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Original Article

Tree-ring climate response of chir-pine (*Pinus roxburghii* Sarg.) in the sub-tropical forest, western Nepal

Rachana Bhandari[1,2], **Bijay Pandeya**[1,2], **Balkrishna Ghimire**[1*]

1 Faculty of Forestry, Agriculture and Forestry University, Hetauda, Makawanpur, Nepal
2 Département des Sciences Fondamentales, Université du Québec à Chicoutimi, Québec, Canada
* Corresponding author: bkghimire@afu.edu.np

ABSTRACT

A dendrochronological study was carried out to investigate the relationship between the growth of chir pine (*Pinus roxburghii*) and climatic variables in the subtropical forest of western Nepal. Using tree ring analysis and meteorological data gathered from a nearby meteorological station, a 78-year (1944 to 2021) long chronology has been created. Temperature and precipitation were found to have a substantial impact on *P. roxburghii* radial growth. Although there were positive correlations between precipitation and tree growth in January, December, and February to April, these relationships were not statistically significant. According to the correlation analyses, there was a negative relationship between the tree growth and the precipitation in September and August of the current year as well as the September of the previous year. Notably, temperature was crucial, as there were significant positive relations found between the minimum and maximum temperatures and tree growth. The temperature of the previous year (September, November, and December) as well as the current year (June to November) had a positive correlation with the growth of tree rings. The results indicated that while temperature was favorable for chir pine radial growth practically all months and seasons, summer to post-monsoon precipitation limited tree growth. Furthermore, the increasing average minimum temperature had a more significant relation with the tree ring growth than the average maximum temperature. Our result demonstrated that the growth of subtropical *P. roxburghii* responded positively to the present scenario of rising temperature and falling precipitation in the study area. This research contributes valuable insights into the complex dynamics of forest ecosystems and their responses to changing environmental conditions.

Keywords: Climate change, dendrochronology, tree ring analysis, precipitation, Nepal Himalaya region

Introduction

The climate around the globe has been changing, which is hastened mostly by the greenhouse effect resulting in global warming and inconsistent precipitation patterns (Tiwari *et al.* 2020). Climate change and global warming are the most widely discussed topics among academicians, government officials, and policymakers (Shah *et al.* 2019). With an annual increase in temperature of 0.04 to 0.06 °C, over the global average, Nepal is particularly vulnerable to the effects of climate change (Shrestha & Aryal 2011; Shrestha *et al.* 2017; Karki *et al.* 2020). Globally, forest ecosystems have been greatly impacted by changes in the environment, such as sharply rising temperatures and modified precipitation patterns. The frequency and intensity of extreme weather events can shift disproportionately large in response to even

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small fluctuations in climate variables, such as changes in their mean or variance. This can present a serious challenge to living things, making it difficult for them to adapt and respond appropriately (IPCC 2014, 2022).

The Himalayan region of Nepal has already been challenged by major climate changes which can be distinguished in the cryosphere and the overall hydrological cycle resulting in extreme socio-economic impacts on the people residing there (Aryal *et al.* 2020). The diversity in topography and climate of the Himalayas has been acknowledged with rich natural archive(s) of climate which encompasses tree rings, ice cores, lake sediments, and so on (Bhandari *et al.* 2019). Amidst all these chronicles, tree rings are thought to be promising with the annual accuracy necessary for the comparison of monthly and annual meteorological data (Fritts 1976; Speer 2010). Dendrochronology and dendroclimatology are two such methods that can help to address this problem for an accurate estimation of past climate (Fritts 1976; Cook & Kairiukstis 1990; Chhetri & Thapa 2010; Speer 2010; Gaire *et al.* 2013; Thapa *et al.* 2015; Shekhar *et al.* 2018; Dhyani *et al.* 2022). Dendroclimatology has been the best opportunity to study the tree's relation to the climate and the climate change-induced impact on the growth of the plant (Fritts 1976; Cook & Kairiukstis 1990; Chhetri & Thapa 2010). The annual growth ring of trees shows differences in their widths i.e., narrow or broad due to the impact of climatic and non-climatic influences on trees (Fritts 1976). These patterns of growth ring widths can be evaluated within a tree and cross-matched with those of other trees belonging to the same species that grow in the same geographic area and experience similar environmental and climatic circumstances. Without obvious seasonality, trees growing in subtropical and tropical climates have a low degree of annual fluctuation in tree ring width (Rozendaal & Zuidema 2011). This may account for the challenge of cross-dating complacent plants (Van der Werf *et al.* 2007; Speer 2010; Wils *et al.* 2011). Natural events, such as forest fires (Vasileva & Panayotov 2016; Szymczak *et al.* 2020); landslides (Struble *et al.* 2020), insect damage (Lynch 2012), and human activities, such as resin or latex collection, might all be dated using the results of tree ring cuts.

Because of its topography and extremely delicate ecosystem, Nepal is more vulnerable to climate change. The lack of extensive instrumental climatic data poses a significant challenge in examining spatiotemporal trends in the forest ecosystem of Nepal (Cook *et al.* 2003). More than 20 different tree species have been examined through dendrochronological research in Nepal; these include common treeline trees found in the higher Himalayan region, such as *Betula utilis* D.Don and *Abies spectabilis* (D.Don) Spach (Tiwari & Jha 2018). Though most of these researches concentrate on conifers, a small number of broad-leaved trees such as *Alnus*, *Betula*, *Castanopsis*, and *Rhododendron* have been taken into consideration. The majority of tree ring research conducted in the Nepal Himalayas has focused on lower temperature zones, including high mountain forests and subalpine treelines. However, some research has also been carried out in subtropical regions (Speer *et al.* 2017; Aryal *et al.* 2018; Sigdel *et al.* 2018).

Conifer species show tremendous potential for dendrochronological research because of their longer lifespans and increased sensitivity to climatic conditions (Bokhari *et al.* 2013). *Pinus roxburghii* Sarg. (Pinaceae), commonly known as 'chir pine' is a native species of the Himalayas that grows in Nepal, Bhutan, India, and Pakistan. It can grow well in almost all types of soil (Jackson 1994). This species, which makes up the fifth most dense tree species in Nepal, is found throughout the subtropical region and makes up 8.54% of the nation's total forest cover (DFRS 2015). Due to the formation of distinct observable annual rings, this pine species is considered to be the most suitable species for dendrochronological study (Bhuju & Gaire 2012). Only a few studies in the Himalayas had previously looked at the dendrochronological potential of chir pine (Bhattacharyya *et al.* 1992; Brown *et al.* 2011; Borgaonkar *et al.* 1999). However, there have been several studies for this species covering both the high and middle mountains of Nepal Himalaya (Bhuju & Gaire 2012; Shrestha *et al.* 2017; Speer *et al.* 2017; Sigdel *et al.* 2018; Aryal *et al.* 2020). In addition, *P. roxburghii* is one of the most significant tree species in terms of the local economy since it gives them access to wood, resins, fuel, cattle beds, and thatching materials. Research indicates that the chir pine forest in its natural state is extremely vulnerable to the availability of moisture during the early growth season, especially in the drier parts of western Nepal (Sigdel *et al.* 2018; Aryal *et al.* 2018). We conducted this study to gain further insight into how climate variables affect *P. roxburghii* growth in the subtropical region of western Nepal. From this study, we intended to reveal the growth-limiting climatic factors for the radial growth of this species in the study area.

Materials and methods

Study area

The study was carried out in the Dhurkot Rural Municipality of the Gulmi District Nepal. The Dhurkot Rural Municipality is located at 28.06-28.17°N and 83.06-83.21°E geographic coordinates representing the hilly area of the country. The study area is located in the western part of Gulmi district (Fig. 1A). The altitude in this area ranges from 1,000 to 2000 m above sea level. The climate characterized the dry winter subtropical to a temperate highland with minimum and maximum means of temperatures ranging from 19 °C to 39.5 °C, respectively. The typical summer temperature is between 29 °C and 33 °C, while the average winter temperature is between 19 °C and 23 °C. Precipitation varies from 620 mm to 1400 mm on average. The region receives 365.7 mm of precipitation annually on average, with the monsoon season beginning in mid-June, peaking in July and August, and then gradually decreasing in early September . The forest is dominated by *Pinus roxburghii*, and associated species include *P. patula* Schiede ex Schltdl. & Cham. (Plantation forest), *Rhododendron* spp., at higher altitudes whereas *Alnus nepalensis* D.Don, *Schima wallichi* (DC.) Korth. and *Castanopsis indica* (Roxb. ex Lindl.) A.DC. are common along the foothills of the forests and in the vicinity of the villages.

Sample collection

We selected forest blocks from the Siddhathan community forest with an area of 168.2 ha for tree core sample collection (Fig. 1A, green points right above). This chir pine forest is located in the southern part of Dhurkot rural municipality with the geographical location 28.07758°N and 83.1325°E (Fig. 1B). The sampling site is situated between 1400 and 1800 meters above sea level. A total of 80 cores from 40 individual *P. roxburghii* trees were collected using a Swedish increment borer (Haglof, Sweden) following the commonly practiced technique (Fritts 1976; Speer 2010) (Fig. 1C). The cores were collected from randomly selected trees in the study area. Out of 80 tree cores, only 55 were cross-dated while the remaining 25 cores were eliminated due to physical damage of the cores and difficulty in cross-dating. The geographical locations, elevation, diameter at breast height (DBH), and height of the individual tree were recorded using GPS, diameter tape, and range finder, respectively. To avoid the sampling error, wounded and unhealthy trees were eliminated during the coring. The sampled cores were collected in paper straws in the field and processed following the standard dendrochronological procedure.

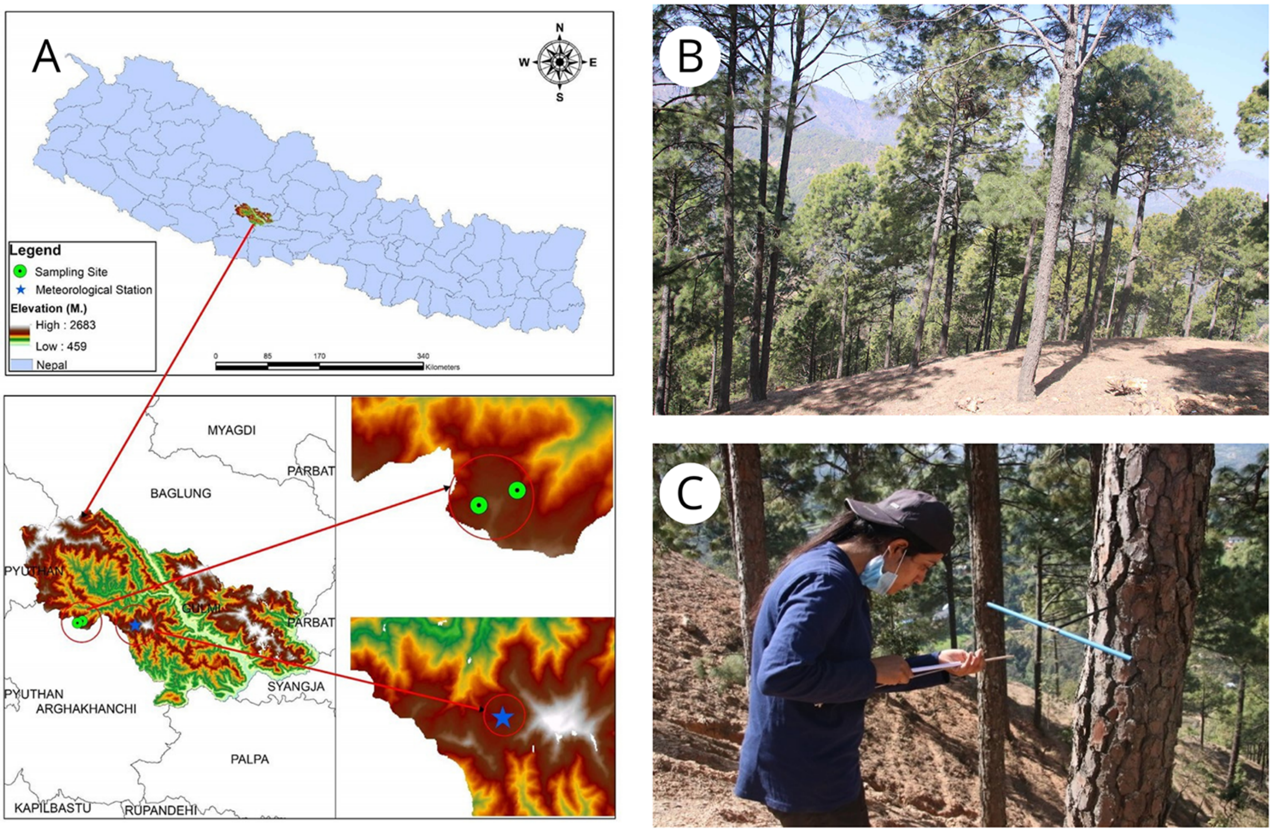

Figure 1. Map of study area in Nepal (A) showing sampling site and weather stations nearby, (B) *Pinus roxburghii* forest stand at study site, and (C) tree core collection of the *P. roxburghii*.

Sample processing

The room-dried wood samples were fixed in the slots of wooden core mounts. The mounted cores were then sanded and polished with gradually finer grades of sandpaper until ring borders were visible under a stereo microscope. The sanded cores were taken to the dendrochronology lab for further analysis. Ring width was measured with the LINTAB, TSAP-Win (Rinn 2003). The tree ring samples were cross-dated by matching the tree-ring width visually utilizing TSAP-Win software. Every single ring in each series was measured at a resolution of 0.001mm (Speer 2010). The COFECHA computer program (Holmes 1983; Grissino-Mayer 2001) was used to test the accuracy of cross-dating and measurement. Tree cores exhibiting poor cross-dating and correlation, displaying minimal year-to-year growth variability, unusual growth trends, breaks, or being identified as very young were excluded before the establishment of the chronology. The corrected ring-width data were standardized by using the computer program ARSTAN (Cook 1985). A negative exponential curve was used to detrend the tree-ring series to remove the biological growth trend related to the tree's age. The detrending of each sample was done to remove the non-climatic age trends, i.e., low-frequency variance (Cook & Peters 1981). Following the detrending of each series, a ring-width chronology for both stands was constructed by computing the average of the detrended tree ring indices across the series for each year using the arithmetic mean method (Fritts 1976). This approach generates a mean value function that emphasizes the signal while smoothing out the noise (Cook 1987; Cook & Kairiukstis 1990). Consequently, standard, residual, and ARSTAN chronologies were developed. Statistical analyses were conducted on the residual chronology statistics spanning the entire period and the standard chronology statistics during the common period. The ARSTAN chronology integrates the residual chronology with a pooled autoregression. The mean sensitivity (MS, relative variation in width between consecutive rings), the first-order autocorrelation (AC1), the mean series intercorrelation (RBAR), and the Expressed Population Signal (EPS) of the chronology were calculated for the common interval.

Climate data

The temperature and precipitation data for the years 1980 to 2021 from the nearest climatic station Tamghas, (alt: 1784m asl; 28.066667°N, 83.25°E) 10km south-east from the study location, was taken from the Department of Hydrology and Meteorology (DHM), Kathmandu (Fig. 1A, blue star right below). The correlation analysis was carried out between the ring width and mean temperature and precipitation to analyze tree growth–climate relationships.

Assessing tree-climate relation

The standardization and mean chronology development, the standard tree ring chronology of *Pinus roxburghii* was related to the instrumental climatic data recorded from the meteorological station. For the correlation and response analysis statistical package 'treeclim' (Zang & Biondi 2015) was used. The correlation analysis was carried out between the ring width and mean temperature and precipitation to analyze tree growth –climate relationships. The seasonal response was analyzed using a function called 'seascorr' included in 'treeclim' which functions equivalently as the function seascorr' (Meko *et al.* 2011) of the MATLAB program (Zang & Biondi 2015). Pearson's linear correlation coefficient was used as the indication of the extent of the relationship between climate and chronology.

Result

Climatic description

The monthly pattern of temperature and precipitation from the year 1980 to 2021 in the study area is shown in Figure 2. The pattern of temperature and precipitation is correlated with each other. The monthly temperature gradually increases from January to April after that the temperature increases rapidly till July and again declines from August to December. The climatic data indicated that temperature varies synchronously with precipitation. The lowest precipitation was recorded in January. Precipitation begin to increase after January, peaked in July, and then declined between August and December.

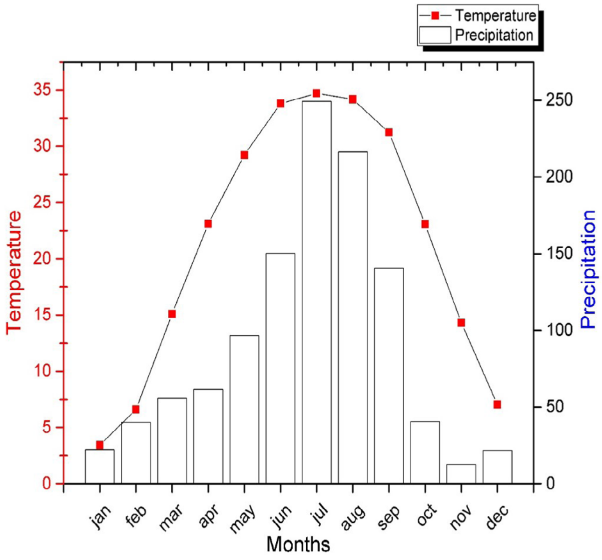

Figure 2. Monthly average temperature and precipitation from meteorological stations of the study area (DHM, Nepal).

Tree ring chronology

We extracted 80 cores from 40 individual trees of *Pinus roxburghii*. Out of the eighty, fifty-five cores were cross-dated and used to create chronologies. The remaining cores were discarded because of defective samples and/or erroneous placement in the mounting frame, as they do not give clear visible rings due to which samples lack reliable synchronization during cross-dating. The independent chronologies with the longest snapping time of 78 years, from 1944 to 2021 were developed from the site (Table 1, Fig. 3 and 4). The standard deviation of the samples and inter-series correlation were 0.30 and 0.41, respectively (Table 1). To assess the standard chronology in-depth, expressed population signal (EPS) cut-off analysis was performed using 0.85 as the threshold value. The RBAR and EPS were calculated using 20-year moving windows with a 10-year overlap and the mean EPS was found to be

0.908 and the mean sensitivity was 0.28 (Table 1, Fig. 4). But according to the statistics, only the years 1970–2010 were adequately reproduced, with an EPS over the threshold value (Fig. 4).

Relationship between radial growth of *Pinus roxburghii* and climatic variables

Precipitation

The radial growth of *P. roxburghii* responded significantly (and mostly negatively) to the precipitation in the study area. The precipitation between February and April only showed a positive response; nonetheless, the relationship was insignificant. We found a significantly negative correlation between radial growth and precipitation during August ($r = -0.33$ $p < 0.05$) and September ($r = -0.30$, $p < 0.05$). Additionally, the precipitation from the previous September had a greater impact on the radial growth ($r = -0.33$ $P < 0.05$) (Fig. 5).

Temperature

Unlike precipitation, the radial growth of *P. roxburghii* was positively correlated with the temperature in the study area. We found a significant correlation between tree growth and temperature of current year June ($r = 0.39$ $p < 0.05$), July ($r = 0.38$ $p < 0.05$), August ($r = 0.49$ $p < 0.001$), September ($r = 0.49$ $p < 0.001$), October ($r = 0.43$, $p < 0.01$), November ($r = 0.54$, $p < 0.001$), and the sum of June-July-August (TJJA) ($r = 0.56$ $p < 0.001$), September-October-November (TSON) ($r = 0.61$ $p < 0.001$), as well as with previous year July ($r = -0.46$, $p < 0.01$), August ($r = -0.39$, $p < 0.05$), September ($r = 0.35$ $p < 0.05$), November ($r = 0.43$ $p < 0.05$), and December ($r = 0.47$ $p < 0.01$) (Fig. 6).

Table 1. Chronology statistics of *Pinus roxburghii* from sub-tropical forest western Nepal.

Cross dated samples	**55**
Master series (years)	1944-2021 (78)
Mean sensitivity	0.28
Interseries-correlation	0.41
Rbar	0.29
Standard deviation	0.30
Expressed population signal	0.907

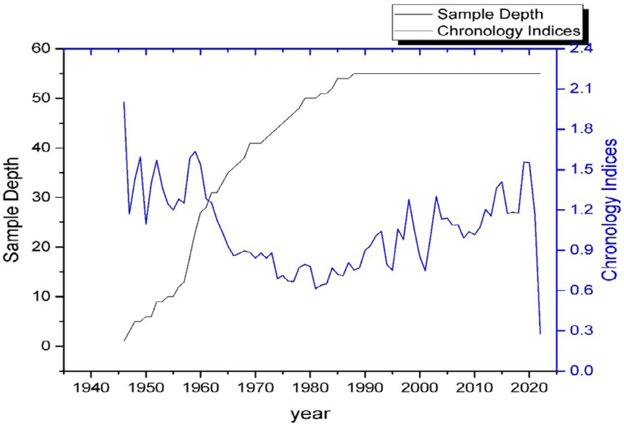

Figure 3. Tree-ring-width site chronologies (blue line) of a *Pinus roxburghii* from Dhurkot with the sample depths (black line).

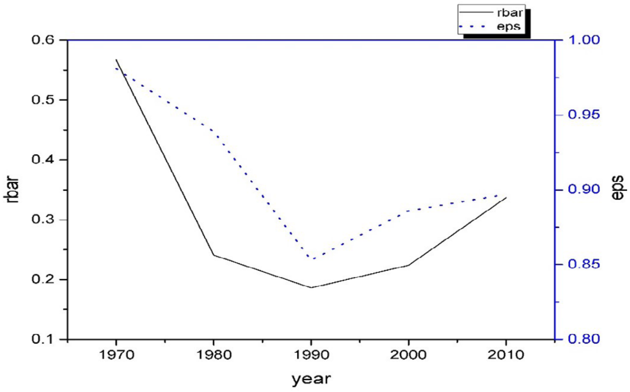

Figure 4. Sample depth variation of mean series inter-correlation (RBAR) and expressed population signal (EPS, dashed blue line) over time (the EPS threshold is 0.85) often used to demonstrate well-replicated chronologies). RBAR and EPS were calculated using 20-year moving windows with a 10-year overlap.

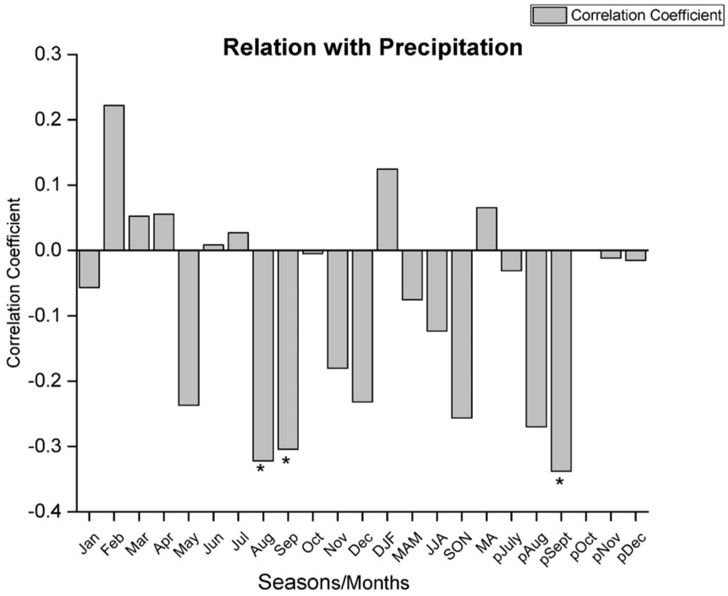

Figure 5. Correlation coefficients between radial growth (tree ring-width) of *P. roxburghii* and the mean of monthly, seasonal precipitation from previous-year July (pJul) to current-year December (Dec). Asterisks indicate significance levels at * $p < 0.05$. DJF: December to February; MAM: March to May; JJA: June to August; SON: September to November; MA: March to April.

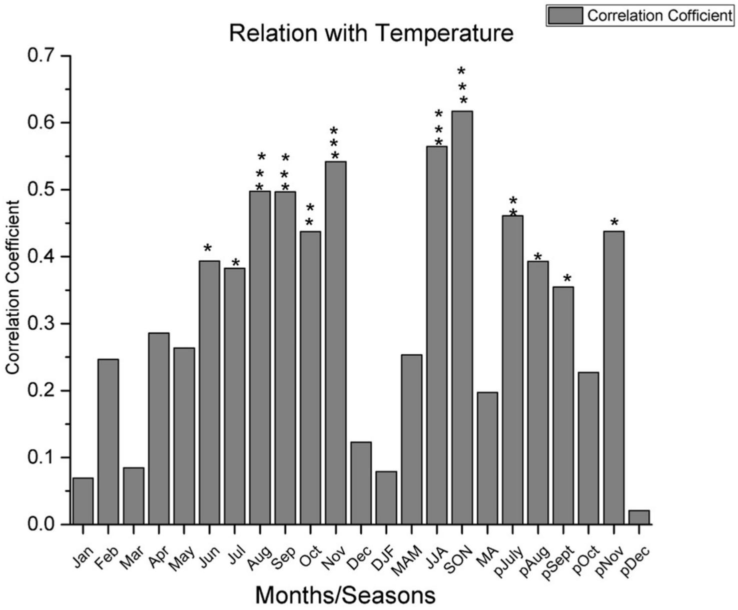

Figure 6. Correlation coefficients between radial growth (ring-width) of *P. roxburghii* and the mean of monthly, seasonal temperature from previous-year July (pJul) to current-year December (Dec). Asterisks indicate significance levels at * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$. DJF: December to February; MAM: March to May; JJA: June to August; SON: September to November; MA: March to April.

Similarly, there was a strong correlation between the radial growth of *P. roxburghii* and both the minimum and maximum temperatures (Fig. 7). It was observed that there was a stronger response to the monthly minimum temperature compared to the maximum temperature. The minimum temperature of the site was significantly correlated with the current year April to November, although the response was stronger from June to November. In addition, the positive correlation of the radial growth was also found with the sum of June-July-August (TJJA) (r = 0.66 p < 0.001), September-October-November (TSON) (r = 0.64 p < 0.001), as well as with previous year July (r=-0.60, p < 0.001), August (r=-0.49, p < 0.001), September (r = 0.42 p < 0.01), October (r = 0.36 p < 0.05), and November (r = 0.49 p < 0.01).

Correspondingly, the maximum temperature also influenced the growth of *P. roxburghii*. The maximum temperature was correlated with August (r = 0.33, p < 0.05), September (r = 0.34, p < 0.05), November (r = 0.44, p < 0.01), and the sum of June-July-August (TJJA) (r = 0.38, p < 0.05), September-October-November (TSON) (r = 0.51, p < 0.001), as well as with previous-year November (r = 0.32, p < 0.05).

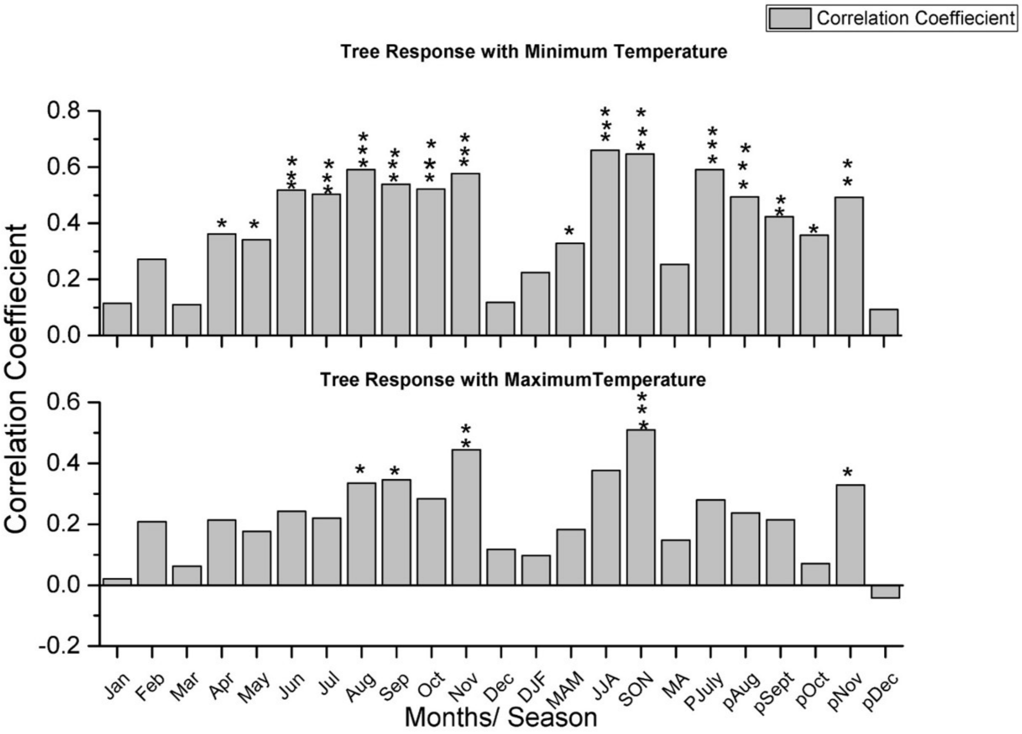

Figure 7. Correlation coefficients between radial growth (ring-width) of *P. roxburghii* and average maximum and minimum monthly and seasonal temperature from previous-year July (pJul) to current-year December (Dec). Asterisks indicate significance levels at * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$. DJF: December to February; MAM: March to May; JJA: June to August; SON: September to November; MA: March to April.

Discussion

Chir pine (*Pinus roxburghii*) is primarily found in arid, exposed, and well-drained areas. It is commonly distributed in the southern aspect of subtropical hills in Nepal. Our study area lies in the warm subtropical region of western Nepal and most of the tree cores for this study were collected within the altitude limit of 1400 to 1800 m asl. The climatic data necessary to evaluate the growth of chir pine in the study area was obtained from the nearest meteorological station, Tamghas. The precipitation and temperature data from the years 1980 to 2021 were taken and analyzed. The climatic data indicated that the precipitation and temperature of the study area showed some irregular fluctuation. An increasing trend was observed in temperature while the precipitation has been slightly declining in recent years, especially after the 1990s which is following the general climatic trend of Nepal Himalaya (DHM 2017; Shrestha *et al*. 2017; Karki *et al*. 2020). By speeding up the rate of evapotranspiration, this increasing trend of temperature creates moisture stress in the plant species (Dawadi *et al*. 2013; Liang *et al*. 2014; Tiwari *et al*. 2017) and may cause the plant to grow more slowly. Furthermore, as the IPCC (2014, 2022) has highlighted, the tendency of this elevated temperature may result in the uncertainty of future precipitation patterns.

The findings showed that the temperature and precipitation levels from the previous year and the current year had an impact on the radial growth of chir pine in our study location. We found that late winter to spring (February, March, and April) precipitation has positive responses to tree growth, even if the correlation was not statistically significant. Pre-monsoon and winter precipitation (May, November, and December) on the other hand, had a detrimental effect on tree development. Rather, in the late to post-monsoon (i.e., August–September) period of both the current and previous year, there was a markedly negative association between precipitation and tree growth. The relationship between the radial growth of chir pine and the spring precipitation in our study area is somewhat in line with Tiwari *et al.* (2020) from Kavreplanchowk, but is contradicted by some other studies from the Himalaya region (Dawadi *et al.* 2013; Tiwari *et al.* 2017; Aryal *et al.* 2018; Sigdel *et al.* 2018). This is reasonable that cool winters and early summer rainy seasons would recharge the ground moisture and promote tree growth during the growing season (Shah *et al.* 2014). The negative relationship between May precipitation and growth, which may be explained by the huge regional scale of these climatic data, is challenging to comprehend. Beyond that, in May, the temperature is high while precipitation is low (Figure 2), which can result in more evapotranspiration and limit the growth of trees as suggested by Gaire *et al.* (2017) and Panthi *et al.* (2017). Previous studies have indicated that pre-monsoon precipitation responded strongly and limited the growth of some tree species such as birch (*Betula utilis*; Betulaceae) (Dawadi *et al.* 2013; Liang *et al.* 2014), Himalayan fir (*Abies spectabilis*; Pinaceae) (Tiwari *et al.* 2017), alpine dwarf shrub (*Cassiope fastigiata* (Wall.) D.Don; Ericaceae) (Liang *et al.* 2013), Himalaya spruce (*Picea smithiana* (Wall.) Boiss.; Pinaceae) (Panthi *et al.* 2017), and *Pinus wallichiana* A.B. Jackson (Gaire *et al.* 2019) in the central Himalaya of Nepal. However, this isn't limited to the Himalayas of Nepal. Similar growth responses have also been reported in different conifer and broadleaf tree species from the nearby region in the western Himalayas (Shah *et al.* 2014; Yadav *et al.* 2014; Sohar *et al.* 2017; Ram 2018), in the eastern Himalayas (Shah & Mehrotra 2017), and the southeastern Tibetan Plateau (Liang *et al.* 2012; Li *et al.* 2017). Rather, we found that the radial growth of chir pine is limited by precipitation from the current years August-September, November-December, and the preceding year August-September. This is because the subtropical forest zone in the western Himalayas experiences more drought stress on tree growth. According to Fu *et al.* (2014), the warmer trend in the spring increases moisture stress for the early growing season and eventually restricts tree growth. In our study area, the negative correlation between tree growth and precipitation could be due to the excessive precipitation during monsoons which can lead to waterlogged soil and reduce the amount of oxygen available to the roots (van Veen *et al.* 2014; Pan *et al.* 2021). This can cause root damage and decreased absorption of nutrients, which in turn can inhibit tree growth (de Oliveira & Joly 2010; Ferry *et al.* 2010; Guo *et al.* 2011). On the other hand, a dry post-monsoon season leads to suppression of growth which may be due to a lack of moisture in the soil and the inability of trees to adapt to the dry season right after the monsoon. In addition, thin or sandy soil layers and hilly slopes may be unable to hold enough water to counteract post-monsoon and winter drought stress to maintain tree growth and survival (Cleaveland *et al.* 2003).

The growth of the chir pine in our study area has demonstrated amazing stability with temperature, regardless of precipitation. Temperature, throughout the year and season, showed a positive relationship with the tree chronology. The study on the identical species in western Nepal (Aryal *et al.* 2018; Sigdel *et al.* 2018) reveals a noteworthy inverse correlation between chronology and the temperature from February to April. Nevertheless, in this study, it was observed that during the same period, the temperature exhibited a positive response to the growth of *P. roxburghii*, even though the relation was statistically insignificant. The temperature starts gradually increasing from February and it exceeds the annual average during March. The combination of high temperatures and low precipitation during the pre-monsoon season (March to May) exacerbates tree stress and inhibits tree growth (Borgaonkar *et al.* 1999; Kharal *et al.* 2017; Gaire *et al.* 2017; Tiwari *et al.* 2017). This slight positive response of pre-monsoon (February-April) temperature in our study area indicated that the temperature before the growing season influences growth during the subsequent growing season (Gaire *et al.* 2013). However, the only case where temperature was positive but non-significantly related to growth might be due to the missing rings and shorter chronology obtained in our study as the longer period of the samples could dilute the response. We found that the mean temperatures during the summer monsoon (July-September) and post-monsoon (October-November) had the greatest impact on tree growth. This follows previous studies in central Himalaya (Cook *et al.* 2003; Bräuning, 2004; Thapa *et al.* 2015; Gaire *et al.* 2020). In contrast, several studies from the Himalayas and surrounding areas have shown a significant negative correlation between temperature and tree ring growth (Yadav & Singh 2002; Dawadi *et al.* 2013; Liang *et al.* 2014; Yadav *et al.* 2014; Gaire *et al.* 2017; Li *et al.* 2017; Panthi *et al.* 2017). This could be the reason that the high summer temperatures often come with longer days, more sunlight, and more precipitation, all of which create optimal conditions for tree growth. Our data shows a strong positive correlation between tree ring growth and not only the growth year but also the seasons and temperature of the preceding year. Some previous studies on blue pine from the neighboring region have also found that winter temperatures of the previous year had a positive relationship with tree-ring growth (Yadav & Bhattacharyya 1996; Yadav & Amalava 1997; Shah *et al.* 2009). This direct relationship between tree growth and winter temperature indicates that chir pine trees carry on a significant amount of photosynthesis during warm winters, with stores of energy reserves used in the following growing season as described for Himalaya pine by Singh and Yadav (2000) and Shah *et* *al.* (2019). In the reports from Qinling Mountains central China, Liu and Shao (2003), Dang *et al.* (2007), and Liu *et al.* (2008), demonstrated a positive correlation between tree rings and temperatures from the previous September to the current July. This underscores a noticeable influence of temperature beyond the typical growing season on tree species. It can be explained that the higher temperature until the post-monsoon can extend the growing season which can be beneficial for the lignification of the cell wall and help in the formation of wider growth rings (Li *et al.* 2017). On the other hand, the warm temperature during the early growing and post-winter season may reduce the winter dormancy level (Waring & Franklin 1979), raise soil leaf temperature, promote rapid root and shoot growth (Peterson *et al.* 2002), and lead to the early initiation of cambial activity, thereby increasing the supply of photosynthates (Splechtna *et al.* 2000). Consequently, higher radial growth with wider tree rings observed in warmer years may be attributed to abundant availability of photosynthates (Oberhuber 2004; Weigt *et al.* 2018).

The response of seasonal and monthly maximum and minimum temperatures to *P. roxburghii* was found to be reasonably constant in this study. Moreover, when the minimum temperature was raised, a notable response of temperature-radial growth was seen, suggesting that the minimum temperature played a significant growth-limiting role for chir pine in the study area. This indicated the prevalence of threshold temperature, either above or below which the tree radial growth responses become less sensitive to temperature (Paulsen *et al.* 2000; D'Arrigo *et al.* 2004; Yadav *et al.* 2014; Kullman 2007). However, irrespective of the positive response of minimum and maximum temperatures (Tmin and Tmax) on tree growth, the precipitation during the same period exhibited either a negative response (Aug-Sept) or did not appear to exert a significant effect (rest of the months). The data suggested that the rate of warming in the Himalayan region is more pronounced compared to many other regions in the world (IPCC 2014, 2022; DHM 2017; MoFE 2019; Thakuri *et al.* 2019). In addition, observational records from the Nepal Himalayas suggest a temperature increase across all seasons, with winter warming being particularly noticeable compared to other seasons (DHM 2017; MoFE 2019). Moreover, the warming trend is observed higher for the average maximum temperature (~0.04 °C per year) than for the average minimum temperature (~0.02 °C per year) (Karki *et al.* 2020). This suggests that the small rise in the annual minimum temperature seems to be more adaptable to pine growth in mountain regions than the increase in maximum temperature. Consequently, the correlation between the growth of pine trees and rising minimum temperature in the study area can be interpreted as, when the average minimum temperature rises, the metabolic rate of the tree increases with the absorption of more nutrients and water, thereby promoting growth. In addition, accommodating warmer temperatures can extend the growing season of trees, allowing them to grow for a longer period and produce more biomass.

Conclusion

We developed a 78-year-long chronology extending from 1944 to 2021 using *Pinus roxburghii* cores in the subtropical forest of western Nepal. This is one of the few studies in that particular region. The result indicated that *P. roxburghii* trees are sensitive to current and previous years' late monsoon to post-monsoon precipitation (August and September). In addition, tree growth showed a positive response to February precipitation although it was not statistically significant. On the other hand, tree growth showed a positive correlation with the temperature of almost all months and all seasons not only the growing year but also the previous year. However, the response was strong with the late summer and autumn (August, September, November, and December) temperatures. In addition, pre-monsoon and post-monsoon precipitation seem to be effective for the radial growth increment of *P. roxburghii*. The result also indicated that the increase in average minimum temperature generally supports the tree ring growth more than the elevated average maximum temperature. Our study concluded that *P. roxburghii* responded positively to the climatic change scenario as higher temperature mostly favors the radial growth of this species in the study area. Nevertheless, additional research on other tree species and locations within the sub-tropical Himalaya region would ideally be required to substantiate such prediction.

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Conflict of Interest

There is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Authors' Contributions

BG and RB conceptualized the research. RB and BP conducted the field work and the experimental work at laboratory and analyzed the data. RB drafted the first copy of the manuscript. BG critically commented and revised the manuscript. All the authors read and approved the final version of the manuscript.

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