Ecological Frontiers 44 (2024) 167–174

Contents lists available at ScienceDirect

Ecological Frontiers

journal homepage: www.sciencedirect.com/journal/ecological-frontiers

Changing climate yet healthy forest stand of *Tsuga dumosa* in temperate zone of central Nepal

Sarita Chaulagain [a,b,1], Sugam Aryal [c], Saroj Basnet [d], Achyut Tiwari [a,*,1]

[a] Central Department of Botany, Tribhuvan University, Kirtipur, Kathmandu, Nepal
[b] School of Agriculture, Food and Ecosystem Services, The University of Melbourne, Parkville, Australia
[c] Friedrich-Alexander-Universität Erlangen-Nürnberg, Institut für Geographie, Wetterkreuz 15, 91058 Erlangen, Germany
[d] Institute of Botany and Landscape Ecology, University of Greifwald, Soldmannstrasse-15, D- 17489 Greifswald, Germany

ARTICLE INFO

Keywords:
Tsuga dumosa
Tree ring
Dendroclimatology
Growth-climate response
Basal area increment (BAI)

ABSTRACT

Nepal Himalaya is experiencing a faster rate of temperature rise than the global average, and the temperature has altered the growth patterns and distribution of mountain trees. A dendrochronological study was conducted for *Tsuga dumosa* (D.Don) Eichler to analyze growth-climate relationship from the temperate forest of central Nepal. We developed 116 year-long tree ring width chronology spanning from 1905 to 2020 CE. The study area showed a significant increase in atmospheric temperature and a decrease in rainfall during the past 42 years. It is found that the spring season (March–May) climate is sensitive to the radial growth of *T. dumosa*. Ring width indices showed a substantial positive correlation with the minimum temperature of January, March, and June of the growth year. Conversely, a negative correlation was observed with the maximum temperature of the previous year's months (July, September, and November), March, and September of the current year, and rainfall during June and November. Basal Area Increment (BAI) trend is positive, indicating the forest is healthy despite the decline in the years 1942, 1978, and 1998. We conclude that the warming of the spring season (March–May), previous year's late growing season and moisture supply (precipitation) during June are critical to the radial growth of *Tsuga dumosa* in the region. However, responses from multiple species and their exposure to different climate regimes would ideally be required to make predictions on the growth climate relationships of forest trees.

1. Introduction

Climate has a significant influence on forest distribution, structure, and ecology and is likely the most important global predictor of vegetation patterns [1]. Several climate-vegetation investigations have revealed that specific climatic regimes are linked to specific plant communities or functional kinds [2]. The average world's temperature has risen by >0.85 °C in the previous century and is expected to rise from 1.1 °C to 6.4 °C by the end of 2100 [3]. The Hindu Kush Himalayan (HKH) region showed the average rate of warming for each decade was 0.19 °C over the past century (1901–2020), however, from 1951 to 2014, the rate of warming increased slightly higher to 0.20 °C per decade [4], and the substantial increase in length of the growing season. In the past few decades (1951–2014), the mountain temperature has been rising at an unexpected rate of 0.5 °C [5]. The environmental changes of a higher scale and extreme climate variation was also projected for the years 2030, 2050, and 2100 in Nepal Himalaya, as an annual increase in atmospheric temperature [6–8], which could have a negative impact on tree growth in already dry areas and a positive impact on tree growth in cold environment.

The changing climate as evidenced by rising temperatures, higher amounts of atmospheric carbon dioxide, changes in precipitation, and the frequency and intensity of climate variability could alter the configuration of the forest ecosystem [9]. The prolonged growing season, shifting species ranges, and variations in the frequency of forest fires caused by climate change substantially influence the world's forests [10] and have an adverse impact on plant species distribution where the area has drier climate [11]. Climate-related variables, such as precipitation, temperature, soil moisture, and the environment in which the plant is growing, have a substantial influence on the growth of trees and are crucial in the formation of tree ring width. The establishment and maintenance of the tree line and the identification of the species line are

* Corresponding author.
E-mail address: achyut.tiwari@cdb.tu.edu.np (A. Tiwari).
[1] Equal Author Contribution

https://doi.org/10.1016/j.chnaes.2023.08.005
Received 23 February 2023; Received in revised form 19 August 2023; Accepted 21 August 2023
Available online 4 January 2024

both influenced by temperature [12]. Therefore, knowing how trees grow and react to climate and other environmental factors would be very useful in improving our adaptation plans and mitigation measures. Knowledge of the growth-climate relationship would provide facts and figures on the current and past climate, allowing us to understand how variable the climate and other environmental factors are, especially in fields where tree growth is susceptible to constricting climatic factors [13].

Nepal is also prone to climate change due to its topography, highly delicate ecology, and a lack of long-term instrumental climatic data, which has become a critical concern in understanding climate change patterns in Nepal. [6,14–16]. Several other techniques might be helpful for the accurate assessment of the previous climate to address this problem, including dendrochronology and dendroclimatology [17–20]. Dendrochronological tools are useful for reconstructing the age structure of a forest stand. It also provides insight into the dynamics of the climate and the condition of the forest by precisely dating the formation of tree rings in many different types of wood [21–23]. The climate data recorded in the annual growth rings of trees provide valuable insights into environmental changes, such as temperature and rainfall, especially in regions that are sensitive to climate fluctuations and are mainly useful in the study of historical climatic conditions, particularly prior to the time when direct climate observations were available [19,21]. The high-altitude region of Nepal has been the subject of dendrochronological investigations, particularly the location of the tree line focusing on the conifer species [18]. It is expected that many tree species' ability to grow and regenerate might be significantly altered by a 1 °C increase in average yearly temperature, which would significantly impact humans who use such species for fuel, fodder, and timber [24].

Most of the dendrochronological studies on growth-climate relationships of tree species are confined to high mountain areas of Nepal [25]. And the forests of middle mountain regions of Nepal Himalaya are less explored in terms of the relationship between tree growth and climate despite of rapidly warming temperatures and higher human activities in the region. Temperate forests in Nepal including the *Tsuga dumosa* are essential sources for giving a wide range of goods and ecosystem services to people [26], and are also an environmentally vulnerable, sensitive, and fragile ecological zone [27]. Thus, we conducted a dendrochronological study of *T. dumosa* trees to determine the limiting climate factor affecting radial growth and to analyze the temporal changes in aboveground production, as measured by Basal Area Increment (BAI).

2. Materials and methods

2.1. Study area

The study area lies in the temperate forest of Central Nepal (27°31′54.3″N, 85°27′05.9″ E) with an elevation (2265–2921 m asl) lies in the temperate zone and is primarily facing southeast with a slope of

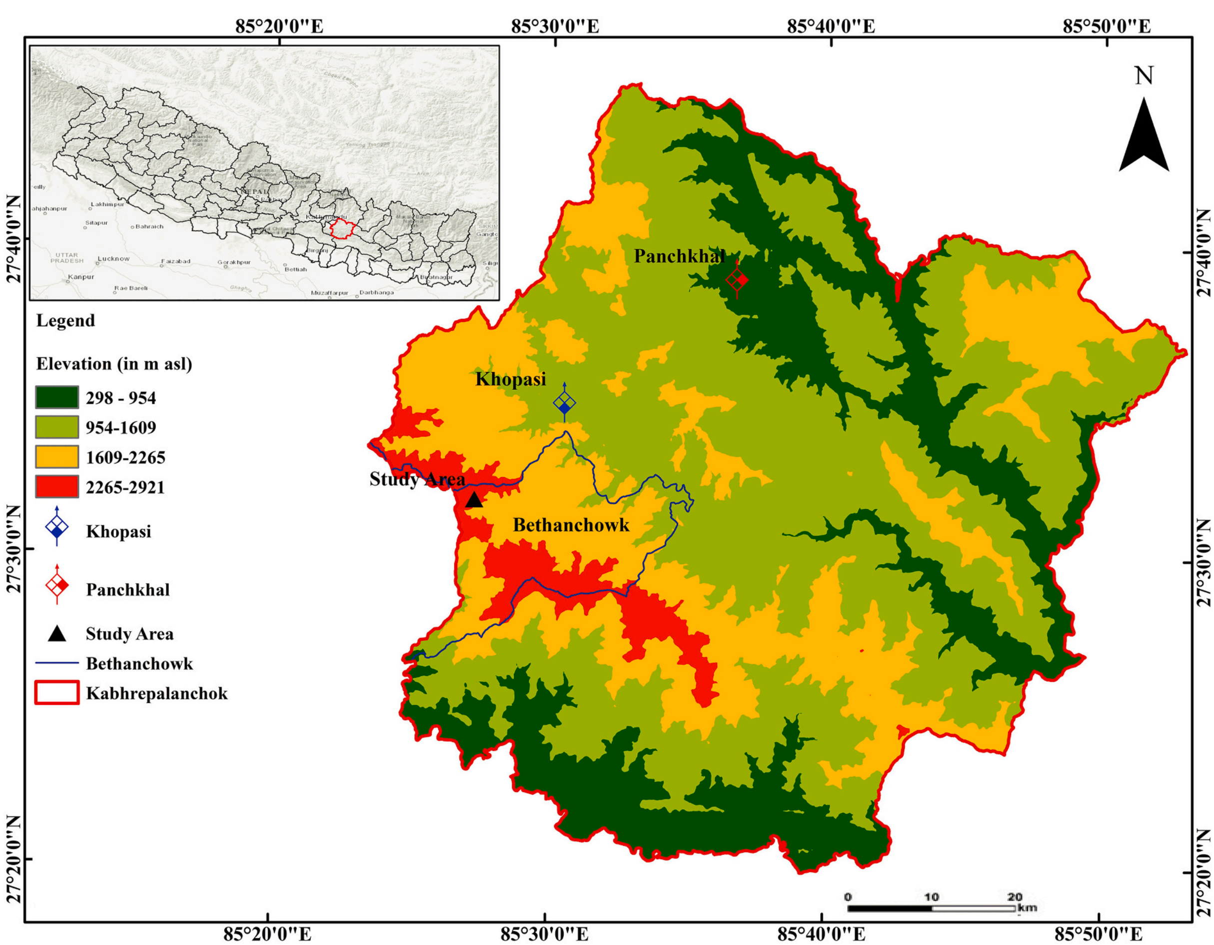

Fig. 1. Location map of the study area.

15–30° (Fig. 1). The major trees found in the forest are *Myrica esculenta*, *Rhododendron arboreum*, *Pinus wallichiana, Tsuga dumosa*. The area represents the temperate forests, a biodiversity-rich area with a varied ecosystem and substantial endemism [28] and has rugged mountain topography with a stronger anthropogenic influence as well as the effects of a rapidly changing climate [29]. The forest consists of excellent natural forests of *Pinus wallichiana* in the lower elevation and *Tsuga dumosa* in the upper elevation. Based on the temperature and precipitation record, the study area represents a temperate climate zone where the winter is drier, and the summer is warm. The maximum temperature (Tmax), mean temperature (Tmean) showed increasing trend while the minimum temperature (Tmin) and annual rainfall represented decreasing trend as given in (Fig. 2).

2.2. Study species

Tsuga dumosa is a native evergreen tree species (20–25 m height, 1.5 m in girth diameter) in the eastern Himalayas and is found in Nepal, Tibetan Plateau, Assam, Burma, East Asia, and Southeast Asia [29]. *T. dumosa* is found in the temperate zone of eastern, central, and western Nepal [30], usually at an elevation of 2000–3600 m., it is one of Nepal's important tree species used for firewood and timber. *T. dumosa* forests are vital for regulating the hydrological cycle and ecosystem functions in the middle mountain region of Nepal [31]. *T. dumosa* is a slow growing tree, with a long lifespan, and is able to tolerate low-light conditions and is also sensitive to prolonged drought [32]. The tree species is characterized by well-defined growth rings, which are formed by a noticeable difference between the small, dark-colored latewood cells and the large, light-colored earlywood cells, and hence serves as highly potential tree species for dendrochronological studies [33].

2.3. Sample collection

Tree cores were obtained from a comparatively less damaged large size trees (healthy crown and no evident fire scars). We collected 60 cores of *Tsuga dumosa* using an increment borer (Swedish Haglof 28″, 3-Thread, 0.200″ (5.15 mm), particularly, 2–3 cores from the chosen trees. The cores were dried in air and mounted in a hardwood frame, a transverse surface with the cross-sectional surface facing upwards [19]. The tree cores were smoothed by sanding with sandpaper of different grid sizes until the ring boundaries are clearly visible. The cores with evident yearly rings were calendar-year-dated. The tree ring measurement was then performed using LINTAB-5 (RINNTECH) hardware and the TSAP-Win application.

After measuring the ring widths, the individual tree-ring series were cross-dated using a matching process by examining the mathematical graphs and cross-dating statistics [34]. The computer program COFECHA was used to find the errors in the cross-dating [35], and ARSTAN was used to standardize [36] tree ring width chronology. To eliminate non-climatic age trends, each sample was detrended using a negative exponential curve. The ring-width chronology of both stands was produced using arithmetic means after detrending each data. [13]. The standard, residual, and ARSTAN chronologies were established. We conducted Pearson's correlation analysis to identify the growth-climate relationship, tree ring width indices were correlated with monthly climatic data (total precipitation, mean air temperatures) from previous year's June to October of the present growth year [13]. We used the R package to evaluate significance using 1000 bootstrap repeats and 95% confidence intervals [37].

2.4. Basal area increment (BAI)

BAI is a widely used tree growth parameter to evaluate the tree and stand development because it enables for exact assessment of tree biomass production [38]. The unstandardized BAI sigmoidal growth model bypasses the detrending and normalizing used in typical ring-width indices (RWI) computation [39,40]. Hence, the temporal trajectory of BAI indicates the real tree growth vigor and forest productivity (in climate-sensitive forests). We generated the mean unstandardized BAI series of all tested trees using individual tree BAI. The following standard formula was used to convert ring width to tree BAI.

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

where "n" is the year that the tree's tree rings were formed and "R" is the tree's radius.

Since some tree cores were missing piths and nearly all of them had complete bark, the bai.out function from the dplR package in R was used to create the BAI chronology [37].

2.5. Climatic data

The temperature and rainfall data from the nearest meteorological stations from Panchkhal (857 m asl; at 20 km distance from study site) and Khopasi (1442 m asl; at 6 km distance from study site) were obtained from the Department of Hydrology and Meteorology (DHM), Kathmandu. We used the rainfall data from Khopasi station, and the records of monthly average minimum and maximum temperatures from

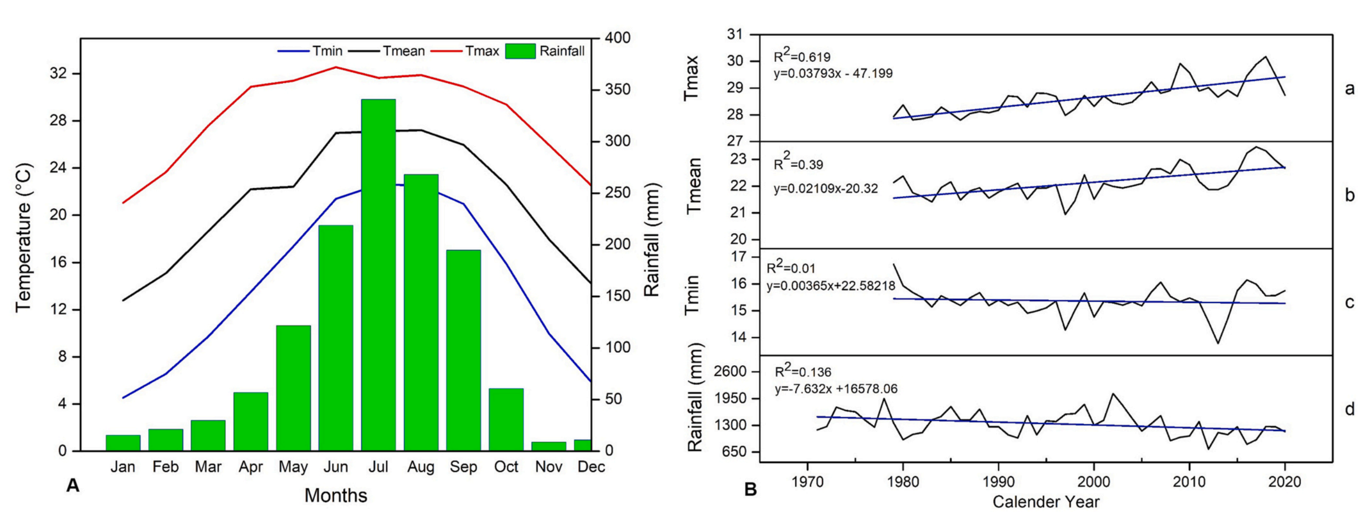

Fig. 2. Climate of the Study Area. (A) Monthly patterns of average temperature and total rainfall, and (B) Annual climatic trend in the study site: a. Rainfall trend, b. Minimum Temperature Trend, C. Mean Temperature trend, d. Maximum Temperature Trend (Source: Department of Hydrology and Meteorology 2020).

Panchkhal station because of lack of temperature data from Khopsai station although it was near to the study site. These temperatures and rainfall data from 1979 to 2020 CE were used for growth climate response analysis.

Based on the temperature and precipitation record, the study area lies in a temperate climate zone where the winter is drier, and the summer is warm. The climatic data of the study area is analyzed by taking the average maximum (Tmax), mean (Tmean), and minimum (Tmin) temperature from 1978 to 2020, including the monthly rainfall from 1971 to 2020. According to the meteorological data, the Tmax and Tmin in the study area are 32.56 °C and 4.53 °C, respectively. Similarly, the highest rainfall occurs in the month of July (Fig. 2). The trend of Tmin, Tmax, and Tmean are shown in (Fig. 3). The Tmax and Tmean increased at rates of 0.037 °C/year and 0.021 °C/year, respectively, with only the Tmax showing a significant trend (R^2 = 0.61, $p < 0.001$), however, Tmin showed an insignificant decreasing trend with a rate of 0.003 °C/year. Rainfall exhibited a decreasing trend of 7.63 mm/yr. for the period 1971 to 2020 CE.

3. Results

3.1. Ring width chronology

Ring width chronology of 116 years was produced from 43 cores of *Tsuga dumosa* from the temperate forest of Central Nepal extending from 1905 CE to 2020 CE (Fig. 3). The chronology has met all the statistical criteria employed in common dendrochronological investigations [41], including mean sensitivity, mean ring width, series correlation, and expressed population signal (EPS) values (Table 1). The inter-series correlation (Rbar) and expressed population signal (EPS) show the common variability within the chronology, EPS > 0.85 is generally considered a reliable representation of the population.

3.2. Growth-climate response

Pearson's correlation between monthly climatic variables and ring-width indices revealed a substantial negative relationship with the maximum temperature of the previous growing year (July, September, November) and March of the growing year, while the radial growth showed a positive correlation with the minimum temperature of January, March, July, and summer season (Fig. 4). We observed the strongest negative correlation between the maximum temperature of the previous September and radial growth (r = −0.41), followed by the maximum temperature of the previous July (r = −0.36). In addition, the maximum temperature in March (r = −0.35) and the previous November (r = −0.33) also showed a considerable negative relationship with ring width. Similarly, the minimum temperature of January (r = 0.35), March (r = 0.37), July (r = 0.30), and spring season (r = 0.29) showed a positive significant correlation with radial growth. Moreover, a strong positive correlation was obtained between tree ring width and rainfall of the previous September (r = 0.32) (Fig. 4).

Table 1
Chronology Statistics of *Tsuga dumosa*.

S. N.	Variable	Value
1	Number of Trees	20
2	Chronology Length	116 (1905–2020)
3	Mean Ring Width (mm)	3.745
4	Mean Sensitivity	0.322
5	RWI Standard Deviation	0.173519
6	Mean Inter Series Correlation (Rbar)	0.441
7	Auto Correlation (ARI)	0.003
8	Subsample Expressed Population Signal (EPS > 0.85)	80 years (1940–2020)

3.3. Basal area increment (BAI)

The mean value of BAI found in the study area is 2198.209 ± 989 mm^2. The BAI of *Tsuga dumosa* tree population in the temperate forest of Central Nepal is positive, however, the BAI declined particularly during the years 1942, 1978, and 1998 (Fig. 5). The climate has a significant positive relationship with the Basal Area Increment as revealed by Pearson's correlation between climatic variables and BAI. We found the strongest positive correlation with the December rainfall (r = 0.39)

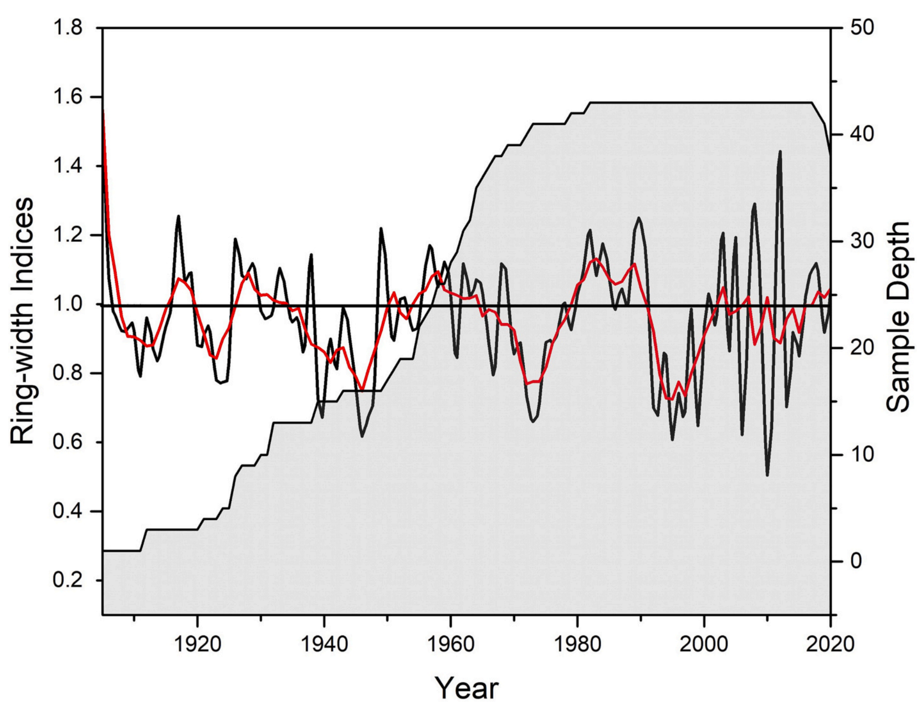

Fig. 3. Tree ring width chronology of *Tsuga dumosa* (RWI-Black line, shaded area shows number of tree core samples, the red line represents smoothing for 5-year window).

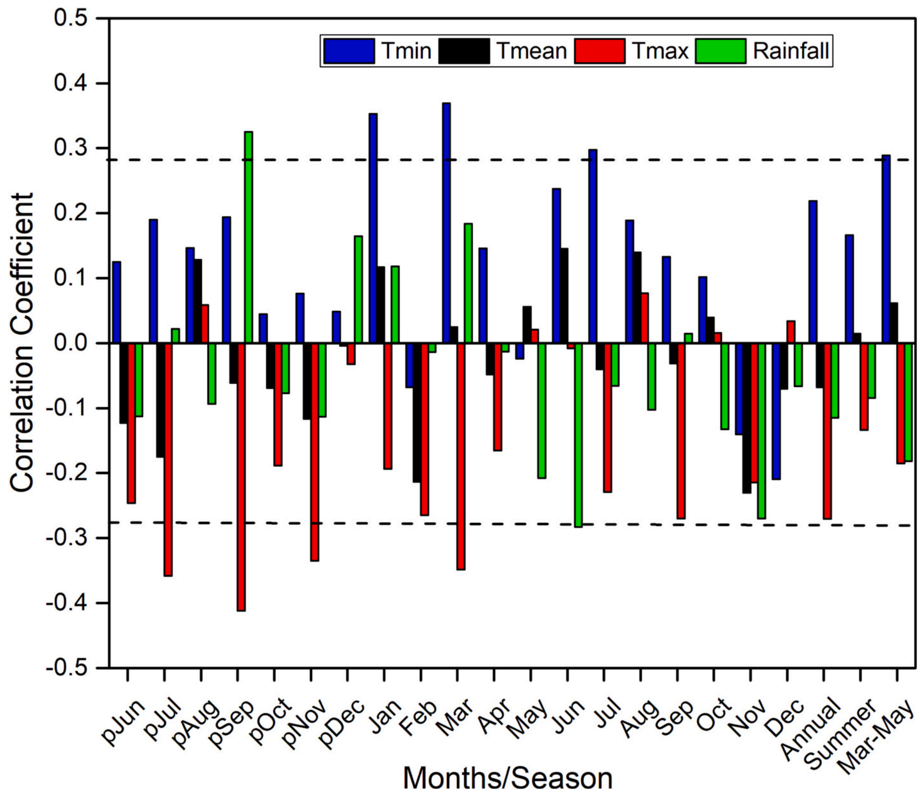

Fig. 4. Correlation coefficients between radial growth and climatic variables for common period of 1979–2020. The upper and lower horizontal black dotted line represents the significance at 0.05, (X-axis showing month/season, Y-axis showing correlation coefficient), (Tmax = maximum temperature, Tmean = Mean Temperature, and Tmin = minimum Temperature).

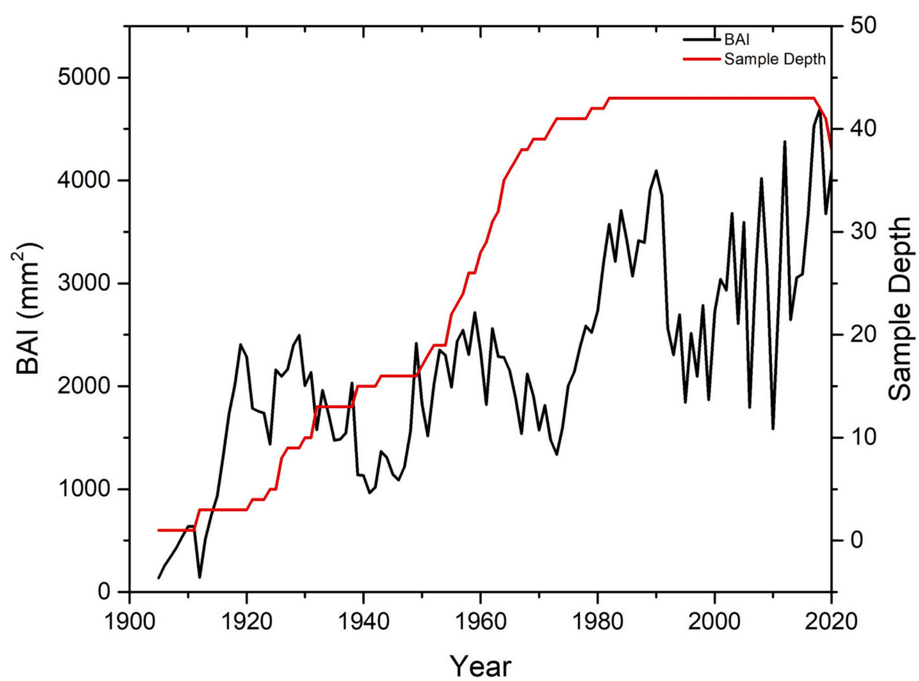

Fig. 5. BAI (Basal Area Increment) trend from 1905 to 2020 CE (Red line- Sample depth and Black line-BAI).

followed by rainfall during October ($r = 0.38$), Previous year's August ($r = 37$) and August ($r = 0.33$). The correlation of Tmax is highest for previous year's August ($r = 0.374$), followed by December (r = 0.37), October ($r = 0.35$), August ($r = 0.31$) and March–May ($r = 0.29$). Positive correlation was observed between BAI and Tmean where the highest correlation between them occurred in August (r = 0.37). Moreover, correlation between BAI and Tmin has been found to have significant positive relationship with Aug ($r = 0.32$), July (r = 0.3), March–May (r = 0.29) (Fig. 6).

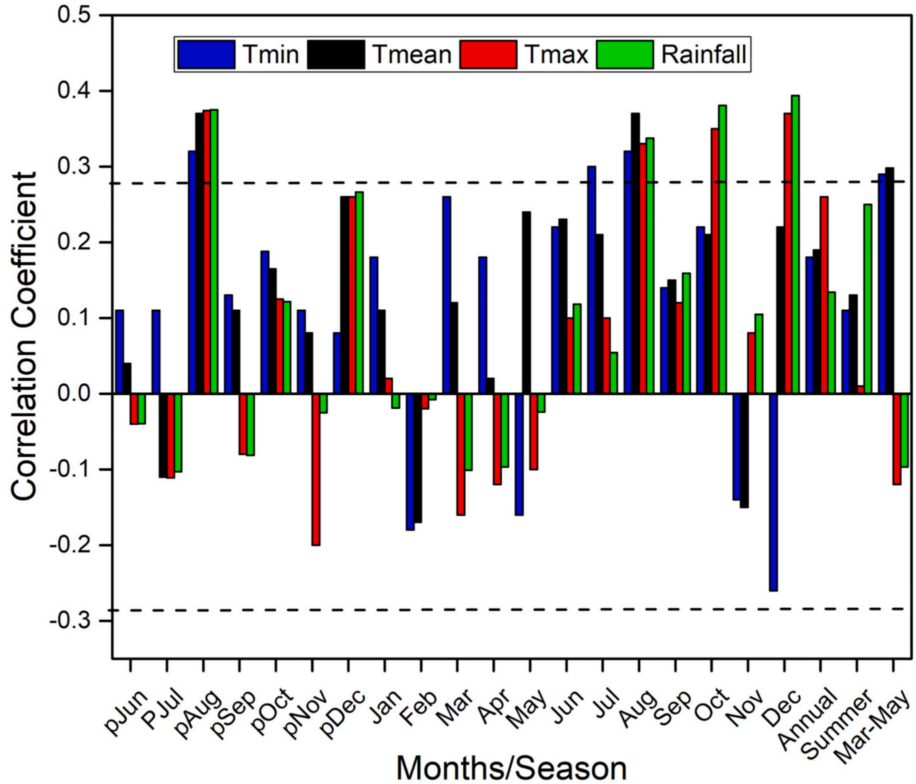

Fig. 6. Correlation coefficients between BAI with temperature and rainfall for common period of 1979–2020. The upper and lower horizontal black dotted line represents the significance at 0.05, (X-axis showing month/season, Y-axis showing correlation coefficient), Tmax = maximum temperature, Tmean = Mean Temperature, and Tmin = minimum Temperature.

4. Discussion

4.1. Tree ring chronology

We produced a 116-year-long ring width chronology of *Tsuga dumosa* from Central Nepal spanning from 1905 to 2020 CE, and it represents relatively the younger forest stand. The dendrochronological studies using *Tsuga Dumosa* from other parts of Nepal included the oldest tree chronologies (1141 years) till the date in Nepal [5]. Additionally, tree ring chronologies of longer time period were produced for *T. dumosa* including a 357-year-long chronology from 1657 to 2013 CE from western Nepal [42], and 610 years (1399–2017 CE) from Manang, central Nepal [31].

4.2. Growth-climate relationship

The *Tsuga dumosa* radial growth showed a significant positive relationship with the minimum temperature of January and March. This may be due to the fact that the study area lies above 2600 m asl that witness snowfall every year in the months of January–March as the snow cover control the soil temperature and temperature directly influence tree growth. The *T. dumosa* tree growth has been observed to be closely related to climatic factors. The radial growth also showed a significant positive correlation with the minimum temperatures recorded in January and March. This interconnection can be linked to the elevation of the study area which is 2600 m asl. At this altitude, the region witnesses snowfall every year between January to March which directly influences soil temperature and has a direct impact on tree growth [43].

The radial growth of *T. dumosa* growth was influenced by minimum temperature during the spring season (March–May). The minimum temperature and tree growth showed a positive correlation suggesting that as the minimum temperature increases during this period, it enhances radial growth. Contrary to our findings, the high mountain of Nepal generally showed negative impact of day temperature (Tmax) to tree radial growth during spring season (March–May) and this is due to increased evapotranspiration leading to soil a water deficit. This deficit consequently results in narrower annual rings, producing reduced radial growth [44–46].

Our results indicated that the minimum temperature and rainfall of June have a negative impact on the growth of *T. dumosa* as the month is summer in Nepal where higher rainfall occurs right after drier months which may be a site-specific response due to the inconsistent relationship with the temperature and precipitation of summer months seen in Nepal [31]. The result is also supported by other studies from various locations in Nepal that demonstrated a positive relationship with the summer temperature [46], while some studies showed a negative relationship between radial growth and summer precipitation [47].

Generally, in the summer season, trees usually get adequate water, thus, high temperature favors photosynthesis and tree growth. However, the soil temperature at higher altitudes is also found to be low due to high cloud cover, and this can have a negative influence on the tree growth [48]. Additionally, in the study area, the growth of *T.* indicates a negative response to summer rainfall indicating that as summer rainfall lowers, it significantly impacts on tree growth. This cumulative effect of low soil temperature and increased summer rainfall can promote the observed negative response of tree growth in the area. Likewise, we found that both the September and March rainfall positively influenced the radial growth of *T. dumosa*., and the similar climate response was observed in mountain forests in Nepal [20]. Further, the maximum temperature of the previous year's July and September was found to have negative impact on radial growth of *T. dumosa* as the maximum temperature reached beyond 30 °C which may provide heat stress to the plant [49].

Our results indicated that the maximum temperature of November negatively affected the radial growth of *T. dumosa* based on measured temperature of soil and air [50]. Further, the maximum temperature of

September also negatively impacted the growth of the species which is the summer month in Nepal that may provide heat stress to the plant [22]. Additionally, the maximum temperature of March gave a stronger negative impact on radial growth of *T. dumosa*. Sharp increases in temperature along with low rainfall during the pre-monsoon season can lead to soil water scarcity, which has a negative impact on the radial growth of trees [51]. There was a noticeable inverse relationship between the radial growth of *T. dumosa* found in western Nepal with spring temperature [42] and a negative correlation of *T. dumosa* growth with the March–May average temperature including a positive correlation with March rainfall, as March–May is the spring season in Nepal [31]. The conifers grown in the higher mountains of Himalaya showed a similar relationship to the temperatures in the early growth period [21,52]. However, warm temperatures and enough moisture throughout the summer (JJAS) [53] growing seasons encouraged the growth of *Abies spectabilis*, while moisture stress during the spring (March–May) seasons primarily constrained the growth of *B. utilis* [54]. The radial growth of *Pinus roxburghii* in the temperate region of central Nepal was positively correlated with the pre-monsoon (April) rainfall, however, rainfall in June and January have a negative impact on the radial growth of Pine [55] indicating that the tree growing in the area was not under climatic stress. However, a very strong correlation between Pine radial growth and spring rainfall and evapotranspiration has been observed in western Nepal which represents a particularly dry region in Nepal [56].

4.3. BAI trend

We found a positive BAI pattern for *T. dumosa* trees in the study area. The significant positive correlation is observed between BAI and climatic variable indicating that the tree growth is not decreased by the climate change, rather increasing trend of rainfall and climate could have encouraged *Tsuga* to expand its trunk [57]. In mature forests, the BAI pattern is usually positive, and it continues to increase in healthy forest stands [58] or may maintain stabilization [59]. However, the BAI trend demonstrates a decreasing trend if the forest is under growth stress [60] or if trees begin to senesce [61]. The BAI pattern found in the study area is normally positive except for a temporal decline in the years 1942, 1978, and 1998 which may be due to stand-level disturbance factors such as effects of grazing, logging, forest fire, or any other external factors [62]. The BAI trend of Chir pine in a planted population of central Nepal was found to be decreased from 1990 to 2000 CE which was due to the absence of a juvenile growth release increment trend [55]. Similarly, the declining BAI of Himalayan Birch was reported from high-elevation mountains in central Nepal associated with climate warming [54. Nepal has been experiencing climate-induced growth decline in drier parts of the Trans-Himalayan zone where there is a positive relationship between the growth of trees with rainfall in the spring season (March–May) [63]. However, the BAI trend of *T. dumosa* found in the area indicated that the climate has not yet impacted the growth pattern. Thus, the decreasing trend of BAI in the years 1942, 1978, and 1998 could be associated with stand-level disturbance factors such as forest fire [62] which is a crucial factor for forest degradation in Nepal where 89% of fire occurs in the dry season [64]. Thus, forest disturbance may stimulate growth performance and tree recruitment than climatic variability which is lesser in duration and intensity [65].

Despite the changing climate, *T. dumosa* is growing well in the area indicating that the species is more likely to adapt to temperature and rainfall variability [53]. The BAI patterns show a positive trend, which may be due to less competition and a more open canopy that might influence increasing / stable BAI, and the similar trend was found at moist treeline trees in central Nepal [63]. The decline in the BAI pattern of *T. dumosa* growing in Central Nepal in 1972 also coincided with the decline of birch [54] where the BAI of *Abies spectabilis* raised sharply after the temperature transition. The positive trend of BAI may be also due to the young age of the forest stand of *T. dumosa* as BAI is greatly affected by age of the forest or maybe due to the exposure to the low competition of associated trees. Overall, the basal area increment of *T. dumosa* in the study site was high, and it is possible that gymnosperms may have an advantage in stressful environmental conditions [66].

5. Conclusion

We produced a tree ring width chronology of *Tsuga dumosa* for 116 years (1905 to 2020 CE) from the temperate forest of Central Nepal. The growth climate study revealed that spring temperature is sensitive to the radial growth of *T. dumosa.* Similarly, the rainfall in the late growing season and minimum temperature in early growth season showed positive influence on radial growth. We observed a negative relationship between rainfall in June in the growing year and radial growth, which is quite unusual and needs further validation. The BAI pattern of *T. dumosa* is generally positive indicating that the forest is healthy and without growth stress except for the growth decline in the years 1942, 1978, and 1998. The temporal fluctuation of BAI of *T. dumosa* trees in the study area demonstrated that the decline is not due to climatic factors but could be associated with stand-level disturbances due to human activities such as grazing, logging, forest fire, or any other. We conclude that the warming of the spring season (March–May), higher temperature of the previous year's months (July, September, and November), March, and September of the current year, as well as rainfall during June would have a negative impact on the radial growth of *T. dumosa* in the region. However, responses from multiple species and their exposure to different climatic conditions and levels of human impact would ideally be required to rely on such predictions.

Declaration of Competing Interest

All the authors declare that there is no conflict of interest with this manuscript.

Acknowledgements

We would like to acknowledge University Grants Commission (UGC), Sanothimi, Bhaktapur, Nepal for providing the grant to carry out the study. We are equally indebted to Nepal Academy of Science and Technology (NAST) and Dr. Anjana Giri for providing the lab facilities required for this work, and Department of Hydrology and Meteorology (DHM) for providing the climate data of the study area.

References

[1] A. Aaheim, R.K. Chaturvedi, A.A. Sagadevan, Integrated modelling approaches to analysis of climate change impacts on forests and forest management, Mitig. Adapt. Strateg. Glob. Chang. 16 (2) (2011) 247–266.

[2] R.T. Watson, M.C. Zinyowera, R.H. Moss, Climate change 1995, in: Impacts, Adaptations and Mitigation of Climate Change: Scientific-technical Analyses, 1996.

[3] IPCC, Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change, in: R.K. Pachauri, L.A. Meyer (Eds.), Core Writing Team, IPCC, Geneva, Switzerland, 2014, p. 151. Available online at, http://www.ipcc.org (Accessed on 2020-05-05).

[4] Y.Y. Ren, G.Y. Ren, X.B. Sun, A.B. Shrestha, Q.L. You, Y.J. Zhan, et al., Observed changes in surface air temperature and precipitation in the Hindu Kush Himalayan region during 1901–2014, Adv. Clim. Chang. Res. 8 (3) (2017), https://doi.org/10.1016/j.accre.2017.08.001.

[5] T.P. Sabin, R. Krishnan, R. Vellore, P. Priya, H.P. Borgaonkar, B.B. Singh, A. Sagar, Climate change over the Himalayas, in: Assess. Of Clim. Chang. Over the Indian Reg, Springer, Singapore, 2020, pp. 207–222.

[6] A.B. Shrestha, R. Aryal, Climate change in Nepal and its impact on Himalayan glaciers, Reg. Environ. Chang. 11 (1) (2011) 65–77.

[7] A.B. Shrestha, C.P. Wake, P.A. Mayewski, J.E. Dibb, Maximum temperature trends in the Himalaya and its vicinity: an analysis based on temperature records from Nepal for the period 1971–94, J. Clim. 12 (9) (1999) 2775–2786.

[8] J.H. Christensen, B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R. K. Kolli, W.-T. Kwon, R. Laprise, V. Magana Rueda, L. Mearns, C.G. Mene'ndez, J. Raisanen, A. Rinke, A. Sarr, P. Whetton, Regional climate projections, in: S. Solomon, D. Qin, M. Manning, et al. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of

the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007, p. 996.
[9] S.A. Suttles, W.E. Tyner, G. Shively, R.D. Sands, B. Sohngen, Economic effects of bioenergy policy in the United States and Europe: a general equilibrium approach focusing on forest biomass, Renew. Energy 69 (2014) 428–436.
[10] T.D. Ramsfield, B.J. Bentz, M. Faccoli, H. Jactel, E.G. Brockerhoff, Forest health in a changing world: effects of globalization and climate change on forest insect and pathogen impacts, Forestry 89 (3) (2016) 245–252.
[11] G.M. Locosselli, R.J. Brienen, M.D.S. Leite, M. Gloor, S. Krottenthaler, A.A. D. Oliveira, et al., Global tree-ring analysis reveals rapid decrease in tropical tree longevity with temperature, Proc. Natl. Acad. Sci. 117 (52) (2020) 33358–33364.
[12] N. Singh, A. Tewari, S. Shah, Treeline species: regeneration status and seedling dynamics in Western Himalayan region, Environ. Ecol. 38 (3B) (2020) 725–732.
[13] H.C. Fritts, Tree Rings and Climate, Academic Press, London, 1976.
[14] S. Aryal, D.R. Bhuju, D.K. Kharal, N.P. Gaire, N. Dyola, Climatic upshot using growth pattern of *Pinus roxburghii* from western Nepal, Pak. J. Bot. 50 (2) (2018) 579–588.
[15] E.R. Cook, P.J. Krusic, P.D. Jones, Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal, Int. J. Climatol. J. R. Meteorol. Soc. 23 (7) (2003) 707–732.
[16] A. Bhattacharyya, V.C. LaMarche Jr., M.K. Hughes, Tree-ring chronologies from Nepal, Tree-Ring Bull. 52 (1992) (1992).
[17] U.K. Thapa, S.K. Shah, N.P. Gaire, D.R. Bhuju, Spring temperatures in the far-western Nepal Himalaya since AD 1640 reconstructed from *Picea smithiana* treering widths, Clim. Dyn. (2014), https://doi.org/10.1007/s00382-0142457-1.
[18] N.P. Gaire, D.R. Bhuju, M. Koirala, Dendrochronological studies in Nepal: current status and future prospects, FUUAST J. Biol. 3 (1 june) (2013) 1–9.
[19] J.H. Speer, Fundamentals of Tree-Ring Research, The University of Arizona Press, Tucson, Arizona, 2010.
[20] P.K. Chhetri, S. Thapa, Tree ring and climate change in Langtang National Park, Central Nepal, Our Nature 8 (1) (2010) 139–143.
[21] A. Tiwari, Z.X. Fan, A.S. Jump, S.F. Li, Z.K. Zhou, Gradual expansion of moisture sensitive *Abies spectabilis* forest in the trans-Himalayan zone of Central Nepal associated with climate change, Dendrochronologia 41 (2017) 34–43.
[22] N.P. Gaire, M. Koirala, D.R. Bhuju, H.P. Borgaonkar, Treeline dynamics with climate change at the Central Nepal Himalaya, Clim. Past 10 (4) (2014) 1277–1290.
[23] E.R. Cook, L.A. Kairiukstis (Eds.), Methods of Dendrochronology: Applications in the Environmental Sciences, Springer Science & Business Media, 2013.
[24] P. Rautela, B. Karki, Impact of climate change on life and livelihood of indigenous people of higher Himalaya in Uttarakhand, India, Am. J. Environ. Prot. 3 (4) (2015) 112.
[25] D. Gautam, S. Basnet, P. Karki, B. Thapa, P. Ojha, U. Poudel, et al., A review on dendrochronological potentiality of the major tree species of Nepal, For. Res. 9 (2020) 227, https://doi.org/10.35248/2168-9776.20.9.227.
[26] A.R. Bhandari, U.R. Khadka, K.R. Kanel, Ecosystem services in the mid-hill forest of western Nepal: a case of Panchase protected forest, J. Inst. Sci. Technol. 23 (1) (2018) 10–17.
[27] J.D.A. Stainton, Forests of Nepal, John Murray, London, 1972.
[28] H. Choe, J.H. Thorne, C. Seo, Mapping national plant biodiversity patterns in South Korea with the MARS species distribution model, PLoS One 11 (3) (2016), e0149511.
[29] C.P. Ghimire, L.A. Bruijnzeel, M.W. Lubczynski, M. Bonell, Rainfall interception by natural and planted forests in the Middle Mountains of Central Nepal, J. Hydrol. 475 (2012) 270–280.
[30] K.K. Shrestha, S. Bhattarai, P. Bhandari, Handbook of flowering plants of Nepal, in: Gymnosperms and Angiosperms: Cycadaceae-Betulaceae vol. 1, Scientific Publishers (India), 2018.
[31] S. Aryal, N.P. Gaire, N.R. Pokhrel, P. Rana, B. Sharma, D.K. Kharal, A. Bräuning, Spring season in Western Nepal Himalaya is not yet warming: a 400-year temperature reconstruction based on tree-ring widths of Himalayan hemlock (*Tsuga dumosa*), Atmosphere 11 (2) (2020) 132.
[32] N.P. Havill, C.S. Campbell, T.F. Vining, B. LePage, R.J. Bayer, M.J. Donoghue, Phylogeny and biogeography of *Tsuga* (Pinaceae) inferred from nuclear ribosomal ITS and chloroplast DNA sequence data, Syst. Bot. 33 (2008) 478–489.
[33] A. Farjon, Index to botanical names of conifers, in: A Handbook of the World's Conifers, Brill, 2010, pp. 1073–1111, 2 vols.
[34] F. Rinn, T.S.A.P. Win, Time Series Analysis and Presentation for Dendrochronology and Related Applications. User Reference Version 0.53, Rinntech, Heidelberg, 2005.
[35] H.D. Grissino-Mayer, Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA, Tree-Ring Res. 57 (2) (2001) 205–221.
[36] E.R. Cook, A Time Series Analysis Approach to Tree Ring Standardization (Doctoral dissertation, University of Arizona, 1985.
[37] R. Core Team, R: A Language and Environment for Statistical Computing, Version 3.0. 2 2013, R Foundation for Statistical Computing, Vienna, Austria, 2019.
[38] C. Zang, F. Biondi, Treeclim: an R package for the numerical calibration of proxy-climate relationships, Ecography 38 (4) (2015) 431–436.
[39] J. Peñuelas, J.G. Canadell, R. Ogaya, Increased water-use efficiency during the 20th century did not translate into enhanced tree growth, Glob. Ecol. Biogeogr. 20 (4) (2011) 597–608.
[40] M.W. Salzer, M.K. Hughes, Bristlecone pine tree rings and volcanic eruptions over the last 5000 yr, Quat. Res. 67 (1) (2007) 57–68.
[41] T.M.L. Wigley, K.R. Briffa, P.D. Jones, On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, J. Clim. Appl. Meteorol. 1984 (23) (1984) 201–213, https://doi.org/10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2.
[42] S. Bhandari, N.P. Gaire, S.K. Shah, J.H. Speer, D.R. Bhuju, U.K. Thapa, A 307-year tree-ring SPEI reconstruction indicates modern drought in western Nepal Himalayas, Tree-Ring Res. 75 (2) (2019) 73–85.
[43] A. Sanmiguel-Vallelado, J.J. Camarero, E. Morán-Tejeda, A. Gazol, M. Colangelo, E. Alonso-González, J.I. Lopez-Moreno, Snow dynamics influence tree growth by controlling soil temperature in mountain pine forests, Agric. For. Meteorol. 296 (2021), 108205.
[44] E. Liang, B. Dawadi, N. Pederson, D. Eckstein, Is the growth of birch at the upper timberline in the Himalayas limited by moisture or by temperature? Ecology 95 (2014) https://doi.org/10.1890/13-1904, 140307191613003.
[45] R.R. Yadav, J. Singh, Tree-ring analysis of *Taxus baccata* from the western Himalaya, India, and its dendroclimatic potential, Tree-Ring Res. 58 (1/2) (2002) 23–29.
[46] D.K. Kharal, U.K. Thapa, S.S. George, H. Meilby, S. Rayamajhi, D.R. Bhuju, Tree-climate relations along an elevational transect in Manang Valley, Central Nepal, Dendrochronologia 41 (2017) 57–64.
[47] N.P. Gaire, Y.R. Dhakal, S.K. Shah, Z.X. Fan, A. Bräuning, U.K. Thapa, D.R. Bhuju, Drought (scPDSI) reconstruction of trans-Himalayan region of central Himalaya using *Pinus wallichiana* tree-rings, Palaeogeogr. Palaeoclimatol. Palaeoecol. 514 (2019) 251–264.
[48] K. Takahashi, Y. Tokumitsu, K. Yasue, Climatic factors affecting the tree- ring width of *Betula ermanii* at the timberline on mount Norikura, Central Japan, Ecol. Res. 20 (4) (2005) 445–451.
[49] B. Dawadi, E. Liang, L. Tian, L.P. Devkota, T. Yao, Pre-monsoon precipitation signal in tree rings of timberline Betula utilis in the Central Himalayas, Quat. Int. 283 (2013) 72–77.
[50] M. Müller, N. Schwab, U. Schickhoff, J. Böhner, T. Scholten, Soil temperature and soil moisture patterns in a Himalayan alpine treeline ecotone, Arct. Antarct. Alp. Res. 48 (2016) 501–521.
[51] D. Gautam, J. Karki, N.P. Gaire, B.E. Roth, S. Bhattarai, S. Thapa, Q.J. Liu, Intra- and interannual climate variability drives the radial growth of *Pinus wallichiana* in the Nepalese Himalayas, Plant Ecol. Diversity 13 (5–6) (2020) 391–400.
[52] U.K. Thapa, S.K. Shah, N.P. Gaire, D.R. Bhuju, Spring temperatures in the far-western Nepal Himalaya since AD 1640 reconstructed from *Picea smithiana* tree-ring widths, Clim. Dyn. 45 (7) (2015) 2069–2081.
[53] J. Panthi, P. Dahal, M.L. Shrestha, S. Aryal, N.Y. Krakauer, S.M. Pradhanang, R. Karki, Spatial and temporal variability of rainfall in the Gandaki River basin of Nepal Himalaya, Climate 3 (1) (2015) 210–226.
[54] R. Bista, P.K. Chhetri, J.S. Johnson, A. Sinha, K.B. Shrestha, Climate- driven differences in growth performance of cohabitant fir and birch in a subalpine Forest in Dhorpatan Nepal, Forests 12 (9) (2021) 1137.
[55] A. Tiwari, N. Thapa, S. Aryal, P. Rana, S. Adhikari, Growth performance of planted population of *Pinus roxburghii* in Central Nepal, J. Ecol. Environ. 44 (2020) 31 (2020), https://doi.org/10.1186/s41610-020-00171-w.
[56] S.R. Sigdel, B. Dawadi, J.J. Camarero, E. Liang, S.W. Leavitt, Moisture- limited tree growth for a subtropical Himalayan conifer forest in western Nepal, Forests 9 (6) (2018) 340.
[57] G. Herrera-Soto, M. González-Cásares, M. Pompa-García, J.J. Camarero, R. Solís-Moreno, Growth of Pinus cembroides Zucc. In response to hydroclimatic variability in four sites forming the species latitudinal and longitudinal distribution limits, Forests 9 (7) (2018) 440.
[58] L. Duchesne, R. Ouimet, C. Morneau, Assessment of sugar maple health based on basal area growth pattern, Can. J. For. Res. 33 (11) (2003) 2074–2080.
[59] D.C. LeBlanc, N.S. Nicholas, S.M. Zedaker, Prevalence of individual-tree growth decline in red spruce populations of the southern Appalachian Mountains, Can. J. For. Res. 22 (6) (1992) 905–914.
[60] A.S. Jump, J.M. Hunt, J. Penuelas, Rapid climate change related growth decline at the southern range edge of *Fagus sylvatica*, Glob. Chang. Biol. 12 (11) (2006) 2163–2174.
[61] J. Weiner, S.C. Thomas, The nature of tree growth and the" age-related decline in forest productivity", Oikos 94 (2) (2001) 374–376.
[62] S. Vospernik, Basal area increment models accounting for climate and mixture for Austrian tree species, For. Ecol. Manag. 480 (2021), 118725.
[63] A. Tiwari, Z.X. Fan, A.S. Jump, Z.K. Zhou, Warming induced growth decline of Himalayan birch at its lower range edge in a semi-arid region of trans-Himalaya, Central Nepal, Plant Ecol. 218 (5) (2017) 621–633.
[64] M.A. Matin, V.S. Chitale, M.S. Murthy, K. Uddin, B. Bajracharya, S. Pradhan, Understanding forest fire patterns and risk in Nepal using remote sensing, geographic information system and historical fire data, Int. J. Wildland Rire 26 (4) (2017) 276–286.
[65] M.D. Abrams, D.A. Orwig, Structure, radial growth dynamics and recent climatic variations of a 320-year-old *Pinus rigida* rock outcrop community, Oecologia 101 (3) (1995) 353–360.
[66] J.S. Sperry, U.G. Hacke, J. Pittermann, Size and function in conifer tracheids and angiosperm vessels, Am. J. Bot. 93 (10) (2006) 1490–1500.