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Growth performance of planted population of *Pinus roxburghii* in central Nepal

Achyut Tiwari[1*†], Nita Thapa[1†], Sugam Aryal[2], Prabina Rana[3] and Shankar Adhikari[4]

Abstract

Background: Climate change has altered the various ecosystem processes including forest ecosystem in Himalayan region. Although the high mountain natural forests including treelines in the Himalayan region are mainly reported to be temperature sensitive, the temperature-related water stress in an important growth-limiting factor for middle elevation mountains. And there are very few evidences on growth performance of planted forest in changing climate in the Himalayan region. A dendrochronological study was carried out to verify and record the impact of warming temperature tree growth by using the tree cores of *Pinus roxburghii* from Batase village of Dhulikhel in Central Nepal with sub-tropical climatic zone. For this total, 29 tree cores from 25 trees of *P. roxburghii* were measured and analyzed.

Result: A 44-year long tree ring width chronology was constructed from the cores. The result showed that the radial growth of *P. roxburghii* was positively correlated with pre-monsoon (April) rainfall, although the correlation was not significant and negatively correlated with summer rainfall. The strongest negative correlation was found between radial growth and rainfall of June followed by the rainfall of January. Also, the radial growth showed significant positive correlation with that previous year August mean temperature and maximum temperature, and significant negative correlation between radial growth and maximum temperature (Tmax) of May and of spring season (March-May), indicating moisture as the key factor for radial growth. Despite the overall positive trend in the basal area increment (BAI), we have found the abrupt decline between 1995 and 2005 AD.

Conclusion: The results indicated that chir pine planted population was moisture sensitive, and the negative impact of higher temperature during early growth season (March-May) was clearly seen on the radial growth. We emphasize that the forest would experience further moisture stress if the trend of warming temperatures continues. The unusual decreasing BAI trend might be associated with forest management processes including resin collection and other disturbances. Our results showed that the planted pine forest stand is sub-healthy due to major human intervention at times. Further exploration of growth climate response from different climatic zones and management regimes is important to improve our understanding on the growth performance of mid-hill pine forests in Nepal.

Keywords: Radial growth, Tree-rings, Basal area increment (BAI)

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* Correspondence: achyutone@gmail.com; achyut.tiwari@cdb.tu.edu.np
†Achyut Tiwari and Nita Thapa contributed equally to this work.
[1]Central Department of Botany, Tribhuvan University, Kirtipur, Kathmandu, Nepal
Full list of author information is available at the end of the article

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Background

Earth's climate has never been static and has shown great variability since its origin, the recent change, however, is accelerated by greenhouse effect causing abrupt temperature rise and unpredictable patterns of precipitation (Houghton 2004). Nepal, a Himalayan country, is highly threatened by impact of climate change. The atmospheric temperature in Nepal has been increasing at a rate of 0.04 to 0.06 °C/year, with a higher rate than the global average (Shrestha and Aryal 2011; Shrestha et al. 1999; Shrestha et al. 2000; Shrestha et al. 2017). Environmental changes including rapidly warming temperature and uncertainty in rainfall pattern have widely affected forest ecosystem all over the world (IPCC 2014). These climatic factors cause changes in growth rate of forest trees, which is directly linked with forest economics and ecosystem services provided by the forests. Temperature usually limits tree growth in poleward and high altitude treelines (Körner 2003; Holtmeier and Broll 2007; Harsch et al. 2009); hence, trees are expected to increase growth and shift poleward and upward with warming temperatures and increased CO_2 uptake (Körner 2000; Borgaonkar et al. 2011; Gaire et al. 2017). However, tree growth in high mountains and dry regions could also be impaired by increases in temperature, mostly due to warming-induced water deficit (Cook et al. 2003, Sano et al. 2005, Lv and Zhang 2012, Dawadi et al. 2013, Liang et al. 2014, Qi et al. 2015, Gaire et al. 2017).

Nepal comprises nearly 45% of land mass (6.61 million ha) as forest including other woodlands (DFRS 2015). The government of Nepal has handed over about one-third of the total forest area to over 30,000 forest user groups, and the community forestry program in Nepal is considered as one of the highly successful avenues in nature conservation as a result there has been substantial increase in forest area in the middle and high mountains of Nepal (DFRS 2015). However, the technical aspect of forest management in Nepal is poorly understood due to less scientific studies on the growth performance of forest trees including forest health and harvesting modality of forest products in the context of changing climate and human interference.

Nepal is more prone to climate change due to its topographic structure and highly fragile ecosystem, and of course, the absence of long-term instrumental climatic data has become a major problem of studying spatiotemporal trends of climate change in forests ecosystem of Nepal (Cook et al. 2003). To overcome this situation, several alternative tools can be helpful for the precise estimation of past climate, analyze the current status, and speculate the future trends in environmental changes. Dendroclimatology offers one of such alternative tools for reconstruction of forest stand structure and can date the time at which tree rings were formed in many types of wood, to an exact calendar year, as well as in understanding climate dynamics and forest health (Chhetri and Thapa 2010, Cook and Kairiukstis 1990, Fritts 1976, Gaire et al. 2014, Speer 2010, Thapa et al. 2014, Tiwari et al. 2017). Hence, the climatic information preserved in the annual ring of trees is a valuable resource for studying the environmental changes such as temperature and precipitation from the climate-sensitive localities, particularly prior to the interval covered by direct climatic measurements (Cook and Kairiiukstis 1990; Speer 2010).

Dendrochronological studies from Nepal have examined more than 20 tree species including the most common treeline trees *Abies spectabilis and Betula utilis* from the higher Himalayan region (Tiwari and Jha 2018). Most of these species are conifers, only a few studies are covered for broad-leaved trees like *Alnus*, *Betula*, *Castanopsis*, and *Rhodondendron.* Tree ring studies in Nepal Himalaya have been more restricted to the lower temperature zones including high mountain forest and subalpine treelines; however, some studies also have been carried out from subtropical region (Speer et al. 2017, Sigdel et al. 2018, Aryal et al. 2018).

Previously, chir pine was examined for its dendrochronological potential in only a few studies in Himalaya (Bhattacharya et al. 1992, Brown et al. 2011, Borgaonkar et al. 1999). However, there have been a number of studies for this species covering both high and middle mountains of Nepal Himalaya (Bhuju and Gaire 2012, Shrestha et al. 2014, Speer et al. 2017, Sigdel et al. 2018, Aryal et al. 2019). Although *P. roxburghii* is also one of the most important tree species for the local people for its multipurpose uses such as timber, resins, firewood, the growth climate relationship, and forest stand health in panted forest are unknown in Nepal. Studies indicated that chir pine natural forests are highly sensitive to moisture availability in early growing season in relatively drier regions of western Nepal (Sigdel et al. 2018, Aryal et al. 2019); hence, we could expect more moisture-related physiological stress to chir pine forests in mid-hills, as central Nepal is experiencing intensified spring drought (Panthi et al. 2017; Nepal et al. 2020). Generally, the local people in the mid-hills of Nepal blame chir pine for transforming the hills to drier condition with drying of spells and suppression of species turnover, and of course, the blame is more intense for planted population. However, we do not have strong evidence to support the blame and to address the controversial issue regarding the impact of chir pine for drying of the ecosystem. We sought to access the growth-limiting climatic factor for radial growth and trend in aboveground biomass production in the form of BAI (basal area increment) using tree ring width of *Pinus roxburghii* planted forest from mid-hills of central Nepal, so that we could access the ecological health of these forests.

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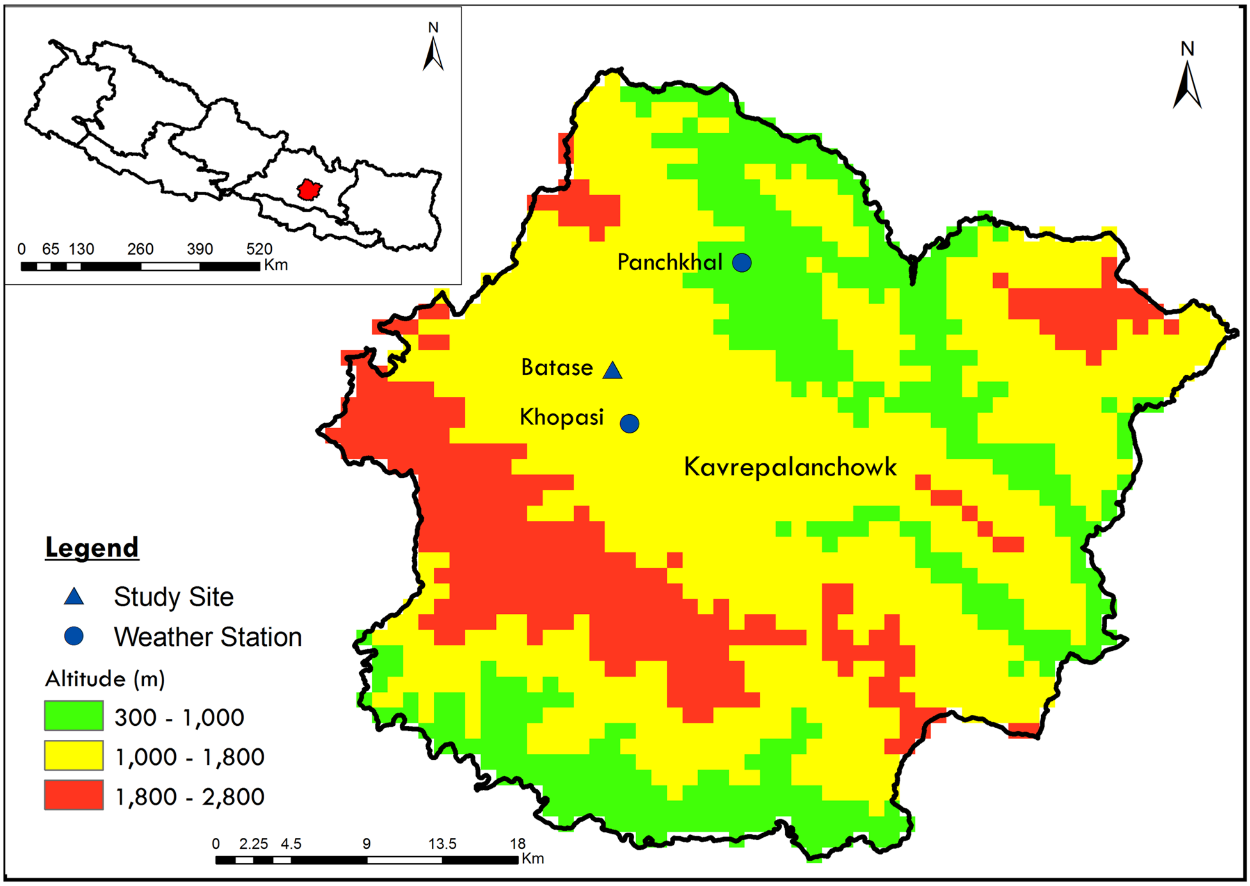

Fig. 1 Map of study area in Nepal showing sampling site and weather stations nearby

Materials and methods

Study area

The study was carried out at the Batase community forest (27.5952° N, 85.5477° E) of Kavrepalanchowk district in central Nepal (Fig. 1). The study area is a planted monoculture chir pine community forestin, the subtropical lower temperate zone in central Nepal. It occupies an area of 61.50 hectares area extending from 1560 to 1627 m elevation, the hill was bare five decades ago, at which seedlings were planted through Australian funding projects in collaboration with Department of Forests, Government of Nepal (DFRS 2015). The forest is now dominated by *Pinus roxburghii* with very few individuals of *Alnus nepalensis* and *Ageretina* sp., the area looks dry with drying of streams and water resources (local people reports) with white loose soil type with erosion in steep slope. Almost from all pine trees, barks were extracted for resin collection, and frequent cut stumps were observed during field visits.

Species

Pinus roxburghii Sarg. (chir pine) is one of the most common conifers in the sub-tropical region of Nepal and is distributed in all aspects of Western Himalaya but is generally found in well-exposed southern slopes in Central and Eastern Nepal. It can grow reasonably well in almost all types of soil (Jackson 1994) and has been proved to be a successful pioneer even at most degraded sites due to its high survival rate. Chir pine occupies 8.54% of total forest cover, being the fifth most dense tree species in Nepal with 7.05% of total volume in forest, and has also been an important planted tree species linked with highly successful community forestry program in Nepal (DFRS 2015). It possesses a biomass of 9.09 tons/hectare in Nepal, which accounts for 5.09% of total woody biomass (Aryal et al. 2018).

Sample collection

The tree core samples were collected from relatively less disturbed forest stand of Batase with bigger pine trees (Fig. 2). We collected a total of 85 cores from 40 *Pinus roxburghii* randomly using increment borer, i.e., two cores and sometimes three cores from the selected trees. The trees were selected with a healthy crown and without visible fire scars. The cores were then immediately kept in the plastic straw pipe with proper labeling. In

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addition, the GPS location, DBH, and height of each individual trees were measured. The cores were air dried for a few days. The cores were brought to the Dendrolab of NAST (National Academy of Science and Technology) Khumaltar, Kathmandu, for lab analysis. The air-dried cores were mounted in a wooden frame with transverse surface facing up (Speer 2010). The cores then were sanded with sanding papers of grids ranging from 120-400 until the ring boundaries were visible under binocular microscope. The cores with visible annual ring were dated to the calendar year.

Then, the tree ring measurement was done using a hardware called LINTAB attached having TSAP-Win program. Every single ring in each series was counted from bark toward the pith under the microscope adjusting the resolution for clear visualization. After the completion of ring width measurement, the individual tree-ring series were cross dated using the alignment technique, looking at the math graph and cross dating statistics as explained by Rinn (2003). The errors in the cross dating was rechecked and confirmed by using the computer program COFECHA (Grissino-Mayer 2001; Holmes 1983); standardization was carried out applying a computer program ARSTAN (Cook 1985) in order to remove age and other long-term variability that are considered as noise in dendrochronological study (Fritts 1976). The detrending of each sample was done using a negative exponential curve in order to remove the non-climatic age trends (Cook and Peters 1981). After detrending each series, ring-width chronology of both stands was developed by averaging the ensemble of detrended tree ring indices across the series for each year using arithmetic mean (Fritts 1976) which produces a mean value function that concentrates on signal and averages out the noise (Cook and Kairiiukstis 1990). Thus, standard, residual, and Arstan chronologies were developed. The residual chronology statistics of the overall period and standard chronology statistics of the common period were analyzed. Arstan chronology includes the residual chronology incorporated with the pooled autoregression. The major chronological statistics like, mean sensitivity, standard deviation, chronology length, mean index, serial correlation, and expresses population signal (EPS) were also computed in order to verify the dendroclimatic analysis. Growth-climate relationships were determined by correlating site standard chronology with monthly climatic variables (total precipitation, mean air temperature) from June of the previous growth year until October of the current growth year (Fritts 1976). Significance was tested using 1000 bootstrap replicates and with 95% confidence intervals in *R* with the R package bootRes (Zang and Biondi 2013; R Core Team 2019).

Basal area index (BAI) chronology

BAI is commonly used to assessing tree and stand growth as it allows precise quantification of tree productivity (Rubino and McMarthy 2000; Peñuelas et al. 2011). The unstandarized BAI sigmoidal growth model avoids detrending and standardizing employed in traditional calculation of ring-width indices (RWI) (Esper et al. 2002; Salzer et al. 2009). We employed individual tree BAI to produce mean unstandardized BAI series of all sampled trees for each year.

Ring widths were converted into tree BAI according to the following standard formula:

Fig. 2 *Pinus roxburghii* forest stand at study area (Batase Sindhupalchok Nepal) (**a**), individual tree with resin tapping mark (**b**)

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

where "*R*" is the radius of the tree and "*n*" is the year of tree ring formation. The BAI chronology was produced using the bai.out function in the dplR package in *R* as some tree cores had missed pith and almost every core had intact bark.

Climatic data

The temperature and rainfall data of Panchkhal and Khopasi Meteorological station were taken from the Department of Hydrology and Meteorology (DHM), Kathmandu, respectively, as they are the nearest climate station from the study sites. Panchkhal station (27.6527° N, 85.6169° E) is situated in north-east direction (16 km), whereas Khopasi station (27.5663° N, 85.5566° E) in south-east direction (6 km) from study area. The rainfall data was recorded from Khopasi (1971-2016 AD) and the temperature record of Panchkhal (1978-2016 AD). These instrumental data of monthly mean, minimum, maximum temperature, and rainfall were used for growth climate response analysis. The paucity of long meteorological records is one of the major difficulties in undertaking dendroclimatic research in Nepal, which is associated with statistical calibrating the tree rings (Bhattacharyya et al. 1992; Shrestha et al. 1999, 2000; Aryal et al. 2018).

Results

Climatic trend

The climate of this area is sub-tropical to temperate as indicated by the climate station data. Climatic diagram of Panchkhal and Khopasi is shown in Fig. 3, where average temperature (1978-2016) and total monthly rainfall (1971-2016) were taken into consideration, which showed that the mean maximum temperature in the Panchkhal area is 32.49 °C and the mean minimum temperature is 6.53 °C, with the highest rainfall in the month of July. There was a gradual increase in rainfall and temperature from May to July, and declining from August to December. However, there was an increasing trend in rainfall and temperature from January to May.

The trends of annual average minimum, maximum, and mean temperature are shown in (Fig. 4). The annual average maximum and mean temperature showed increasing trend with the rate of 0.032 °C/year and 0.014 °C/year respectively, and the trend is significant only for maximum temperature. The rainfall showed non-significant declining trend.

Tree ring chronology

We produced a 44-year long tree ring width chronology from 25 trees (29 cores) of *Pinus roxburghii* planted population from Batase (Kavrepalanchowk) in the central Nepal (Fig. 5). The chronology has fulfilled all the statistical parameters used in standard dendrochronological studies such as mean sensitivity, series correlation, and expressed population signal (EPS) values (Table 1). The main difficulty of cross dating the tree ring width series was the most frequently occurring false rings, due to which many tree cores could not be cross dated. Similarly, the stand was relatively younger as the oldest tree was of 44 years; hence, it was obvious that the ring growth showed more fluctuation through time. The chronology statistics are presented in Table 1.

Growth-climate relationship

We found a negative correlation between summer rainfall and tree radial growth. The strongest negative correlation was found between radial growth and rainfall of June (r = −0.47) followed by the rainfall of January (r = −0.31) (Fig. 6). It was also seen that the rainfall of November also showed negative significant correlation with radial growth; however, this is not more influential for radial growth as to be the ending phase of growth of the given year. It was found that previous year August mean temperature and maximum temperature showed a significant positive correlation with radial growth (r = 0.33, 0.20 respectively). However, significant negative correlation was observed between radial growth and

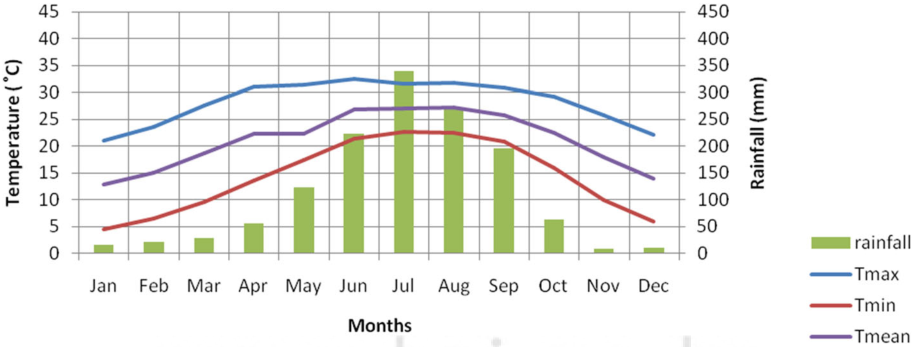

Fig. 3 Monthly patterns of average temperature (Panchkhal) and monthly total rainfall (Khopasi) (DHM, Nepal)

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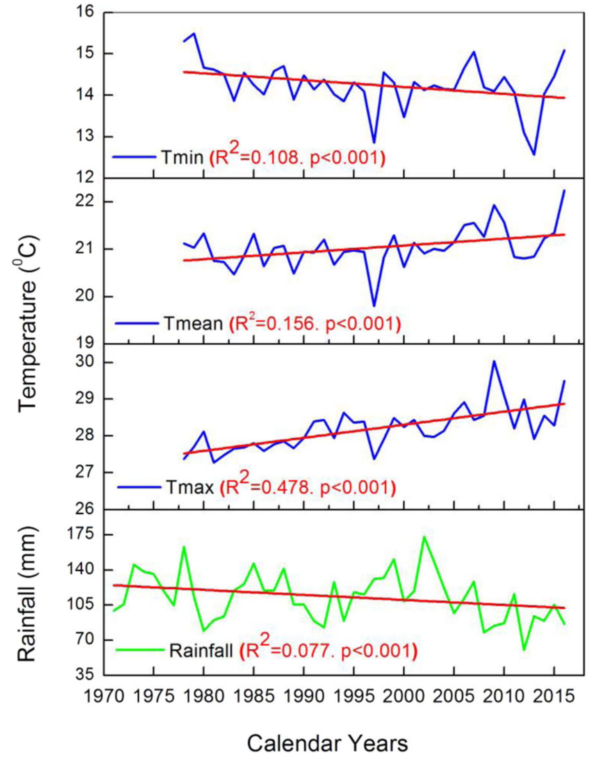

Fig. 4 Trend of annual temperature (maximum, mean, and minimum) and annual rainfall in climate stations nearby study site

maximum temperature (Tmax) of May (r = −0.32) and of spring season (March-May) (r = −0.29) (Fig. 7).

Basal area increment (BAI)

The BAI pattern in the studied chir pine forests appeared abnormal (Fig. 8) due to the clear growth suppression phase during the years of 1990-2000 AD, and due to the absence of juvenile growth increment trend (Jiao et al. 2017; Tiwari et al. 2017) However, the growth release phase after 2000 AD showed that the poor forest health was recovered. In mature forest stands, age-related trends of BAI are generally positive. BAI may continue to increase in healthy stands (LeBlanc et al. 1992; Duchesne et al. 2003), or stabilize (LeBlanc et al. 1992), but it does not show a decreasing trend until trees begin to senesce or unless trees are subject to significant growth stress (Weiner and Thomas 2001; Duchesne et al. 2003; Jump and Hunt 2006).

Discussion

Climatic trend

The warming trend in the study area is associated with higher rate of increase in maximum temperature (Tmax), and the trend is typical for central Himalaya (DHM 2017, Shrestha et al. 2017, Karki et al. 2019). This temperature trend is associated with higher rate of evapotranspiration to increase moisture stress for the forest trees (Dawadi et al. 2013; Liang et al. 2014; Tiwari et al. 2017), given the uncertainty of future precipitation patterns as indicated by IPCC (2014). The climatic trend of the study area representing the sub-tropical region of central Himalaya showed the great similarity with climate of whole Nepal despite some regional differences.

The entire central Himalayan zone has shown remarkable warming of maximum temperature although the rate of warming is site specific (DHM 2017, Shrestha et al. 2017). But the minimum temperature and rainfall were decreasing (Fig. 4) with the rate of 0.016 °C/year and 0.54 mm/year respectively, although the trend is not significant. The warming trend of the study area is a little low in comparison to whole Nepal (0.04 °C/year) for the period of 1980-2012 (Karki et al. 2019) and the global-surface global temperature trend (0.85 °C/year) for the period of 1880-2012 as mentioned by IPCC 2013. Similarly, the cooling trend of the study area is also lower than that of whole Nepal (0.02 °C/year) as mentioned by Karki et al. (2019), indicating that the area is getting warmer and drier with the decreasing trend of rainfall. The higher trend of day temperature (Tmax),

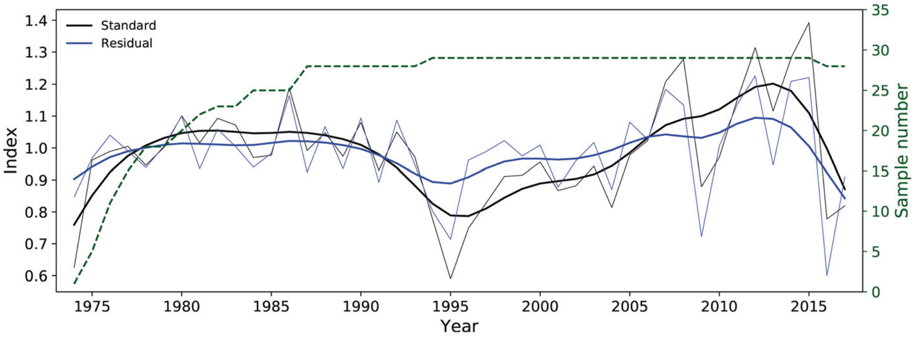

Fig. 5 Tree ring-width chronology (standard and residual) of *Pinus roxburghii* (using ARSTAN), the left vertical panel showed ring-width indices and the right vertical panel showed number of tree cores measured. Both standard and residual chronologies were smoothed for a 5-year period

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Table 1 Chronology statistics

1st year	Last year	Chronology length	Mean index	Standard deviation	Mean sensitivity	Serial correlation	EPS (2000)
1974	2017	44	0.987	0.167	0.13	0.446	0.875

more or less stable trend in annual rainfall, and the occurrence and severity of droughts especially in the winter and pre-monsoon seasons have contributed warmer and drier climate in central Himalaya (Panthi et al. 2017; Nepal et al. 2020). Consequently, the warming trend would affect tree growth patterns and trends in aboveground biomass production as it has already been observed in the Trans-Himalayan drier valley of Nepal (Tiwari et al. 2017).

Growth-climate relationship

We found positive correlation between radial growth and rainfall of March and April, although the correlation was not significant. The similar studies from western Nepal (Panchase) showed significant positive relationship between March, April rainfall, and radial growth (Aryal et al. 2018). Many studies in Nepal Himalaya showed spring season moisture sensitivity in tree growth (Dawadi et al. 2013; Tiwari et al. 2017; Aryal et al. 2018; Sigdel et al. 2018). Chir pine is a subtropical conifer most commonly found in dry, exposed, and well-drained southern aspects of sub-tropical hills in Nepal Himalaya. Irrespective of the strong moisture sensitivity of high mountain forest including treelines and timberlines in Nepal Himalaya (Dawadi et al. 2013; Liang et al. 2014; Gaire et al. 2017), pine radial growth in the study area showed weaker correlation with spring season (March-May) rainfall, and negative relationship with summer rainfall indicating that higher rainfall and lower day temperature during the early growing season (March-May) is preferred by chir pine forest.

The negative relationship between radial growth and temperatures is in accordance with various studies in Nepal Himalaya both from high mountain forests including treeline and timberline (Dawadi et al. 2013; Tiwari et al. 2017), and from sub-tropical regions at lower elevations (Aryal et al. 2018, Sigdel et al. 2018). However, irrespective of the negative response of maximum temperature (Tmax) on tree growth, the rainfall in the same period did not appear to have a significant positive effect. This could be due to less amount of rainfall to recharge water in the deep soil to be absorbed by

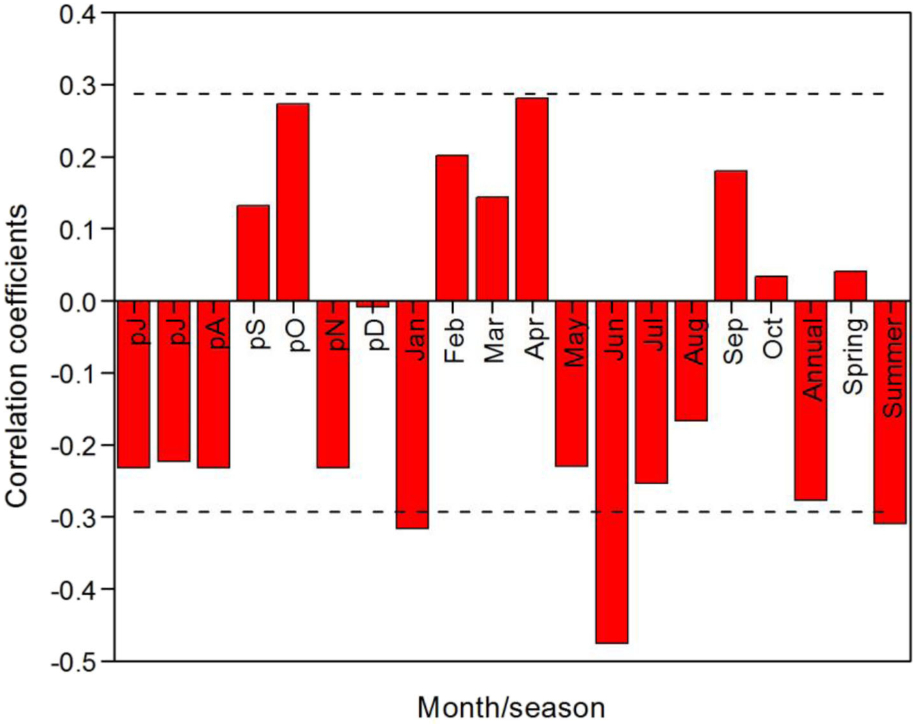

Fig. 6 Correlation coefficients between radial growth and total monthly rainfall of June-December in the previous year (pJ…pD) to June-October of the current year (J…O), spring season, summer, and annual climate, dashed horizontal lines indicate significant correlation at 95% confidence limit for a two-tailed test

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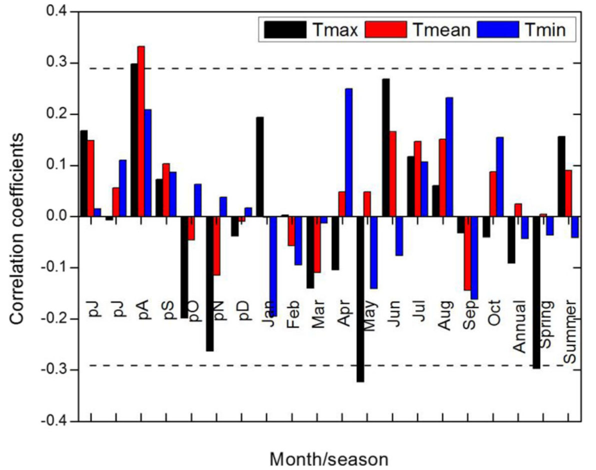

Fig. 7 Correlation coefficients between radial growth and total monthly maximum (Tmax), mean (Tmean), and minimum (Tmin) temperature of June-December in the previous year (pJ…pD) to June-October (J…O) of the current year spring, annual, and summer months, the dashed horizontal lines indicate significant correlation at 95% confidence level for a two-tailed test

the tall trees, failure of steep slope for retaining water, and a higher rate of evaporation during the season. Interestingly, the correlation strength between radial growth and spring season (March-May) rainfall is found decreasing from western to eastern region through mid-hills of Nepal showing that the climatic response to radial growth is site specific (Aryal et al. 2018, Sigdel et al. 2018). The low correlation strength in our study could be due to topographic structure with specific regional environmental conditions, and this corresponds to the fact that the total rainfall trend in Nepal is stronger in the eastern region that becomes weaker while going from eastern to western Nepal (Pokharel et al. 2019). We present that chir pine planted populations at Batase showed the similar response to temperature and rainfall at natural pine forests (Aryal et al. 2018, Sigdel et al. 2018). Although the strength of the correlation is low for spring season rainfall, more rainfall during the month of June showed negative impact on radial growth. Hence, we emphasize that the intensification of spring season drought in the future may have a negative impact on radial growth highlighting the moisture sensitivity of chir pine (Dawadi et al. 2013; Liang et al. 2014; Sigdel et al. 2018).

BAI

We found a sharp decline in BAI during 1994-2008, and the lack of juvenile growth release phase in chir pine trees. This may be due to the very slow growth for a few early years as the trees were planted. Further, our tree cores were extracted from the diameter of breast height; hence, we might have missed some early years' wood formation. The relatively unhealthy BAI trend with decline of BAI over times indicated that the forest was not healthy, which could be associated with premature resin extraction and higher human disturbance pressure in the forest stand (Fig. 2). The unhealthy trend of BAI could be associated with younger age of forest stand (50 years >) and prolonged pre-monsoon drought (common in central Himalayan region), as many studies indicated the vulnerability of younger trees under worsening long-term drought (Vose and Swank 1994, Ruiz-Benito et al. 2015, Pompa-García and Hadad 2016). In comparison to the stronger competitive advantage of old trees for resources, the middle and young trees obtained less moisture and nutrition with lower trunk height, shallower root systems, and less trunk runoff, were more susceptible to long-term drought, and showed growth decline (Kloeppel et al. 1993, Pichler and Oberhuber 2007). However, our results indicated that the decline in BAI for the investigated chir pine forest did not show a strong impact of environmental factors (no remarkable drought events during the growth suppression years), rather it could be the results of human disturbance such as fire, grazing, and resin collection. Climate-induced growth decline has already been observed for drier parts of the Trans-Himalayan zone of Nepal, where tree growth was found to be positively correlated with spring

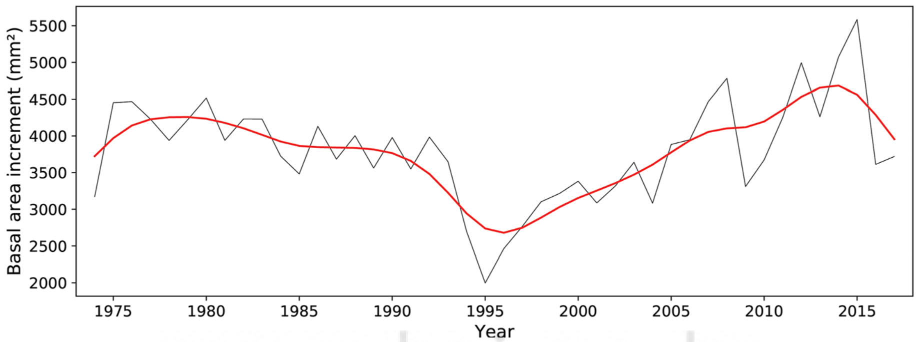

Fig. 8 BAI (basal area increment) through time, the smoothing line operated for a 5-year period

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season rainfall (March-May) (Tiwari et al. 2017). The negative impact of temperature-induced drought to pine forest growth has also been reported in different regions of Asia, *Pinus taiwanensis*, *Pinus massoniana* in the Dabie Mountains in subtropical China (Cai et al. 2020), *Pinus koraiensis* (Korean pine) of Changbai Mountain in northeast China (Yu et al. 2013) and *Pinus latteri* of Northeastern Thailand (Rakthai et al. 2020) all showed decreased growth at lower elevations under climate change characterized by warming and drought.

The BAI trend in the study area showed that the chir pine forest was not in good health and is showing poor performance in terms of carbon assimilation. And climatic factors did not show any strong impact on radial growth as indicated by our growth-climate relationship results. The sharp decline of BAI in times, and growth release afterward indicated that the growth is highly sensitive to human disturbance factors and resin extraction. The impact of forest disturbance in growth suppression was also indicated for *P. roxburghii* from similar climatic conditions in Kathmandu, Nepal (Speer et al. 2017).

Conclusions and management implications

Chir pine forest in Batase (Kavrepalanchowk) district region was 44-50 years old as evidenced from our ring count, and the stand age matches the plantation history of the forest. The radial growth of *P. roxburghii* showed significant negative correlation with both rainfall and temperature of different seasons. And the limiting factor for tree radial growth is not a single one. The BAI trend showed deviation from normal sigmoidal pattern (increasing) indicating that the forest is sub-healthy, although there was a substantial increment of BAI following the great decline of BAI after 1995. However, a sharp decline in BAI after 1995 until 2005 was very much clear, which could be the influence of resin extraction and other potential disturbance in the forests. The community users also explained the past trend of resin collection and higher disturbance in the forests. This study indicated the planted pine forests in the mid-hills of Nepal are much affected by human activities than changing climate. The magnitude of the impact of anthropogenic factors should be more closely observed for managing the forests in a sustainable basis. We suggest that forest managers should choose only one option as their desired product from pine forests. If they would wish to get more quantity of logs they should stop resin extraction, and if they would wish to get more resin they should not expect higher timber yield in the forests. Further replication of sites and taking cases of different climatic conditions would refine our knowledge on impact of modern climatic changes and human influence in the mid-hill forests. A detailed study on tree physiological performance and climate sensitivity of tree species is highly recommended before selecting the species for mass scale plantation.

Abbreviations

BAI: Basal aArea iIncrement; DBH: Diameter at breast height; DFRS: Department of Forest Resource and Survey; DHM: Department of Hydrology and Meteorology; EPS: Expresses pPopulation sSignal; GPS: Global Positioning System; IPCC: Intergovernmental Panel on Climate Change; m: meter; mm: millimeter; NAST: Nepal Academy to Science and Technology; sp.: Species; Tmax: Mmaximum temperature; Tmean: Mean temperature; Tmin: Minimum temperature

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Authors' contributions

AT and PR conceptualized and designed the research, NT collected sample and performed the laboratory measurement. AT, SA[1], and SA[2] performed data analysis. The authors read and approved the final manuscript.

Authors' information

Achyut Tiwari, PhD, is an Assistant Professor at the Central Department of Botany, Tribhuvan University, Kathmandu, Nepal, with research interests in forest ecology (dendroecology). Neeta Thapa is a MSc student at Central Department of Botany, Tribhuvan University; Sugam Aryal is a MSc student at Institute of Geography, University of Erlangen Nürnberg, Dr. Prabina Rana is a senior scientific officer at Nepal Academy of Science and Technology Nepal and Mr. Shankar Adhikari is an undersecretary at Department of Forests, Government of Nepal.

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Availability of data and materials

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Competing interests

All authors declare that they have no competing interests.

Author details

[1]Central Department of Botany, Tribhuvan University, Kirtipur, Kathmandu, Nepal. [2]Institute of Geography, University of Erlangen Nürnberg, 91058 Erlangen, Germany. [3]Nepal Academy of Science and Technology, Khumaltar, Lalitpur, Nepal. [4]Ministry of Forests and Environment, Government of Nepal, Kathmandu, Nepal.

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