A 14-month's climatic window starting from previous year September to current year October was used for response analysis and to identify growth limiting climatic factors. Temporal stability of the response was assessed by using the "treeclim" R package using a 30 years climatic moving window with one-year time offset (Zang & Biondi, 2015).

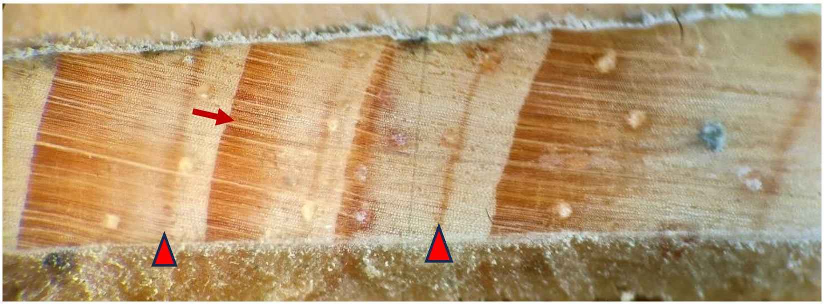
3. Results and Discussion

Growth Characteristics of Chir Pine from the Melamchi Area

We sampled trees having different diameter sizes. The average DBH (diameter at breast height) of trees in the sampling area was 29.86 cm. In the sampled trees there is a distinct ring boundary (Figure 4) in most of the years; however, diffused ring boundaries as well as false ring bands (Figure 4) were also recorded in many samples. Only a few series had zero flag in COFECHA though the majority of the series have shown high (>10) CDI value in TSAP-win software with moderate interseries correlation r-bar (> 0.4). Similar situation was obtained in the pine samples from Nagarkot area where only three sampled series showed zero flag in COFECHA (Speer et al., 2017). Presence of false rings is common observations for this species in previous studies too (Aryal et al., 2018, 2024; Bhattacharya et al, 1992; Bhattarai et al., 2025; Speer et al., 2017; Thapa & George, 2019). Similar to our observations, the chir pine trees sampled from the Nagarkot region in Kathmandu valley where false rings were observed in several consecutive years (Speer et al., 2017). The chir pine trees in the study sites of Melamchi were 25 to 83 years old with an average age of 60 years (Table 1). The overall average radial growth of all sampled trees was 2.71 mm per year with individual tree's average growth ranging from 1.89 mm to 4.69 mm, while the maximum growth of the individual trees ranges from 5.33 mm to 13.48 mm per year (Table 1). Even in the same tree growth was different in the different radial directions of a stem. Radial growth of the species in Kathmandu Valley was observed to be 0.25±0.05 cm/yr, 0.31±0.08 cm/yr, and 0.32 ±0.03 cm/yr at Sallaghari (Bhaktapur), Singh Durbar and Thapathali (Kathmandu), respectively (Bhuju & Gaire, 2012). The growth rate of the trees varies with size and age in addition to the influence of topo-climatic factors (Fritts, 1976).

Figure 4

Picture showing True Annual Tree Ring (horizontal arrow) and False Rings Band (triangle)



Eighty-three years long tree-ring width site chronology of chir pine spanning from 1941 to 2023 AD was developed in the present study which revealed growth fluctuations over time with some low and high growth periods (Figure 5). There is a slide decline in the growth during recent few years. Previous studies developed 50 yrs to ~300 years long chir pine chronologies in different regions of Nepal (Aryal et al., 2018; Bhattacharyya et al., 1992; Bhuju & Gaire, 2012; Sigdel et al., 2018; Verma et al., 2018). The chronology statistics (Table 1) of our chronology revealed moderate mean sensitivity (0.33) and r-bar, but a high EPS value compared to commonly used

EPS threshold value of 0.85 (Fritts, 1976; Wigley et al., 1984). As the EPS value was different in the different detrending options and program, here we used a running R-bar and EPS value obtained from the RCSSigfree program as it was highest among different options we tried. The statistics obtained in the chronology are comparable to that obtained in the pine from Nagarkot region but relatively low compared to the data of the same or other conifer species in the different studies in Nepal (Aryal et al., 2018; Bhattarai et al., 2025; Bhuju & Gaire, 2012; Chhetri & Cairns, 2015; Sigdel et al., 2018; Speer et al., 2017).

Since many chronology statistics like EPS are also dependent in the sample depth, age and shared response captured in trees, a low EPS values could be the result of the low sample depth, incorporation of young trees in the samples, individualistic growth pattern of young trees and or poor crossdating resulted from false rings. In a study in the Nagarkot region, pine stands at a heavily impacted site also resulted in the poor crossdating with the encounter of the several false rings (Speer et al., 2017). Similar to the pine samples from Nagarkot, our study site was also close to a mountain road, a picnic spot and often used for cattle grazing by local peoples.

Figure 5

Tree-ring width standard (blue) and residual (red) chronology of chir pine from Melamchi region with sample depth (shaded area) (a), and running EPS and R-bar with EPS threshold value (b)

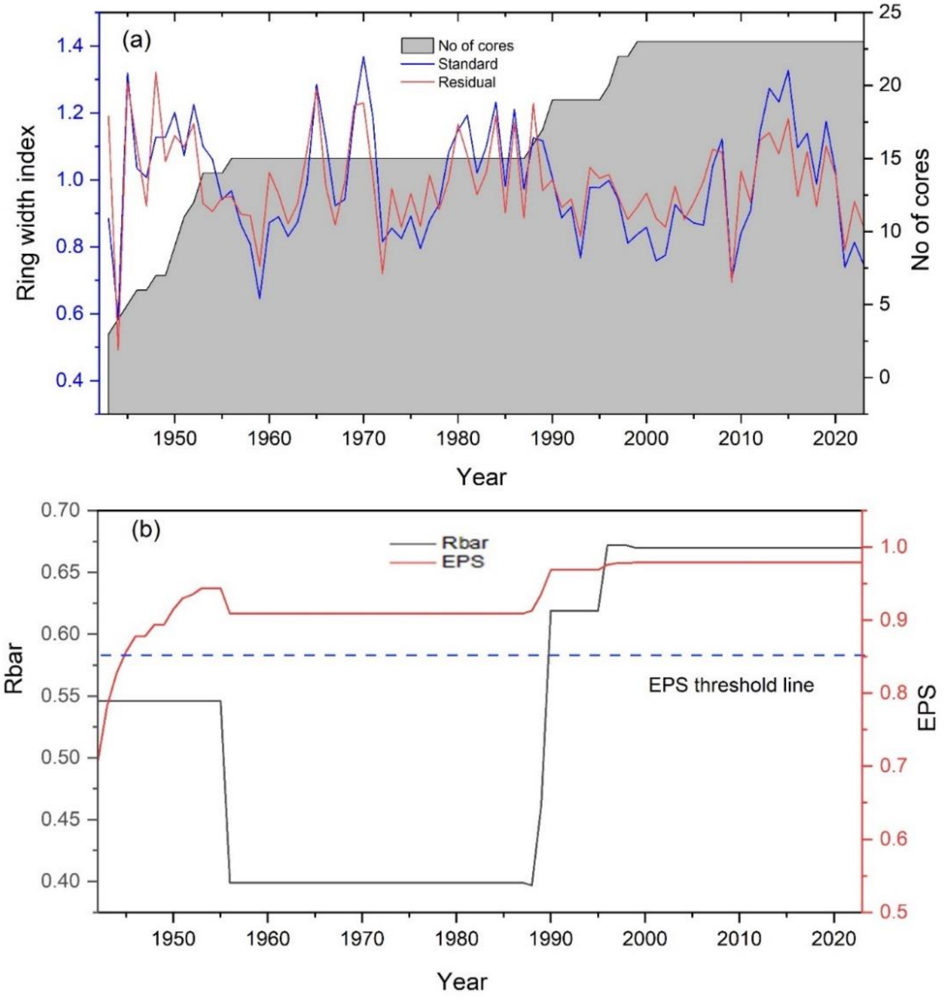


Table 1

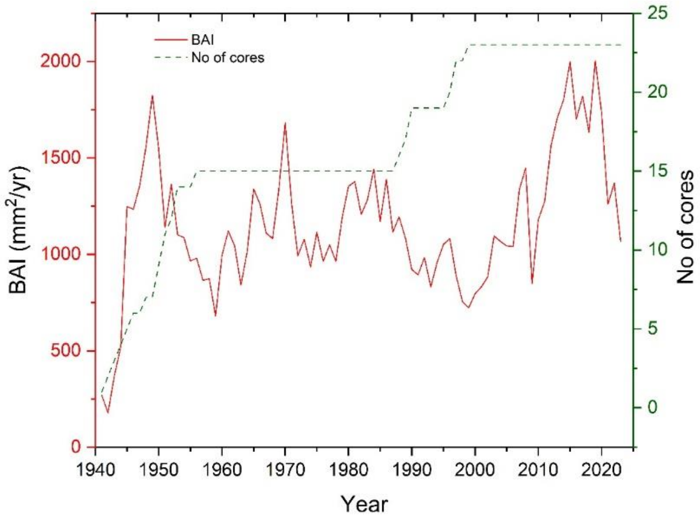
Chronology statistics of Pinus roxburghii from the Melamchi region of Nepal

Parameters	Value
Average DBH (cm)	29.62
No of samples	23
First year	1941
Last year	2023
Period	83
Mean age (yr)	60
Average radial growth rate (mm/yr)	2.71
Standard deviation (SD)	1.83
Skew	1.20
Mean Sensitivity in COFECHA	0.33
First order autocorrelation (AC1)	0.67
R-bar	0.43
Expressed Population Signal (EPS) (using RCSsigfree)	0.97

The basal area increment of the pine trees was also calculated. The average annual BAI was found to be 1153.92 mm^2 per year (Figure 6). The BAI chronology of the chir pine revealed an overall growing stage of the forest with growth suppression during some period (Figure 6) which indicates that the forest is in a growing stage. We don't have previous literature to explain exactly how the BAI curve of the chir pine follows. However, previous studies indicated that BAI of many species follow a sigmoid growth curve (Baral et al., 2022; Gaire et al., 2023b; Tiwari et al., 2020).

Figure 6

Basal Area Increment (BAI) chronology of the Chir pine from the Melamchi Area in Nepal



Growth-Climate Response of Chir Pine

Different detrending options was tried to develop various versions of the chronologies. The chronologies using the spline growth curve or double detrending using modified negative exponential and age dependent spline curve captured more climatic signals. Therefore, here we present the response of the residual tree-ring width chronology developed using the double detrending. The study found a significant positive relationship (Pearson's correlation coefficient) between the pine chronology and precipitation during current year February and significant negative with May month precipitation and average temperature of February month (Figure 7). Similarly, we obtained a negative relationship between pine growth and monthly maximum temperature during the current year February (Figure 8). The climate graph shows dry periods during late autumn and winter (November, December and January) months (Figure 2) which may explain a positive response with precipitation and negative with temperature during February month.

The result indicated that favorable climate in February is very critical for chir pine growth in the study area as it is the beginning period of the annual growth. Negative relation with May month's precipitation could be related to the high precipitation (cloud cover) related temporary cooling during peak growth period leading to a growth retardation or less growth, as the study area receives more than 2000 mm annual precipitation majority being received during subsequent monsoon season (June to September). There is no persistent pattern in the climatic response of chir pine growth across entire Nepal Himalaya rather it varies with site condition and climatic regime of the region and prevailing disturbance events (Aryal et al., 2018, 2023, 2024; Bhandari et al., 2024; Bhattarai et al., 2025; Chauhan et al., 2017; Sigdel et al., 2018; Speer et al., 2017; Thapa & George, 2019; Tiwari et al., 2020; Verma et al., 2018).

However, spring season moisture stress to tree growth is most widely observed growth-climate response in the Nepal and India Himalaya in the pine and other conifer and broadleaved species (Dawadi et al., 2013; Gaire et al., 2019, 2022; Panthi et al., 2020; Sigdel et al., 2018; Tiwari et al., 2020). The positive relationship with precipitation in February and the negative response with spring season's February month temperature (average and maximum) is a shared response to the previous studies (Aryal et al., 2018; Sigdel et al., 2018; Tiwari et al., 2020).

Study on chir pine from Nagarkot region obtained a positive relationship with precipitation during the current year March and November month (Speer et al., 2017). Similar to our observation, the chir pine growing in the Chure region of Makwanpur district has displayed a weaker relationship with CRU precipitation during growing seasons (Aryal et al., 2024). Chir pine chronology from the Nagarkot area showed significant negative correlations with precipitation during previous and current September but positive correlations with current March and November (Speer et al., 2017). We don't have exact growth phenology of chir pine from Melamchi area to say scientifically when the growth starts and when the growth ends for which monitoring using dendrometer data and quantitative wood anatomy in future will shed a light on exact cycle of pine growth and their climatic sensitivity (Aryal et al., 2023).

Figure 7

Relationship between the tree-ring residual chronology of chir pine with monthly average temperature (Tmean) and precipitation (PPT). The solid bar indicates significant relation while the dashed bar indicates statistically insignificant correlation

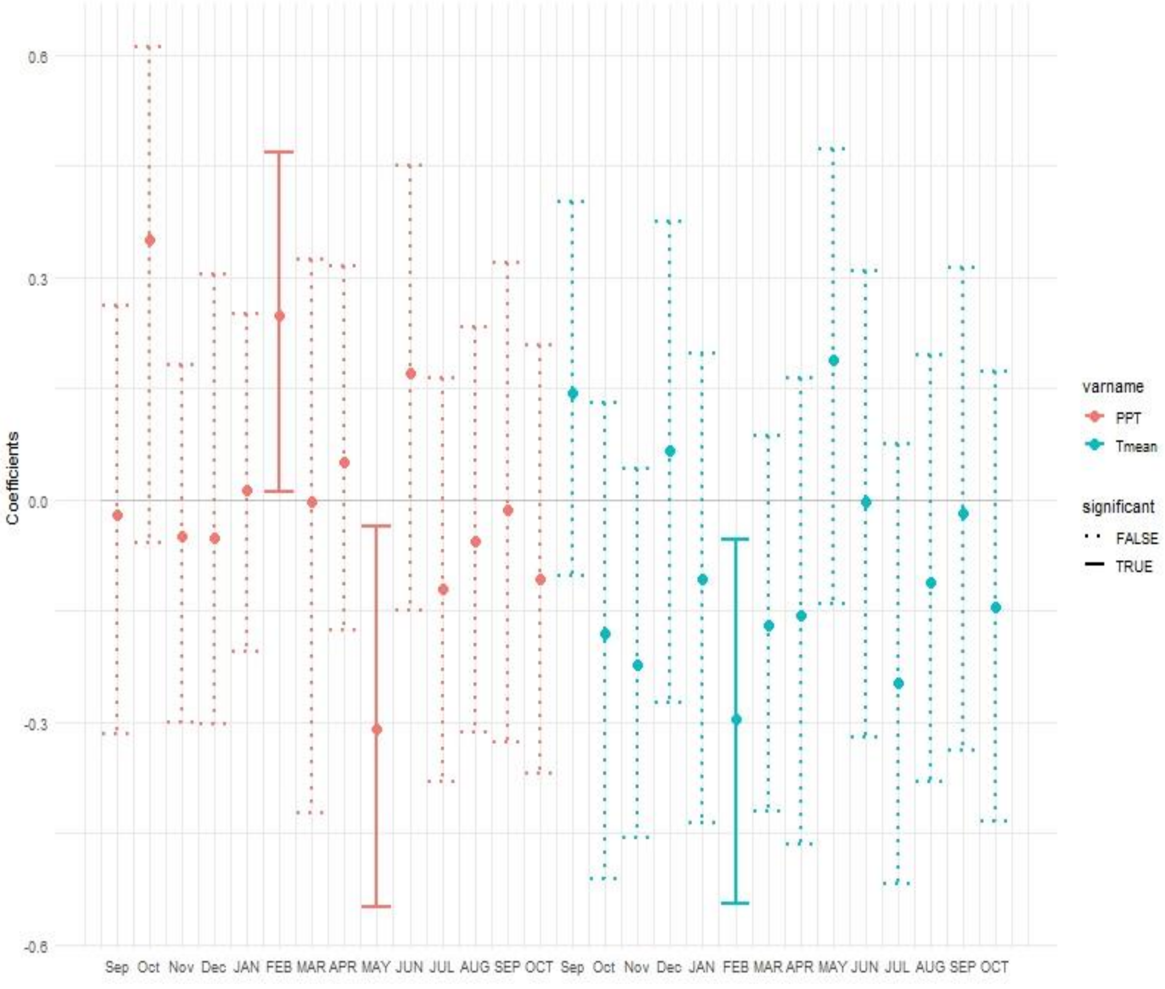
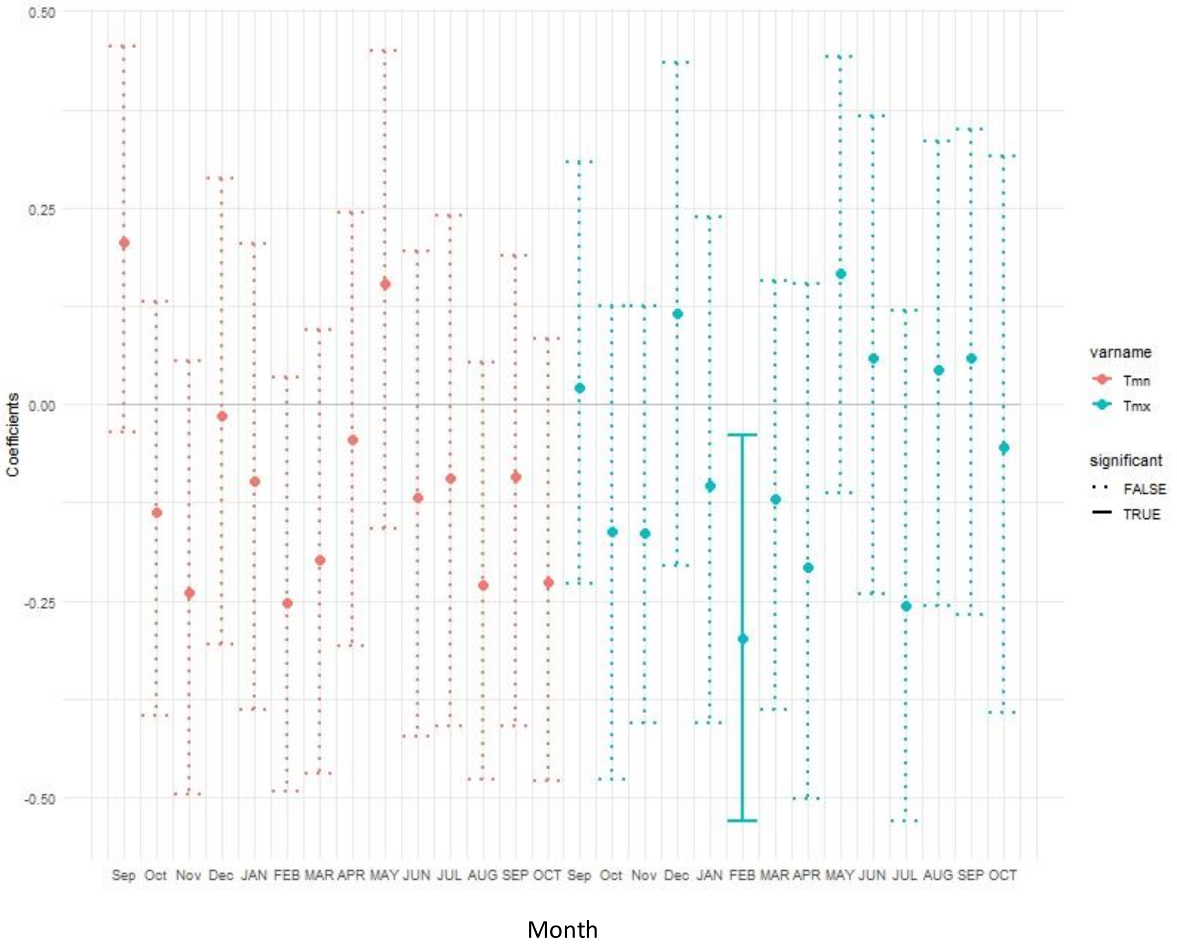


Figure 8

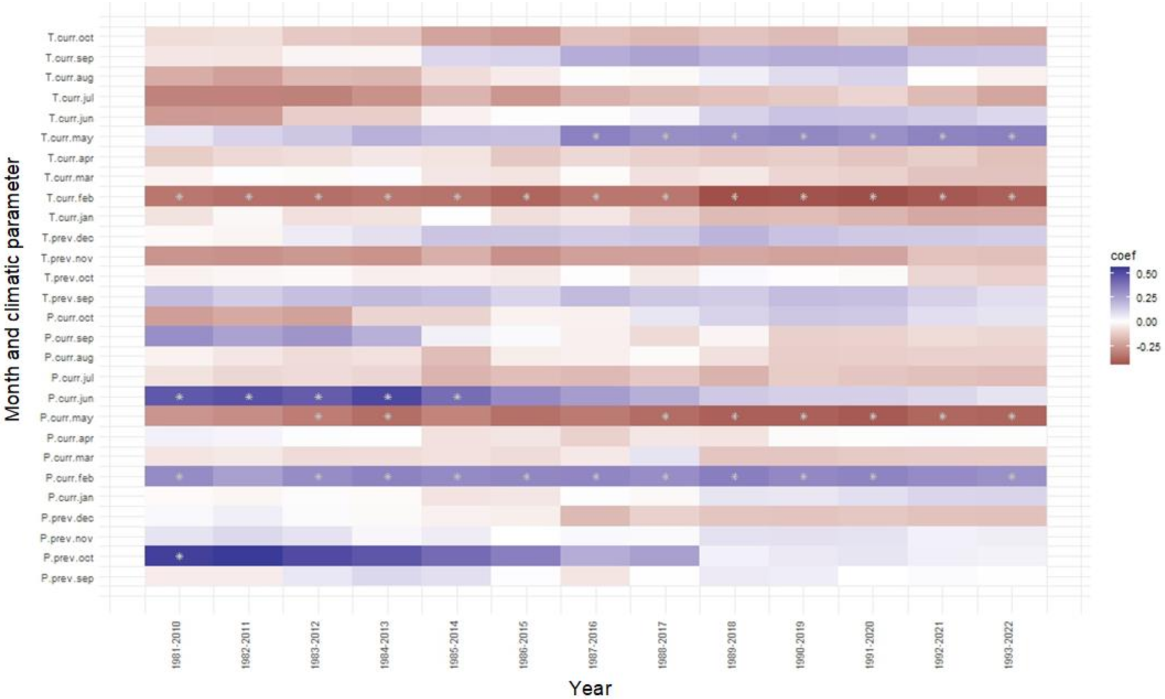
Relationship between the tree-ring residual chronology of chir pine with monthly maximum (Tmx) and minimum (Tmn) temperature. The solid bar indicates significant relation while the dashed bar indicates statistically insignificant correlation



The present study analyzed the temporal stability of the growth-climate response of the chir pine. The result indicated that the response is stable to changing over time (Figure 8). The response of pine growth to the February and May month precipitation and February month temperature is persistent over time (Figure 9). Looking at the temporal stability of the growth response to seasonal average climate, there is no obvious shift in the response, though there are changes in the strength of association between the tree growth and climatic parameters. Response of growth with May month temperature is positively intensified. The response of growth to current year June and previous year October is weakening during recent years. Though there are limited studies in the temporal response of pine growth to climate in the Nepal Himalaya, studies on the *Abies spectabilis* (Gaire et al., 2020; 2023b; Schwaab et al., 2018) and *Shorea robusta* (Baral et al., 2022) have reported temporally stable to changing response of growth to climatic parameters. A study from the Gaurishankar Conservation Area observed temporal shift in the growth limiting factor in *Abies spectabilis* (Schwab et al., 2018).

Figure 9

*Temporal (Moving correlation) variation in climatic response of pine growth in Melamchi Area. The filled color indicates correlation coefficient and * symbol indicates significant response, P and T denotes temperature and precipitation*



4. Conclusion

A dendroecological educational field research work successfully developed an 83 years long tree-ring width site chronology of chir pine from the Melamchi region of Nepal spanning from 1941 to 2023 AD. The quantitative radial growth analysis revealed that the species is growing radially at a rate of 2.7 mm per year on an average. Despite the presence of some false rings, study found that chir pine of the region has huge dendrochronological potential and hence can be used for multi-aspect tree-ring research especially to explore the impact of climate change on forest and forest health. The basal area increments chronology of the species indicating a growing stage of the pine forest. Both temperature and precipitation in different months and seasons are acting as major growth-limiting climatic factors for the pine. Studies incorporating more samples as well as sampling from multiple sites can provide a robust picture on long-term pine growth and their climatic sensitivity along environmental gradients in the Himalayas. Future education field studies can extend the scope of the research incorporating multiple tree species and focusing on contemporary environmental issues.

Acknowledgements

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