



Growth dynamics of *Shorea robusta* Gaertn in relation to climate change: a case study from tropical region of Nepal

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Abstract

Key message The growth of *Shorea robusta* is positively correlated with temperature, whereas the relation to moisture is weak.

Abstract Tree-ring analyses provide a rich archive of information on environmental attributes affecting tree growth. Tree-ring studies conducted so far have mostly focused on temperate species, and research on tropical trees is limited. This study aims to develop a tree-ring chronology of *Shorea robusta* and understand the climatic sensitivity of its growth in the tropical region of Nepal. Tree-ring samples of *S. robusta* were analysed following the standard dendrochronological sample analysis procedure. A 134-year-long ring-width chronology of *S. robusta* was developed, extending from 1851 to 2018, which is the longest chronology reported for this species. The chronology statistics revealed its high dendroclimatic potential with moderate $R\text{-bar}$, high expressed population signal, and low autocorrelation. The mean annual radial growth was 2.87 mm per year, while the mean basal area increment (BAI) was 9.245 cm² per year. The ring width, BAI chronology and size-based growth analysis revealed an increasing growth trend of the species, which is likely favoured by the ongoing climate change. The tree growth of the species was positively correlated to temperature throughout the year; however, the relation to moisture parameters was weak. The temperature sensitivity of the species is stable over time, though a slight temporal difference exists in the strength of association.

Keywords *Shorea robusta* · Tropical forest · Tree ring · Growth · Basal area increment · Nepal

Introduction

Tropical forests play an important role in the global carbon cycle, where understanding the response of tropical forests to a changing climate is important (Clark et al. 2010; Corlett 2011). Considering the significance of the tropical forests in relation to climate change, tree-ring studies have now slowly expanded to broadleaved species (Sano et al. 2009; Pumijumnon and Buajan 2013; Anhuf and Schleser 2017; Zhao et al. 2019; Locosselli et al. 2020). Tree-ring analysis is widely used to study environmental patterns and

processes, including the effects of climate on tree growth (Fritts 1976; Xuzhi 1991; Speer 2010; Babst et al. 2019; Dyola et al. 2020). It allows reconstruction of historical growth and physiology of trees (Hiltner et al. 2016) and provides answers to several questions related to forest history, species distribution, forest management, nature conservation, forest productivity, and forest ecology (Xu et al. 2017, 2019; Baral et al. 2019; Locosselli et al. 2020). Information on diameter growth rates, stand age and survival is necessary required for making sustainable forest management plans, which can be obtained from tree-ring analyses (Babst et al. 2014; Girardin et al. 2016; Islam et al. 2018; Xu et al. 2019).

The application of tree-ring analysis has immense scope in Nepal, as the country has diverse climatic conditions and vegetation types within a small geographical area. Though several studies were conducted on temperate and subalpine regions of the Nepal Himalayas, they were focused on softwood species, which are easier to analyse than hardwood species like *Shorea robusta* (Gaire et al. 2013; Speer et al.

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2016; Thapa et al. 2017). Studies on dendroclimatic potential and climatic sensitivity and response of hardwood species are very limited, particular in *S. robusta Gaertn* forests (Sapkota et al. 2009; Baral et al. 2019).

Of the 44.74% forested land in Nepal, 50% lies in tropical and sub-tropical regions in which *S. robusta* is the dominating species (DFRS 2015). Thus, the growth pattern of *S. robusta* with changing climate is essential to know their climate sensitivity and response. Moreover, the sensitivity of tree growth to climate can vary over time according to the strength of climatic harshness and the magnitude of climate change (Babst et al. 2019; Rakthai et al. 2020). Therefore, analyses assessing the sensitivity of climate–growth response are necessary to determine the impact of climate change on tree growth (Gaire et al. 2020; Rakthai et al. 2020). A few studies from Nepal have focused on the temporal stability of the climate–growth relationship; however, there is no clear and unidirectional temporal response, i.e. some studies show similar response over time, while others reveal changing response (Shrestha et al. 2015; Schwab et al. 2018; Gaire et al. 2020). Hence, how changing climatic patterns affect the growth of *S. robusta* and their climatic sensitivity needs to be better studied.

Tree-ring studies from the Asian tropics have focused on multiple applications, including climatology (climate–growth relationships, past climate reconstructions), ecology, forestry (basal area increment, regeneration, cambium dynamics), among others, by using multi-proxy tree-ring parameters (Anhuf and Schleser 2017; Islam et al. 2018; Rahman et al. 2018, 2019; Zhao et al. 2019; Rakthai et al. 2020; Zaw et al. 2020). *S. robusta*, a highly acknowledged economically valuable species of Nepal, is widely distributed up to a maximum of 1500 masl (Jackson et al. 1994) and represents 15.3% of the forest area of the country (DFRS 2015). The study, carried out for a national survey, indicated that *S. robusta* had the highest stem volume (31.76 m³/ha or 19.28%), followed by *Quercus* spp. (24.39 m³/ha) and *Pinus roxburghii* (11.62 m³/ha) (DFRS 2015). It is mainly used for timber purposes, although due to the current protection-oriented management system, the tree species is not utilized so effectively. The normal rotation period of this species is 80 years in community forest management plans, without considering the site factor, resource condition, climatic conditions and the related growth patterns. Studies available on the growth rate of *S. robusta* are limited; therefore, both physical and economical rotation and the driving factors behind, thus the physical, as well as economical rotation age, are hard to identify.

Though Baral et al. (2019), assessed the wood anatomical properties of *S. robusta* and studied the climate sensitivity of *S. robusta* in the central region of Nepal, information on the temporal growth trends and prediction of the annual increment were missing due to limited field observations. The

observations in Baral et al. (2019) concluded that changes in precipitation and temperature played an important role in its growth, leading to further investigations in this study to analyze the climate–growth responses of *S. robusta* and its temporal variation for a longer time period and using a larger sample size.

Material and methods

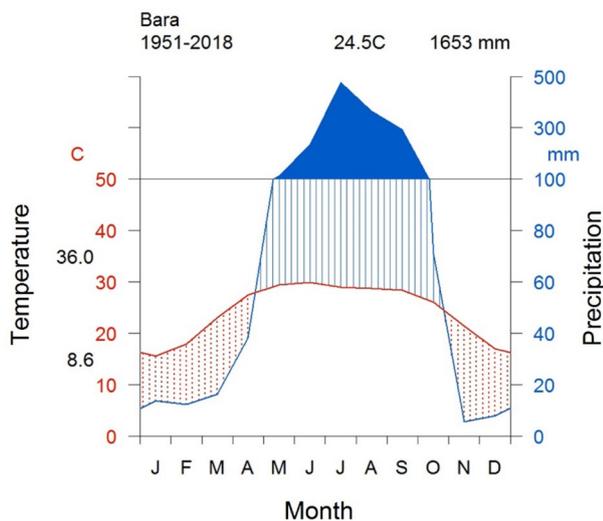
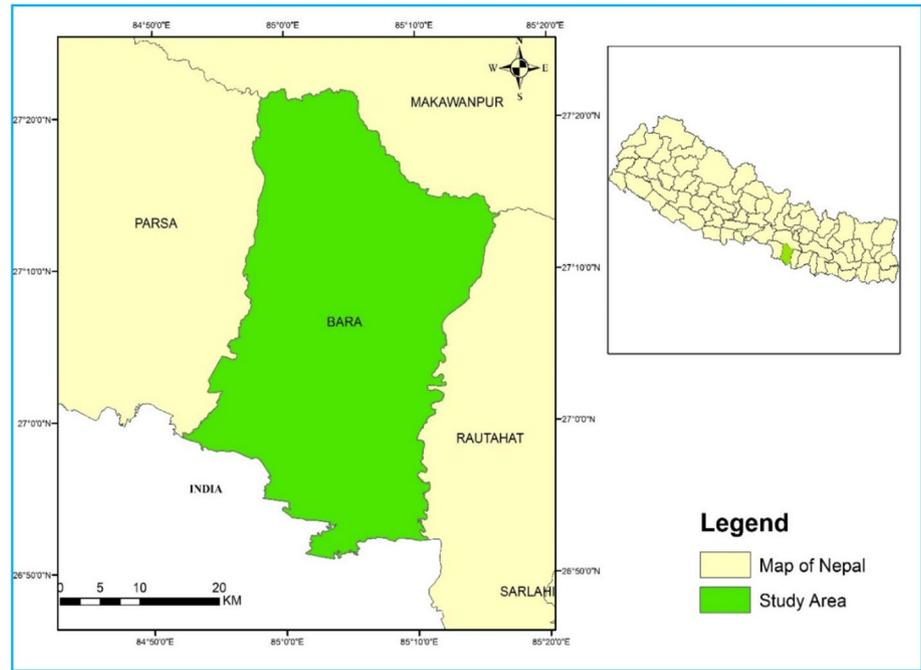
Study area and climate

The study was conducted in Bara district, central Terai (Fig. 1), a tropical region of Nepal. This area is dominated by *S. robusta* species, along with other associated species such as *Semecarpus anacardium*, *Holarrhena pubescens* and *Terminalia alata*. The elevation of the study area ranges between 200 and 300 m, and it experiences a maximum average temperature of 36 °C in July, and a minimum temperature of 8.6 °C in January. The average annual temperature is 24.5 °C with annual precipitation of 1653 mm (Fig. 2). Much of the annual rainfall (> 83%) occurs during the summer monsoon season (June–September) with high intensity from mid-June to mid-July. In the study area, there has been a rapid and persistent increase in the annual average temperature (mean, maximum and minimum) since the 1950s (Fig. 3).

The selected sites fall under the buffer zone of the protected area, where there was no major change in land use. There was limited logging, especially for timber and firewood collection, whereas no incidents of forest fires and other biotic interferences such as grazing and lopping have been recorded.

Sample collection and preparation

During April–June 2019, the Timber Corporation of Nepal felled trees for the construction of an oil pipeline. Discs were obtained from 78 felled trees. Among the trees felled, we selected high-quality logs (i.e. non-pathogen-affected, good-quality timber), representing eight diameter classes in the interval of 10 cm (10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, > 80). For each tree, the diameter at breast height, tree height, crown height, and crown length of the standing trees were measured, GPS coordinates were recorded and information about the neighbouring tree species, including distance from the selected tree, was recorded. In total, 78 discs were brought to the Dendrochronology Laboratory of the Nepal Academy of Science and Technology (NAST) for analysis. The samples were processed and analysed following a standard dendrochronological procedure as prescribed by Fritts (1976) and Speer (2010). The samples were smoothed and left for air drying for a month.

Fig. 1 Map of the study area**Fig. 2** Climograph of the study area in Bara district in Nepal, revealing the distribution of monthly temperature and precipitation. The letters in the X-axis indicate the names of months from January to December

The air-dried cross section of the cut stumps were sanded and polished using a sanding machine with different grades of sandpaper (grid size of 120–3000) until ring boundaries were visible under a stereo zoom microscope.

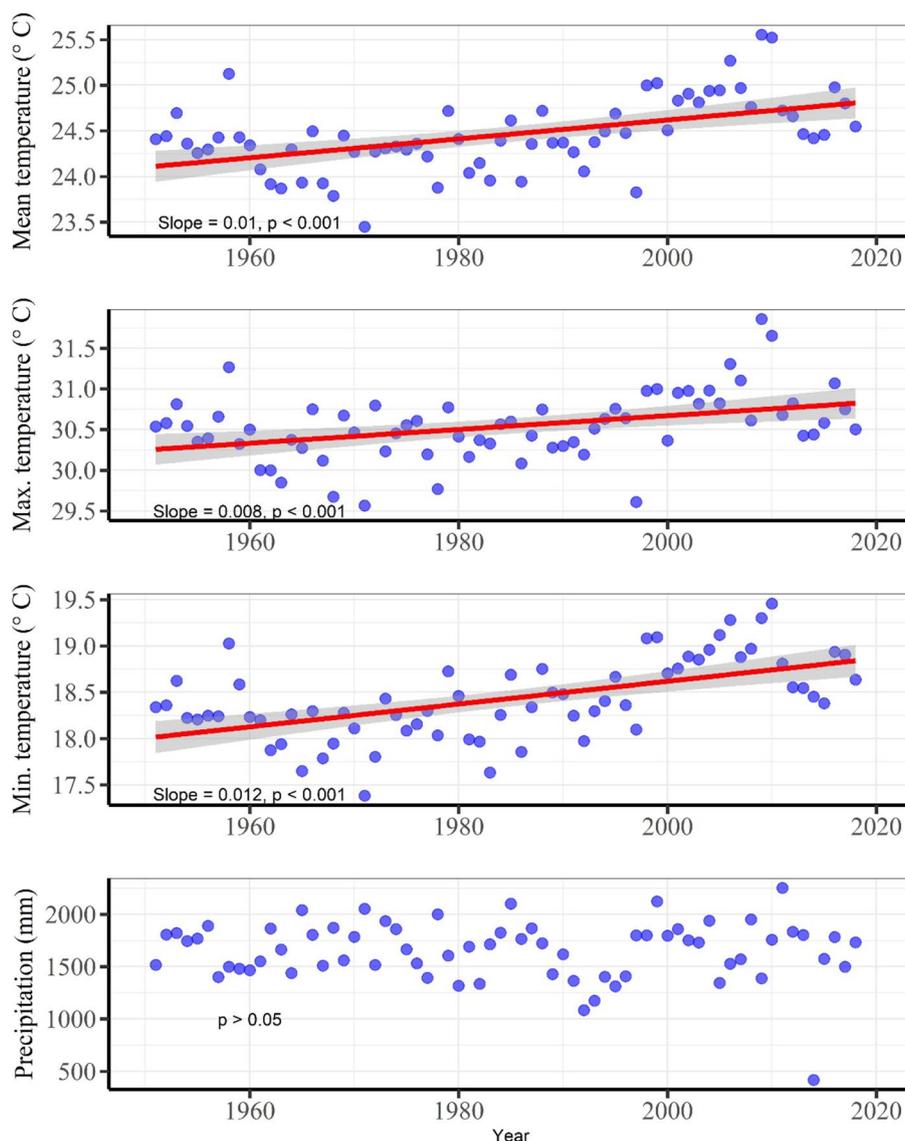
Every single ring in each sample disc was counted from the pith to the bark direction using the stereomicroscope. Counting was done in four radii in each cross section with proper observation of the samples under a microscope with necessary rotations in all directions. In most of the cut stump

samples, the pith was not centrally located. Therefore, the ring width of the species was not symmetrical in all directions, and, in many cases it was pinched in some locations and locally missing in those sections.

After counting each ring in the sample, the tree-ring width (TRW) was measured with a precision of 0.01 mm using LINTAB5™ attached to a computer having TSAP-WIN software (Rinn 2003). Altogether, 312 raw TRW time series were developed. The TRW series were cross-dated in TSAP by checking math graphs and cross-dating statistics (GLK, CDI, *t*-statistics) and rechecking all the samples (Rinn 2003; Islam et al. 2018). The errors in cross-dating were further evaluated using the quality control computer program, COFECHA (Holmes 1983). Further detected errors were corrected. After cross-dating, we averaged the four radii TRW data of each tree to develop individual raw TRW chronology before standardization. Among a total of 78 cross sections, 69 samples were used for final analysis, while the remaining nine samples were discarded because most of them were hollow at the centre.

The ring width is influenced by tree age, stand and site conditions, climate, and other environmental variables (Fritts 1976). Therefore, to isolate the climatic influence on tree growth, we standardized the raw ring-width series using different mathematical models (Fritts 1976). There are several detrending options like conventional detrending using a negative exponential curve, regional curve standardization, or signal-free standardization. We tried different standardization techniques using the *dpLR* package in R (Bunn 2008) and *RCSsigFree* programs (Melvin and Briffa 2008). After checking the preliminary climatic responses

Fig. 3 Climatic trend in the study area for the period 1951–2018 based on the Climate Research Unit's grid climatic data (CRU TS4.03)



of different versions of *Shorea* chronologies, we selected the chronologies developed by signal-free standardization for final use as it captured strong climatic signals. Detrending was carried out using RCSsigFree software (<http://www.ideo.columbia.edu/tree-ring-laboratory/resources/software>). Each raw ring-width series was detrended by fitting an age-dependent spline curve of two-thirds length of each series, and the index was computed using the ratio method. The final signal-free tree-ring chronology was computed by using the bi-weight robust mean function (Cook and Kairiukstis 1990). Chronology quality was checked using the mean between-tree correlation (\bar{R}) and expressed population signal (EPS) criteria (Wigley et al. 1984; Briffa 1995). The growth statistics were also calculated using the dplR package in R (Bunn 2008).

Basal area increment analysis

The change in growth of a tree in a time period is determined by basal area increment (BAI) (Bunn 2008). Individual raw TRW series was calculated through an average of four raw ring-width series of each tree before being subjected to BAI measurement. Ring-width data were converted into tree BAI following the standard formula:

$$BAI_t = \pi R_t^3 - \pi R_{t-1}^2, \quad (1)$$

where R is the tree radius and t is the year of tree-ring formation. Ring-width measurements were converted to BAI using the function `bai` out in the R package `dplR` (Bunn 2008). Then, we used the individual tree BAI to produce mean and unstandardized BAI series for each year. The BAI was also presented according to different size (age and dbh) classes.

Growth trend analyses using size-class isolation

To calculate the tree growth over time at a constant ontogenetic stage, growth trends were evaluated at fixed diameters (Peters et al. 2015; van der Sleen et al. 2015), using the size-class isolation (SCI) (Peters et al. 2015) method. We calculated the 5-year average tree-ring width (TRW_{sci}) in five fixed diameters: 10, 15, 20, 25, and 30 cm. For this analysis, we included the central ring (the ring at fixed diameter) and the two rings formed before and after the central ring (van der Sleen et al. 2015; Panthi et al. 2019). The SCI removes the year-to-year variations in tree growth due to year to-year climate variability. Since SCI depends on large sample sizes but fully accounts for potential trends in tree age/size, it is taken as a reliable method for detection of growth trends (Peters et al. 2015).

Growth–climate relationship

The nearest meteorological station to the sampling site had a very short record of climatic data for analysis; therefore, CRU-TS4.03 gridded climatic data (Harris et al. 2014) were used to determine the influence of climatic variables on tree growth. We averaged the values of the nearest four CRU grid cells (84.5–85.5°E and 26.5–27.5°N) covering our sampling site and extracted data using the KNMI climate explorer (Trouet and Oldenborgh 2013). We computed average monthly values for temperature (maximum, minimum and mean) and precipitation for the period 1951–2018. Likewise, to identify the influence of droughts on tree growth, we used two drought indices, namely standardized precipitation and evapotranspiration index (SPEI) of 3 months (SPEI03) and self-calibrated Palmer drought severity index (scPDSI) for the period 1951–2017 (Vicente-Serrano et al. 2010; van der Schrier et al. 2013; Begueria et al. 2014). A climatic window of 19 months starting in June of the previous growth year to December of the current growth year was used to compute correlations between the monthly climatic variables and the tree-ring-width chronology. Similarly, to examine the influence of seasonal climate on radial growth, we performed correlation tests between the TRW chronology and climate variables for three different seasons: winter (DJF, December–February), spring/pre-monsoon (MAM, March–May), summer/monsoon (JJAS, June–September) (Gaire et al. 2020). Bootstrapped Pearson’s correlation coefficient was used to check the strength of the association using the package “treeclim” (Zang and Biondi 2015).

Results and discussion

Tree-ring-width chronology of *S. robusta*

By using 276 tree-ring series from the 69 cut-stump samples, a 134-year-long ring-width chronology of *S. robusta* was

developed extending from AD 1885 to 2018 (Table 1). There were wide variations in the age of the sampled trees with a mean age of 59 years (23–134 years). The mean AGR (annually average radial growth rate) was 2.87 mm/year, which ranged from 1.78 to 4.15 mm/year.

The R-bar is moderate (0.223); however, the expressed population signal (EPS = 0.952) is higher than the commonly used threshold of 0.85 (Wigley et al. 1984) since the year 1948 (Fig. 4). This indicates that our chronology represents the population signal and is promising for studying the relationship between climate and growth (Cook and Kairiukstis 1990). The chronology statistics of *S. robusta* obtained in the present study are similar to those obtained for other tropical tree species from the Himalayas and adjacent regions in Asia (Shah et al. 2007; Ram et al. 2008; Borgaonkar et al. 2010; Shah and Mehrotra 2017; Rahman et al. 2018, 2019; Zaw et al. 2020). The RWI chronology we developed is the longest chronology for this tropical species so far reported at the global level. Our RWI chronology (Fig. 4) revealed slightly fluctuating growth over time with a persistent increase in growth after 1950s, which might have been favoured by the increasing temperature in the area. Similar positive growth trends have been observed during recent decades in some of the previous tree-ring studies from other high-altitude regions in Nepal (Thapa et al. 2017; Baral et al. 2019; Gaire et al. 2020; Panthi et al. 2019). The growth trend in the *Shorea* chronology is very similar to that of *Toona* (*Toona ciliata*) growth from the eastern Himalayas (Shah and Mehrotra 2017).

The wood anatomical study in Islam et al. (2018) and Baral et al. (2019) helped to identify and verify the ring boundary detection of *S. robusta*. Moreover, for detecting the boundary precisely and identify possible false rings and better understand the growth dynamics of the species, recently we have installed digital dendrometer and also

Table 1 Summary statistics of the *S. robusta* chronology from Nepal

Parameters	Statistics
No of trees	69
First year	1885
Last year	2018
Minimum age (years)	23
Maximum age (years)	134
Mean age (years)	59
Mean AGR ± SD (mm)	2.87 ± 1.43
Median AGR (mm)	2.53
Minimum AGR (mm)	1.78
Maximum AGR (mm)	4.15
Mean BAI ± SD (mm ² /yr)	924.51 ± 806.33

AGR average radial growth rate; BAI basal area increment; SD standard deviation

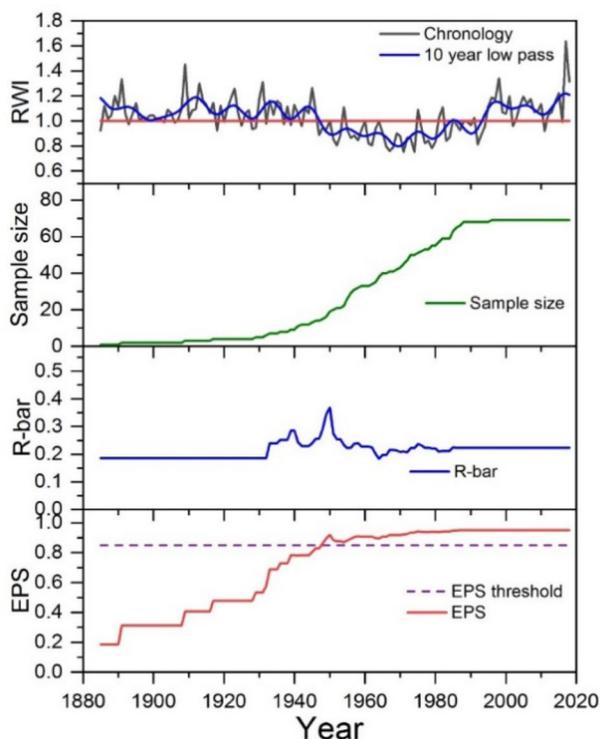


Fig. 4 The standard chronology of *S. robusta* with a red-coloured curve representing 10 years spline-smoothing curve (uppermost), sample size used for building this chronology along with running R-bar value and EPS (expressed population signal). The RWI denotes ring-width index

collected microcores every 15 days to have a better confirmation of the findings. However, these cambium dynamics studies are still ongoing and it is too early to conclude on the cambium dynamics of the species.

Basal area increment (BAI) analysis

The average BAI of *S. robusta* was 924.5 mm² per year (Table 1). The average BAI chronology of *S. robusta* showed an increasing trend over the entire period with slight fluctuations (Fig. 5a). We found a similar recent BAI pattern in the all dbh classes (< 30, 30–50 and > 50 cm) during the recent decades (Fig. 5c). However, if we present BAI according to age class (age 50 = 0–50; age 100 = 50–100, and age 150 = > 100 years old), there is a slightly different BAI pattern, i.e. there is slight decrease in BAI in old-aged trees during recent years and decades (Fig. 5b).

The BAI generally follows a sigmoid growth curve (Tiwari et al. 2017). Therefore, our graph indicates that the trees felled at the study site for this observation were still at the growing stage. BAI increase for young trees is expected from the sigmoidal model because BAI should increase along with an increasingly larger leaf canopy (Spiecker et al.

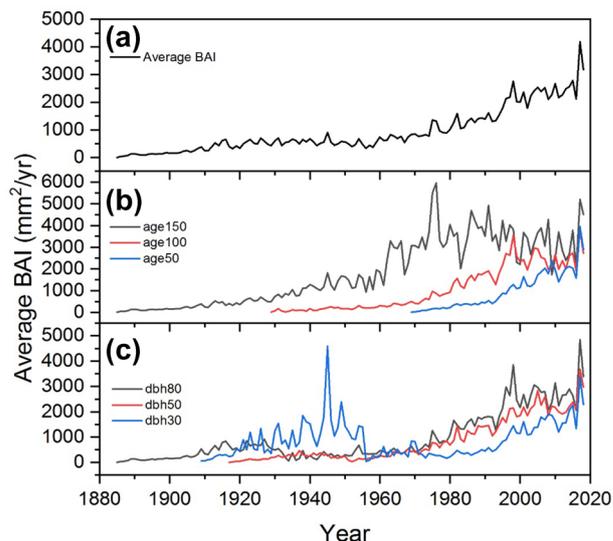


Fig. 5 Average BAI chronology of *S. robusta* (a) along with the average BAI in three age classes (b) and dbh classes (c). BAI is presented in three age classes (age 50 = 0–50; age 100 = 50–100, and age 150 = > 100 years old) and three dbh classes (< 30 cm = dbh30, 30–50 cm = dbh50, and > 50 cm = dbh80)

1996). If the forest reaches its maturity, the BAI growth may stabilize. Previous studies from Nepal have also observed an increasing trend in earlier growth stages compared to a decreasing trend in BAI at a later stage depending on the species, climate and site conditions (Tiwari et al. 2017; Baral et al. 2019; Panthi et al. 2019; Gaire et al. 2020). The BAI increments are useful to know the status of forest health, as well as to calculate forest biomass, carbon sequestrations and ecosystem productivity (Babst et al. 2014; Pandey et al. 2014; Girardin et al. 2016; Rakthai et al. 2020). This supports also the findings of Baral et al. (2021) that reliable growing stock estimates of *Shorea* should take into account the effects of wider spacing and longer crowns on stem taper and allocation patterns. Since our average BAI chronology showed a continuous increment over time, it indicates that the *Shorea* trees were in a healthy growing condition and sequestering the carbon in their biomass. However, separating the BAI trend by size classes (age, dbh) would be important to test if the majority of the trees did not reach maturity, indicating the early growth signal in the BAI trend only (Silva et al. 2016; Quadri et al. 2021). Though there are only a few number of sample (i.e. five trees) in old-age trees (age150 class), it shows decreasing BAI during recent decades. Previous studies found similar to different BAI pattern in different size classes (Silva et al. 2016; Quadri et al. 2021). Therefore, assessing the BAI in different size classes will give a better idea on tree growth including a levelling off threshold of expected maturity and allowing a more confident interpretation of the data.

A linear relationship between growth and time revealed a positive trend in tree growth (TRW_{sci}) over time in all size classes (Fig. 6). Some studies in the Nepal Himalayas have also found a positive growth trend in the tree-ring chronology in recent decades (Thapa et al. 2017; Gaire et al. 2020). However, there is no such size-based growth study of this tree species available from the tropical region of Nepal for comparing the growth patterns of different sized trees.

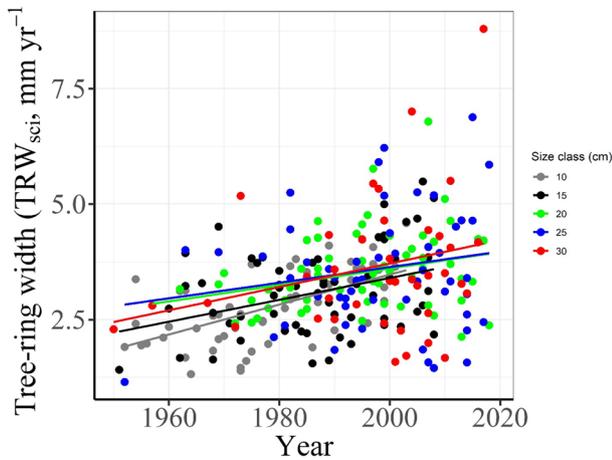


Fig. 6 Trends of growth of tree-ring widths (TRW_{sci}) of *S. robusta* in central Himalaya. TRW_{sci} was calculated as 5 year averaged tree-ring width at five fixed tree sizes (10, 15, 20, 25, and 30 cm in diameter) to account for ontogenetic effects on tree growth. In the figure, annual radial growth is shown in mm per year. All regressions are significant (p less than 0.05)

Growth–climate relationship of *S. robusta*

The analysis of the climate–growth relationship of *S. robusta* indicated that growth is positively correlated with temperature in most of the months and seasons of the current growth years (Fig. 7). There was a significant positive correlation between the growth of *S. robusta* and temperature during winter (December–February) and summer (June, August and September) (Fig. 7). In terms of seasonal response, there was a significant positive relationship with winter and summer minimum, maximum and mean temperatures. In the spring season, the relation was significant only with the minimum temperature. However, there was a positive relationship between growth and precipitation in September of the previous growth year (Fig. 7). The relationship with precipitation and drought indices was relatively weak compared to that with temperature. This indicates that the historical amount and distribution of the precipitation in the area is sufficient for the growth of *Shorea* trees. Trees can get sustained supply of necessary water from groundwater sources. Therefore, precipitation higher than the threshold value can have neutral or even negative effects on the growth of the species. A previous study on the tree-ring analysis of *S. robusta* in the hilly area of Chitwan (Baral et al. 2019) found a positive correlation with temperature during autumn and winter seasons and a positive relationship with annual, spring summer season precipitation. Compared to the response of the species in Chitwan (Baral et al. 2019), we found a weak correlation with precipitation. However, these contrasting findings could be related to differences in the site

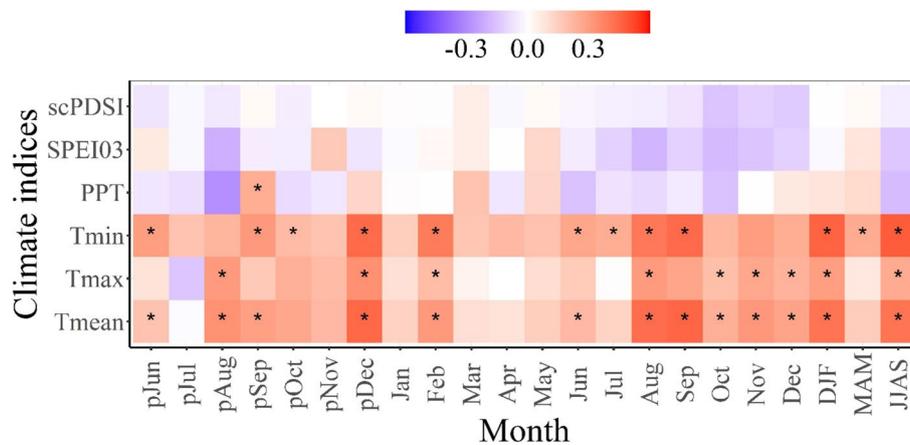


Fig. 7 Heat map revealing correlation (Pearson’s correlation coefficient) between *S. robusta* tree-ring-width index chronology and climate parameters (scPDSI=self-calibrated Palmer drought severity index, SPEI03=three monthly standardized precipitation evapotranspiration index, PPT=precipitation, T_{mean} , T_{min} and T_{max} indicate mean, minimum and maximum temperature). Blue colour represents negative correlation, white represents no correlation and red represents

positive correlation. The symbol * indicates the correlation significant at 95% or above confidence level. pJun to pDec indicates the months of the preceding growth year, June–December, while January–December represents the month of the current growth year. DJF, MAM, and JJAS indicate the winter, spring and summer seasons, respectively

conditions. Other studies from Nepal also indicate temperature or moisture limitation in tree growth (Tiwari et al. 2017; Aryal et al. 2020; Panthi et al. 2019; Gaire et al. 2020). Our region falls in the humid tropical region in Nepal (Talchabhadel et al. 2019), which could be the reason for obtaining a positive relationship with temperature.

Studies on the growth–climate relationship in the tropical regions of Asia and other regions have indicated that temperature or precipitation are two major growth-limiting climatic factors (Ram et al. 2008; Borgaonkar et al. 2010; Shah and Mehrotra 2017; Rahman et al. 2018, 2019; Rakthai et al. 2020; Zaw et al. 2020). Similar to our finding, Shah and Mehrotra (2017) found a positive correlation between the growth of *Toona ciliata* (a sub/tropical species) and temperature (mean, maximum and minimum) during most of the months of the current growing season in the humid eastern Himalayas, while the relationship with precipitation was weak. Growth of the tropical teak trees in the south Asian region was limited mainly due to moisture stress at the beginning or main growing period (Borgaonkar et al. 2010; Shah et al. 2007; D'Arrigo et al. 2011; Zaw et al. 2020). Rahman et al. (2018) found that the growth of a tropical tree species, *Chukrasia tabularis*, in Bangladesh was influenced by temperature mainly during the early growing season. Similarly, radial growths of four tropical broadleaved tree species in western Thailand are limited by a wet season high temperatures and dry season precipitation (Vlam et al. 2014). However, the tropical teak growth in dry regions in Myanmar was mainly limited due to the temperature-induced moisture stress during dry winter–spring season, with a significant negative correlation with temperature and

a positive correlation with precipitation and scPDSI of the same season (Zaw et al. 2020).

The results of the seascorr analysis (seasonal correlation using partial correlation) between tree-ring-width chronology and climate (temperature as primary variable and precipitation as secondary variable) are shown in Fig. 8. The seasonal response showed a significant positive response between tree-ring chronology and monthly temperature in winter (December and February) and summer (August–September) and rainfall in early spring (March) months. In a 3-month period, the October temperature revealed a significant positive correlation with growth. Analyzing the means for a longer 6- and 12-month period, it was found that temperature and precipitation have no statistically significant response on the growth. The water table in the Terai region is at a high level and trees can easily obtain water from groundwater sources. Precipitation higher than the threshold value (in excess of plant's need) may have a neutral influence on growth. In the Terai plain area of Nepal, with precipitation in excess of the soil capacity, water recharge can cause waterlogging, ultimately negatively affecting tree growth. That could be a reason for the relatively weak relationship with precipitation. Though high temperature throughout the year, especially in winter and summer, was found to favour the growth of *Shorea* trees with positive growth trend, how the growth trend of the species will be in response to future climate change, especially in a drying and warming world, is uncertain and a topic of future research.

The moving correlation analysis using seasonal climatic data for the period 1951–2017, using a 30-year climatic window and a 5-year window offset revealed that the climatic

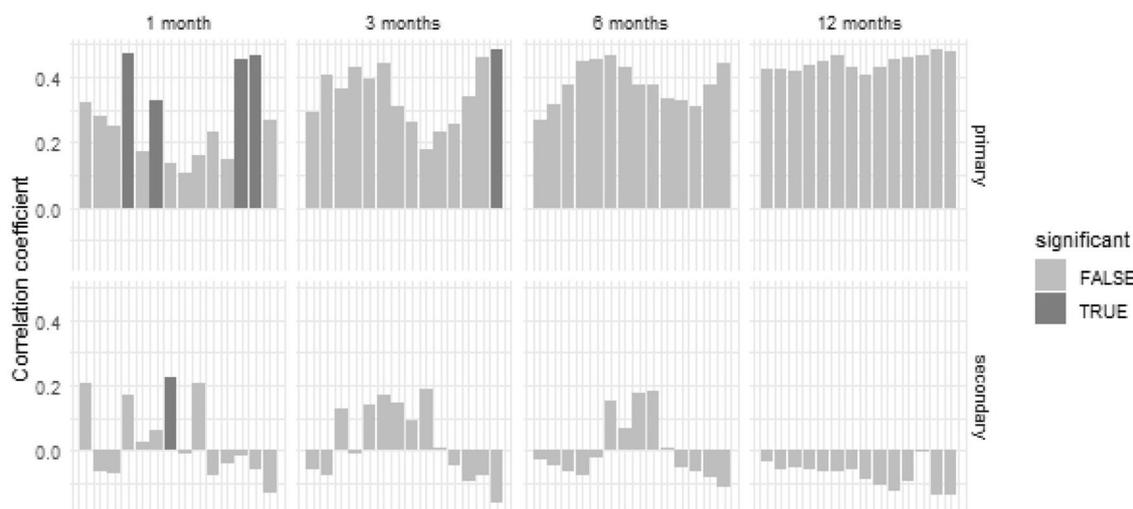


Fig. 8 Seascorr analysis results between the *Shorea* tree-ring-width index chronology and temperature as primary and precipitation as the secondary climatic variable. The analysis uses 1-month, 3-month, 6-month and 12-month mean temperatures and cumulative rainfall for

ending months from September of the preceding growth year to October of the current growth year. A significant response (at 95% confidence limit) is shown in the black shaded bar

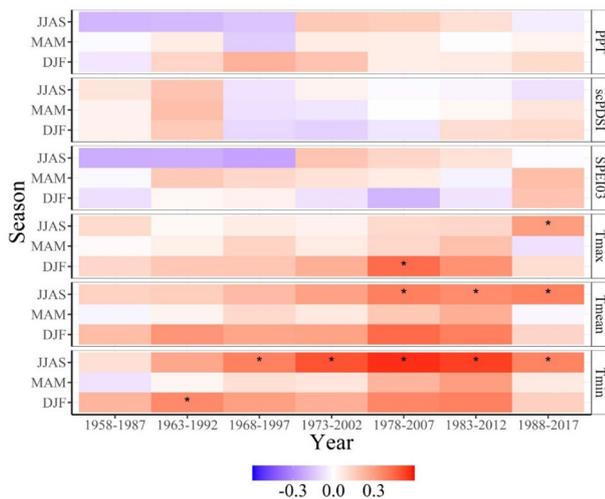


Fig. 9 Moving correlation between the *S. robusta* tree-ring-width index chronology and seasonal climatic data (DJF: winter, MAM: spring, and JJAS: summer) for the period 1951–2017. The analysis was done using a 30-year climatic window with a 5-year window offset. The significant response is indicated by the * symbol

response of *S. robusta* is temporally slightly changing (Fig. 9). The direction of the response with the temperature is almost the same throughout the analysis period despite slight variations in the magnitude of the response.

The temporal response of tree growth to climate in different regions of the world is stable or changing, depending on the species, site conditions and study region. Globally, tree growth became limited by atmospheric water demand, while growth sensitivity to temperature decreased in cold dry environments (Babst et al. 2019). While an increasing number of studies investigated changes in tree growth sensitivity in the temperate and boreal forests (Wilmking et al. 2004; Carrer and Urbinati 2006; Schwab et al. 2018), such studies on tropical forest species in Asia (Rahman et al. 2019; Zaw et al. 2020; Rakthai et al. 2020) are very few. Changes in tree growth sensitivity to climate change have also been reported for some other species such as *Abies spectabilis* in the Rolwaling valley in Gaurishankar Conservation Area (Schwab et al. 2018), blue pine in Manang (Shrestha et al. 2015), *Chukrsia tabularis* in Bangladesh (Rahman et al. 2019) and *Pinus laterelli* in Thailand (Rakthai et al. 2020). In Bangladesh, climatic sensitivity of the tropical *Chukrsia* species is changing over time and getting stronger during recent years (Rahman et al. 2019). However, tropical teak trees' response to moisture indices in Myanmar was temporally stable (Zaw et al. 2020). Since the importance of the moisture for the *Shorea* growth is increasing in recent years, it can be hypothesized that a prolonged drought period in the future might adversely affect the growth of the species by neutralizing the positive effects of increasing temperature in the Terai region of Nepal.

Conclusion

The TRW chronology, BAI chronology and size class isolation-based growth assessment indicate that the growth of the species in the lowland Terai region is increasing over time. The growth of *Shorea* is mainly favoured by the area's warm and moist climate. The temperature sensitivity of the species is almost stable, while its moisture effect is not significant. Future studies incorporating phytosociological, along with dendrochronological and wood anatomical aspects, will be useful to expand our knowledge of the climatic sensitivity and growth dynamics of this important tree species in response to climate change.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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