Tree-ring climate response of two Larix species from the central Nepal Himalaya

Article *in* Tropical Ecology · June 2020

DOI: 10.1007/s42965-020-00082-w

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Tropical Ecology
https://doi.org/10.1007/s42965-020-00082-w

International Society for Tropical Ecology

RESEARCH ARTICLE

Tree-ring climate response of two *Larix* species from the central Nepal Himalaya

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Received: 12 April 2019 / Revised: 12 November 2019 / Accepted: 9 June 2020

Abstract
Changes in the global temperature and precipitation regime have been significantly driving species responses, notably in sensitive areas such as the Himalayas. By conducting a study at two high altitude (3200–4100 m) valleys (Langtang and Tsum) situated in the central part of the Nepal Himalayas, we presented tree-ring width site chronologies for two *Larix* species (*Larix griffithii* and *L. himalaica*) for the first time. The longest chronology spans from 1771 to 2015 AD and showed a recent decline in the growth of *Larix* species in both sites, controlled mainly by drought. Tree growth showed a negative response to temperature and a positive response to precipitation, indicating that moisture stress is limiting the growth of the species. Based on the *Larix* ring width chronology statistics and climate response results, these species have good potential for past climate reconstruction such as temperature, rainfall or drought indices. Also, the study revealed that the Himalayan endemic *Larix* species investigated are promising for tree-ring based multi-aspect environmental change studies in the future.

Keywords Climate response · Himalayas · *Larix* · Nepal · Tree-ring

Introduction

The Himalayas are geographically highly variable and have a poor climate data network leading to a dearth of climate data for this region (Shrestha et al. 1999; IPCC 2013). This low quality of data is particularly limiting as changes in climatic conditions impact the Himalayas, yet the data cannot support the decision-making process. The Nepal Himalayas, including both the Eastern and Western Himalayas, is influenced by the South Asian monsoon in summer and the mid-latitude westerlies in winter (Benn and Owen 1998) with east–west moisture and temperature gradient in summer and vice versa in winter. Approximately 80% of the precipitation received during the summer monsoon is the chief source of moisture in the Himalayas (Sharma 2014). The region has experienced less precipitation and prolonged drought in recent decades (Sano et al. 2012). Along valleys, there is great variability in precipitation over short horizontal distances and strong seasonal differences in lapse rates exist (Immerzeel et al. 2014).

The Himalayas, characterized by high spatial and temporal variations in precipitation and temperature, are sensitive areas for responses to climatic change and impacts on natural and human communities. Temperature and precipitation, being the two most important factors affecting tree growth, are often recorded in tree-ring width chronologies simultaneously (Liu et al. 2015). Tree-ring studies have shown various responses regarding space, time, and species. For example, Gaire et al. (2017) showed that growing season temperature coupled with enough moisture favors *Abies*

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Published online: 16 June 2020

spectabilis growth. However, for the *Betula utilis* growth spring moisture stress limit the growth. These species have spatiotemporally variable regeneration in the Eastern Himalayas (Gaire et al. 2017). Nepal has experienced high warming trends as in most of the Himalayan region (Shrestha et al. 1999; Shrestha et al. 2012). This leads to the forests of the Nepal Himalayas being subjected to temperature-induced drought stress.

Most of the dendroclimatic studies in the Nepal Himalayas focused on treeline dynamics (e.g., Chhetri and Cairns 2015, 2018; Gaire et al. 2014, 2017; Liang et al. 2014; Tiwari et al. 2017). These studies have shown a mixed response of tree species regarding drought or moisture limitations for different species e.g., *B. utilis* (Liang et al. 2014), *A. spectabilis* (Chhetri and Cairns 2015; Gaire et al. 2014, 2017; Suwal et al. 2016), and *Pinus wallichiana* (Shrestha et al. 2015). The results are, therefore, difficult to generalize to cover vast areas below treelines.

There has been a recent growth in the number and quality of dendroecological studies investigating the species previously mentioned, e.g., *A. spectabilis* (Chhetri and Cairns 2016; Gaire et al. 2017), *B. utilis* (Gaire et al. 2017), and *P. wallichiana* (Shrestha et al. 2015; Gaire et al. 2019) from the Himalayas but few have investigated *Larix* species in Nepal (Bhattacharyya et al. 1992; Cook et al. 2003; Bhatta et al. 2018). We selected *Larix* species as they are endemic to the Himalayas and they have not been studied from multiple sites before in Nepal and so represent a previously untapped resource for understanding the effects of changing climate in the area. We studied the tree-rings of *L. griffithii* and *L. himalaica* from the upper temperate and subalpine forests in two high altitude valleys of the Nepal Himalayas to investigate the response of these species to climatic variables. The study aimed to see if *Larix* species from the Nepal Himalayas can be used for dendroclimatic studies and if they have the potential for climate reconstruction studies.

Materials and methods

Study area

Two study sites—Langtang valley of Langtang National Park (LNP), central Nepal; and Tsum valley of Manaslu Conservation Area (MCA), central Nepal—were selected for the present study. They lie in the high Himalayan valleys, a protected area system of Nepal (Fig. 1; Table 1). LNP was established in 1976 and is one of the nearest parks to Kathmandu. The park is 1710 km^2 in area and extends from 32.2 km north of Kathmandu to the Nepal-China border in the northeast, the Bhote Koshi River in the east, and Trishuli River in the west. The major vegetation in the LNP are *Pinus*

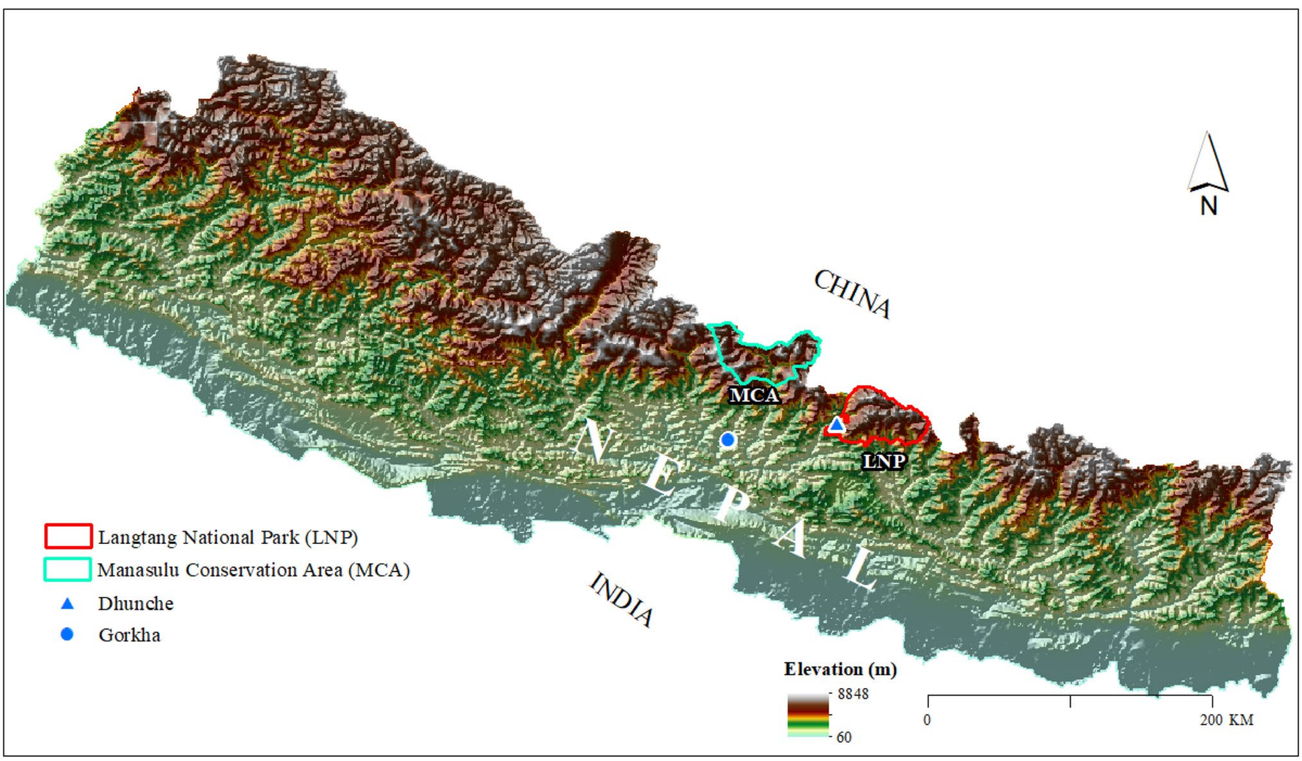

Fig. 1 Location of Langtang National Park (LNP), central Nepal; and Manaslu Conservation Area (MCA), central Nepal. (Dhunche and Gorkha are meteorological stations)

Table 1 Description of sampling sites and meteorological stations

Description of sampling sites					
Site	Latitude (°N)	Longitude (°E)	Elevation range (m)	Aspect	Study species
LNP	28.16–28.19	85.44–85.63	2473–3862	North	*Larix himalaica*
MCA	28.40–28.58	85.02–85.12	2654–3688	North	*Larix griffithii*
Description about meteorological stations					
Name	Latitude (N)	Longitude (E)	Elevation (m)	Time-span	Aerial distance to sampling site (km)
Dhunche	28.11	85.29	2011	1980–2016	30
Gorkha	27.99	84.62	1035	1980–2016	75

roxburgii, *Quercus lamellose*, *Q. semecarpifolia*, *Abies spectabilis*, *Betula utilis*, *Rhododendron spp*., moist and dry alpine scrubs. MCA was established in 1998 and cover 1663 km^2 in area. *Abies spectabilis*, *B. utilis*, *Rhododendron campanulatum*, *R. anthopogon*, and *Sorbus microphylla* are major vegetation in the MCA. Human communities in these areas are longstanding, represented by a collection of old mountain villages dominated by livestock based agrarian economic systems. Recent developments in tourism, however, have shifted the priority from livestock to tourism in these areas. Due to inaccessibility, the abundance of tourists is relatively low, indeed when compared to other well-trodden destinations such as the Annapurna and Everest regions. Mostly the trekking and expedition route transverse the steep slopes with trails of villages and livestock grazing routes.

Valley floors can be densely forested but are mostly cleared by local communities leaving larger trees confined to distant and steep parts of the region. Subalpine deciduous conifer forests of *L. griffithii* (Cheng et Law) Farjon 1990, also known as *L. griffithiana* (Lindl. et Gord.), forms small patches in MCA. Scattered trees of *L. himalaica* (W. C. Cheng and L. K. Fu) Farjon and Silba are found in the Langtang valley of LNP.

The climate in the area is dominated by the Asian monsoon, with the highest portion of precipitation in June–September (JJAS) (Fig. 2a). As the valleys are beyond the snow-peak mountains, local precipitation levels are low compared to the low-lying areas which also have stations to measure temperature and precipitation. The moisture retained in the soil varies with geology, slope, and aspect. The moist north facing slopes, due to delayed snowmelt and low solar radiation, experience fewer human impacts compared to the relatively dry east and south facing slopes. Generally, Dhunche ($r = 0.10$, $p < 0.05$) and Gorkha ($r = 0.23$, $p < 0.05$) stations are experiencing a warming trend in annual temperature but fluctuations ($r = 0.09$, $p < 0.05$) in rainfall (Fig. 2b).

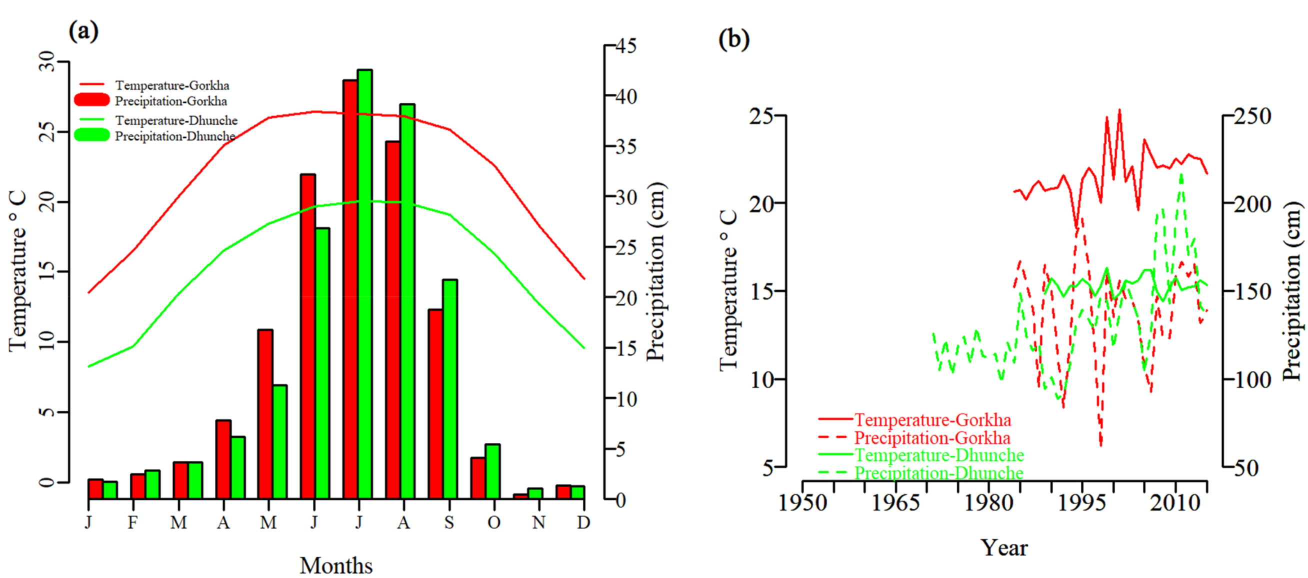

Fig. 2 Monthly average temperature and precipitation from meteorological stations of the study area (**a**) and their annual trend (**b**)

Table 2 Dendrochronological statistics for *Laryx griffithii* and *L. himalaica* from the Nepal Himalayas

Variables	LNP	MCA
No. of trees (cores)	17 (28)	31 (62)
Chronology length	95 (1921–2015)	245 (1771–2015)
Mean ring width (mm)	2.41	1.82
Standard deviation (SD)	0.99	1.25
Mean sensitivity (MS)	0.27	0.24
Series inter-correlation (Rbar)	0.27	0.35
Autocorrelation (AR1)	0.43	0.39
Signal-to-noise ratio (SNR)	6.7	8.7
Expressed Population Signals	0.87	0.89
(EPS > 0.85)	1974	1890

LNP Langtang National Park, *MCA* Manaslu Conservation Area

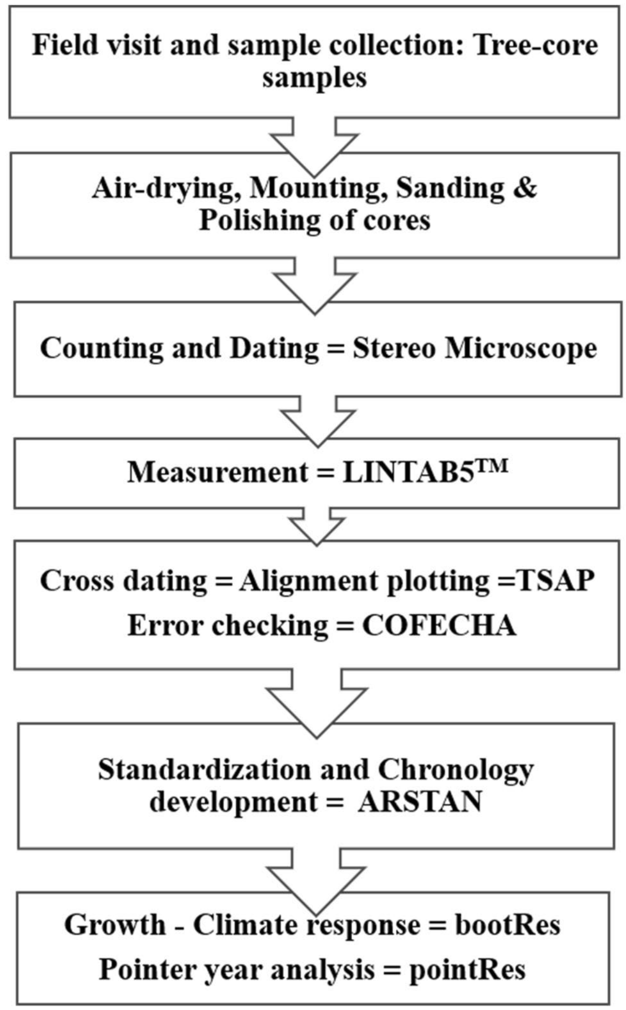

Fig. 3 Flowchart of sample collection and analysis

Sample collection

Anthropogenically least disturbed and mature forest stand was selected for the sampling. Tree-ring core samples were collected using an increment borer (Haglöf, Sweden) following commonly used techniques (e.g., Fritts 1976; Speer 2010). The cores of *L. griffithii* and *L. himalaica* were collected from breast height (1.3 m). One to two cores per tree were collected from a total of 48 trees (Table 2). Collected cores were placed in labeled plastic straw pipes and transferred to the Dendro-lab of Nepal Academy of Science and Technology (NAST) for laboratory analysis. Figure 3 described the steps of field sampling, software used, and data analysis process.

Processing of the samples

Cores were air dried for 20 days, mounted in a core wooden frame with the transverse surface facing up. The surface of each dry core was cut with a sharp razor blade, sanded, and polished using successively finer grades of sandpaper (100–1000 grits size) to enhance the visibility of annual rings. Each ring was counted under a stereo zoom microscope (Leica) and was assigned a calendar year with a known date of outer ring formation. The ring width of each core was measured to the nearest 0.01 mm with the LINTAB^{TM5} (Linear positioning table) measuring system connected to a PC with the TSAP-Win (Time-series analysis package for windows) software package (Rinn 1996). All tree cores were cross-dated by matching patterns of wide and narrow rings to account for the possibility of ring-growth anomalies such as missing or false rings or measurement errors (Fritts 1976; Speer 2010). Each tree-ring width series was visually and statistically cross-dated (Gleichläufigkeit, t-values, and the cross-date index CDI) using the software package TSAP-Win as per Rinn (2003). The accuracy of cross-dating and measurements were further checked using the COFECHA program (Holmes 1983; Grissino-Mayer 2001). Those tree cores which were poorly cross-dated and correlated, have low year-to-year variability in growth or unusual growth trends, breaks, or were found to be very young (less than 40 years), were removed before the development of chronology.

Pointer-year (narrow or wide) in the trees was studied to identify their climatic sensitivity, especially during extreme climate events. Most established pointer-year analysis methods, i.e. normalization in a moving window (Cropper 1979; Neuwirth et al. 2007), and relative growth change (Schweingruber et al. 1990) were used. R package pointRes was be used for that analysis which has both options (van der Maaten-Theunissen et al. 2015).

The corrected ring-width data were standardized using the computer program ARSTAN (Autoregressive standardization) (LDEO 2015), using conventional detrending methods with a negative exponential, linear, or cubic spline curve for each series. In those cores which did not fit the negative exponential or linear trends, interactive detrending using a spline of 32 years with a 50% frequency response cutoff was used (Cook and Peter 1981). The detrended ring-width-index series were then pre-whitened by fitting autoregressive modeling to remove any autocorrelation effects (Cook 1987). After detrending, each time series was averaged using the bi-weight robust mean function (Cook 1985). Three chronologies: standard, residual, and arstan were prepared using the ARSTAN by incorporating the corrected sample.

Various tree-ring chronology statistics such as mean sensitivity (MS, Mean sensitivity is the measure of relative difference in width between the consecutive rings), standard deviation (SD), autocorrelation (measure of the degree to which a given year's growth is correlated with the preceding year's growth, with high values indicating that a significant portion of the observed ring width is a function of the preceding year's growth rather than exogenous factors), within tree correlation, between tree correlation, mean series correlation, signal-to-noise ratio (SNR, is an expression of the strength of the observed common signal among trees in the ensemble), expressed population signal (EPS, is the measure of adequacy of the sample depth to represent the developed site chronology) (Wigley et al. 1984), series inter-correlation (Rbar) (Briffa 1995), and variance explained were calculated to assess the quality of the site chronologies.

Climatic response of radial growth

The available temperature and precipitation data (1980–2016) from the nearest stations of the respective districts, namely, Gorkha and Dhunche (Fig. 1; Table 1) were used for climate response analysis. Missing values in the station's data were computed by the average value of the same month's data. Before the commencement of growth-climate response, the seasonality of tree growth was defined. Although past studies have not reported the exact growth period for trees in the Nepalese Himalayas (Cook et al. 2003), field observation, and tree-ring data have shown that the radial growth of *Larix* ceases in October. The climate in the preceding growing season often influences tree growth in the following year (Fritts 1976), therefore, the influence of temperature and precipitation since June of the previous growth year until October of the current growth year was analyzed. The correlation coefficient (Pearson) was used to quantify the relationship between tree-ring chronologies and climate variables, i.e., monthly average temperature and total monthly precipitation. The relationships between the tree-ring width, standard, or residual chronology of each species, and monthly average temperatures and total precipitation were analyzed by correlation functions and response functions using 'bootRes' package (Zang and Biondi 2013) based on R software (R Core Team 2016).

Results

The analysis of tree-rings of *L. griffithii* from MCA showed that trees from this site had characteristics suitable for dendroclimatic studies, including clear demarcation of early wood and late wood cells, compared to those of *L. himalaica* from LNP. Based on the ring-width analysis, two ring-width site chronologies of *L. griffithii* (MCA) and *L. himalaica* (LNP) were prepared. The site chronologies of LNP and MCA extended from 1921–2015, and 1771–2015 AD, respectively (Fig. 3). These chronologies have good dendroclimatic potential with moderate mean sensitivity, high standard deviation, and low to moderate autocorrelation (Table 2).

In the site chronology from two sites, the mean sensitivity was found to be the highest for LNP and the lowest for MCA with the maximum standard deviation found in MCA. The average radial growth for *L. griffithii* from MCA was 1.82 mm/year, while that of *L. himalaica* from LNP was 2.15 mm/year. Signal-to-noise ratio was the highest for LNP and the lowest for MCA, with an expressed population signals of 0.87 and 0.89, respectively (Table 2). The tree-ring site chronologies revealed fluctuations in the growth over time with slightly decreasing growth in recent years (Fig. 4).

Pearson correlation between the radial growth (tree-ring chronology) of *L. griffithii* and *L. himalaica* (Fig. 5) with monthly climate data (monthly average temperature and total precipitation) showed variations in climatic response between the sites. Insufficient precipitation and or temperature induced moisture stress is the primary limiting factor controlling growth. In MCA, there is a significant positive relationship between the radial growth and the precipitation during September of the previous year ($p < 0.05$), but there is a negative relationship with the temperature of September of the current year ($p < 0.05$) (Fig. 5). There is a significant negative relationship ($p < 0.05$) between the radial growth of *L. griffithii* in LNP and monthly mean temperature of June and September of the current year (Fig. 5). There is a negative correlation between the radial growth and monthly total precipitation in most of the months in LNP (Fig. 5), although the statistical power for this is weak. The relationship between the radial growth and precipitation during January of the current growth year is negative and statistically significant ($p < 0.05$) (Fig. 5).

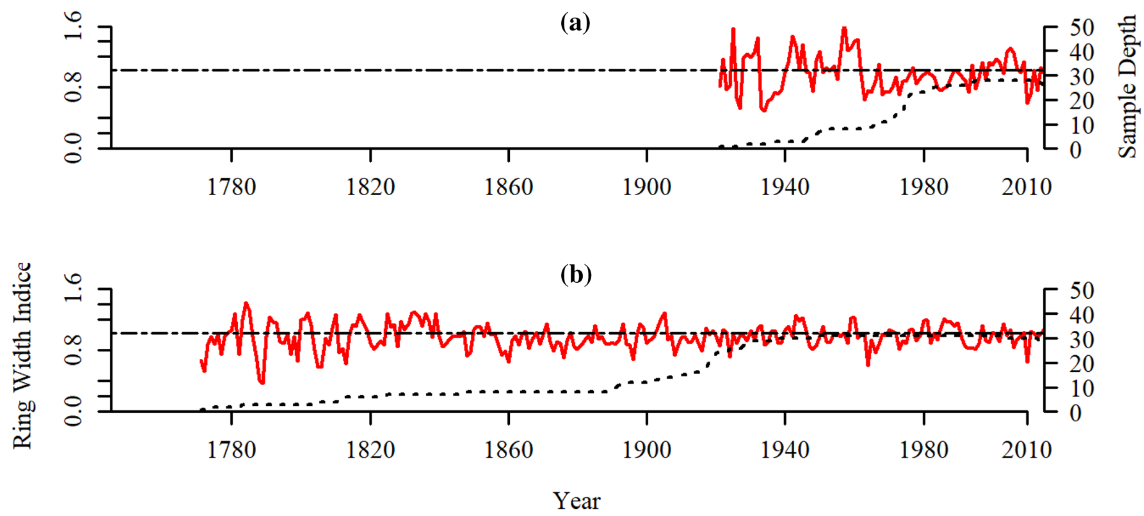

Fig. 4 Tree-ring-width site chronologies (solid red line) of **a** *Laryx himalaica* from Langtang National Park (LNP), **b** *L. griffithii* from Manaslu Conservation Area (MCA), with the sample depths (dotted line)

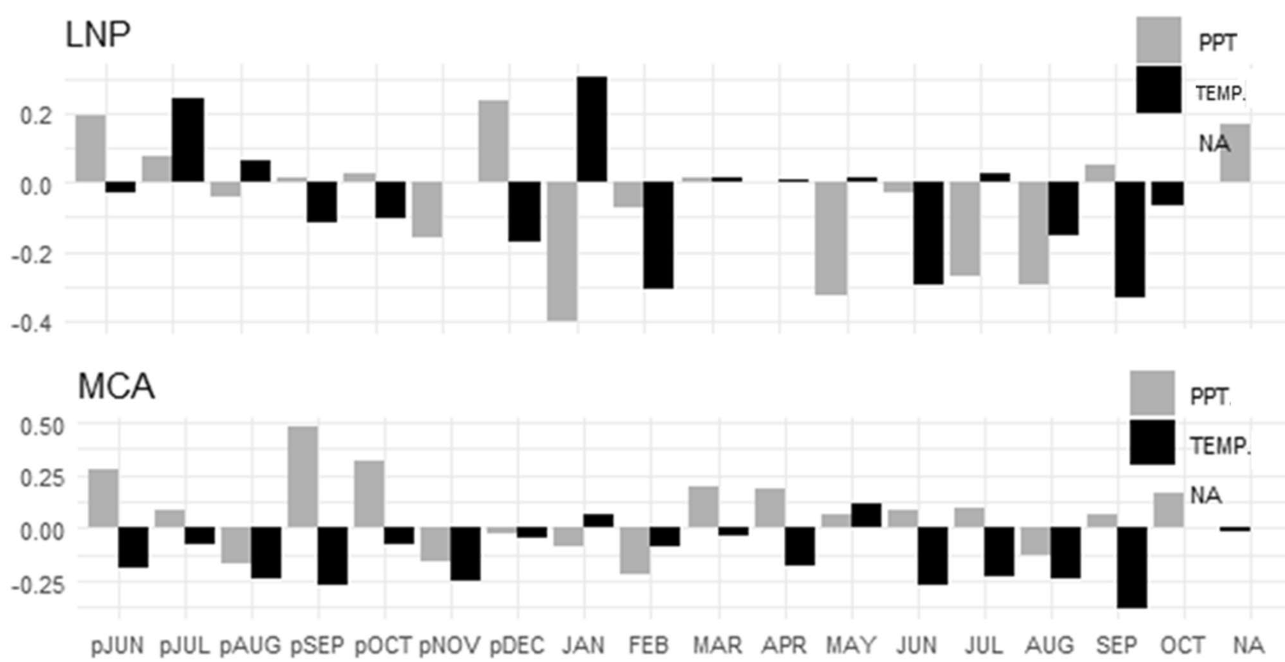

Fig. 5 Correlation between the radial growth (tree-ring chronology) of *Laryx griffithii* in Manaslu Conservation Area (MCA), and *L. himalaica* in Langtang National Park (LNP), with monthly climate data of the Nepal Himalayas. pJUN-pDEC denotes the previous year June to December and JAN-OCT indicaters current years month starting from January to October. NA is annual data

The pointer year analysis showed that drought events have been increasing, especially after 1900, regarding both frequency and intensity as seen from the change in mean growth deviation (Fig. 6). There are common (with common pointer year) as well as site-specific signals (with site-specific pointer year) depicted by narrow and wide pointer years. For LNP region, 1934–35, 1963, and 2010 were narrow pointer year whereas 1929 and 1957 as wide pointer year. In MCA, 1908, 1924, 1964 and 2010 were narrow pointer years.

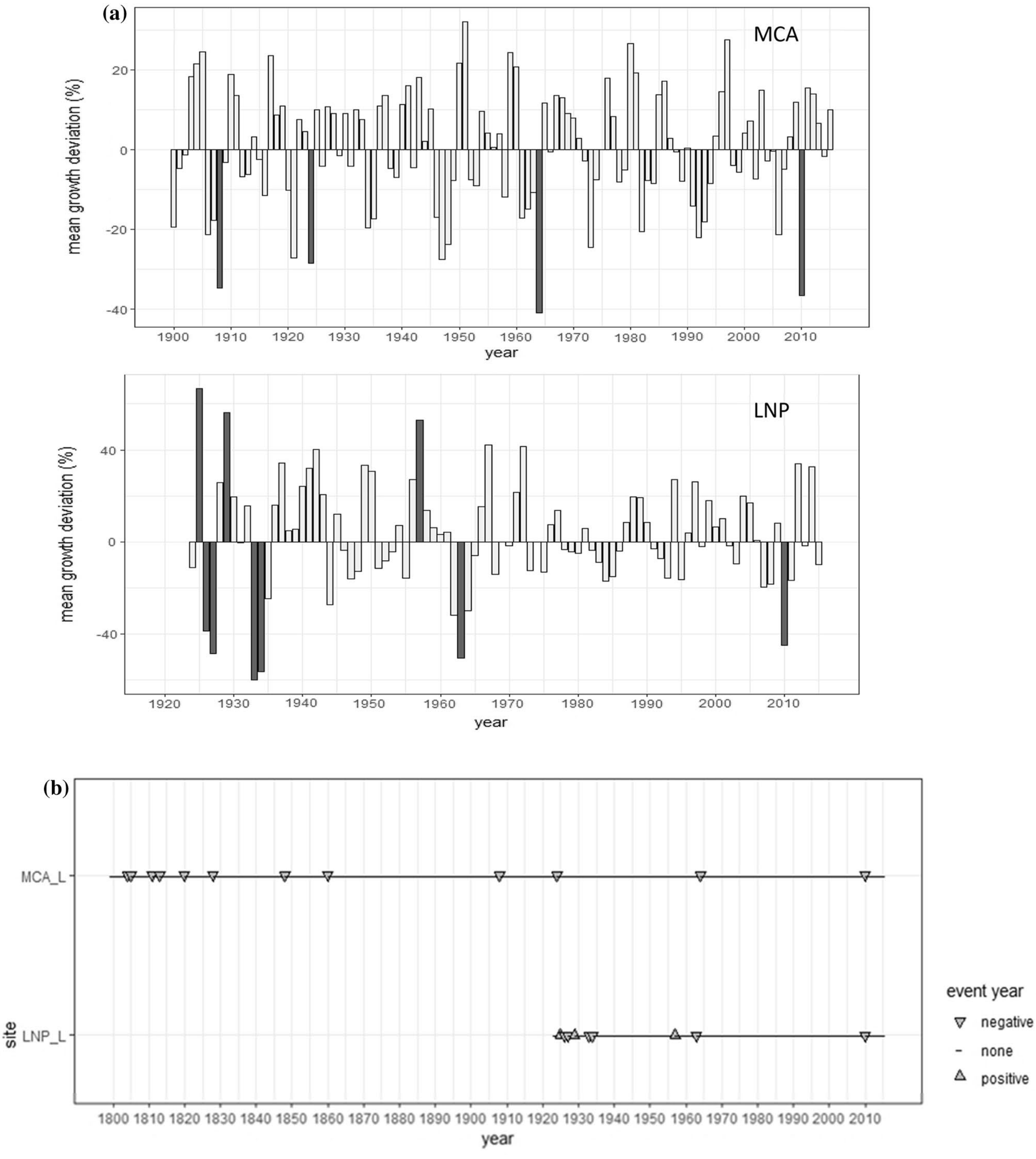

Fig. 6 Narrow and wide pointer year in *Larix* chronologies for 1900–2015 based on the relative growth change method **a**, and list of narrow and wide pointer year **b**. *MCA* Manaslu Conservation Area, *LNP* Langtang National Park

Discussion

The chronology characteristics of two species of *Larix* obtained from sites (Langtang National Park–LNP and Manaslu Conservation Area–MCA) in Nepal showed the dendroclimatic potential of these species (Fritts 1976; Cook and Kairiukstis 1990; Speer 2010) with moderate mean sensitivity, standard deviation, and inter-series correlations. This potential is shown in the statistical results, as chronologies passed the threshold EPS value of 85% (Wigley et al.

1984). These site chronologies, however, did not show a persistent pattern of growth, and slight variations in the growth behavior among different sites was observed for decadal or longer scale comparisons. Increased growth is seen after the 1950s–60s, whereas more recently (around the 2000s) a decrease in growth is seen in LNP. Chronology statistics found in the present study are comparable with those found in *Larix* species by other researchers (e.g., Bhattacharyya et al. 1992; Chaudhary and Bhattacharyya 2000; Shah et al. 2014) and other conifer species (Table 3) from the Himalayas (e.g., Cook et al. 2003; Sano et al. 2005; Gaire et al. 2011, 2014; Kharal et al. 2014, 2017; Thapa et al. 2015; Shrestha et al. 2017).

No previous studies from the Nepal Himalayas have reported on the growth-climate response of *L. griffithii* and *L. himalaica*, but a few studies have been carried out from the eastern Himalayas of India (Chaudhary and Bhattacharyya 2000; Shah et al. 2014). In a study regarding the high moisture site of Arunachal Pradesh, eastern Indian Himalayas, Chaudhary and Bhattacharyya (2000) found higher growth related to increased temperature during November of the previous and May and July of the current growth year for *L. griffithii*. For precipitation, they found that August and September of the previous year and July of the current year have an inverse relationship, on the other hand, January and February of the current year exhibit a direct relationship with growth.

For *L. griffithii* in MCA, a year with cool and moist summer is beneficial as revealed by the growth response. For the same species in moist regions in the Eastern Himalayas of India, however, warmer conditions during May and July are favorable for growth (Chaudhary and Bhattacharyya 2000). Additionally, moisture supply in the early growing season appeared to affect tree growth in the cold arid region of Kinnaur in the Western Himalayas (Yadava et al. 2016). These varied climatic responses reflect great heterogeneity in topography and climatic regime making generalizations regarding growth-climate relationships difficult. Shah and Bhattacharyya (2012) studied the spatiotemporal variation in growth response of three pine species from northeast India. Their results showed nonuniform inter-species tree growth variations and no common influence factor on the radial tree growth in the region, which may be related to anthropogenic impact or non-climatic factors.

Before the commencement of monsoon rains, higher winter precipitation may become favorable for tree growth by maintaining enough soil moisture for the rapid growth of trees during spring and early summer (Chaudhary and Bhattacharyya 2000). The efficacy of gridded data, though widespread in climatic studies, has been doubted when monitoring climatic patterns of point locations in the mountainous Himalayan region (Yadava et al. 2016). They are, however, the only available long-term datasets for high altitude areas in the Nepal Himalayas and have been used in previous climatic studies concerning tree-rings (e.g., Liang et al. 2014; Chhetri and Cairns 2015; Gaire et al. 2017, 2019).

A negative correlation with temperature is not a typical response in most months, however, in the dry inner valleys of the Nepal Himalayas, cool and moist years favor the growth of conifers (Cook et al. 2003; Gaire et al. 2014; Kharal et al. 2017). A positive relationship with precipitation and negative relationship with temperature indicates towards the drought stress for the growth. The response observed between growth and temperature during the summer months in MCA and KCA, is also observed in the relationship between growth and climate of the many conifers from the dry sites of the Nepal

Table 3 Summary of the selected growth-climate response from the central Himalayas

References	Species	Response with temperature	Response with precipitation	Study area
Present study	*Larix himalaica* *Larix griffithiana*	− Summer + Winter	+ Pre-monsoon	LNP MCA
Chhetri and Cairns (2016)	*Abies spectabilis*	+ Winter		MBNP
Dawadi et al. (2013)	*Betula utilis*	− May	+ Pre-monsoon − August	LNP
Gaire et al. (2011)	*Abies spectabilis*	− Pre-monsoon	+ Pre-monsoon	LNP
Gaire et al. (2014)	*Abies spectabilis*	− Pre-monsoon − Monsoon		MCA
Gaire et al. (2019)	*Pinus wallichiana*	− Spring − Summer	+ February–August	Dolpo
Liang et al. (2014)	*Betula utilis*		+ Pre-monsoon	LNP
Sano et al. (2005)	*Abies spectabilis*	− Pre-monsoon	+ Pre-monsoon	Humla
Thapa et al. (2015)	*Picea smithiana*	− Pre-monsoon		KNP

pre-monsoon: March, April, May; monsoon: June, July, August, September; winter—October, November, December; *LNP* Langtang National Park, *MCA* Manaslu Conservation Area, *MBNP* Makalu Barun National Park, *KNP* Khaptad National Park, + strong positive response, − strong negative response

Himalayas (Cook et al. 2003; Gaire et al. 2014; Kharal et al. 2014) and the western Indian Himalayas (Yadav 2009). The growth-climate in LNP was found to be slightly different and weaker when compared to the other sites. This weak relationship might be due to the presence of young trees that are more influenced by non-climatic factors.

Based on an analysis of the growth-climate responses of different tree species it seems that, in the Himalayas, the growth response of trees to climate change and variability is spatiotemporally different and not unidirectional (Chaudhary and Bhattacharyya 2000; Sano et al. 2005; Gaire et al. 2011, 2017, 2019; Kharal et al. 2014, 2017; Liang et al. 2014; Schickhoff et al. 2015) leading to inconsistencies in the terms of the climate-growth relationship (Shrestha et al. 2015). The tree-ring response to Palmer Drought Severity Index (PDSI), however, agrees regarding the decreasing trend of precipitation or moisture over the past two centuries; also the reduction of monsoon activity has been reported by Sano et al. (2012).

The response from the Indian Himalayas (Chaudhary and Bhattacharyya 2000) is also slightly different from the results of the present study. This variation is probably due to site conditions and climate, or differences in the influence of the monsoon system. Moreover, the use of data from different stations with varied patterns of climatic variables might be a source of weak relationships. It has been demonstrated that an increase in temperature in the pre-monsoon and monsoon season without adequate rainfall increases evapotranspiration leading to a soil-moisture deficit and consequently limiting tree growth (Fritts 1976; Sano et al. 2005; Gaire et al. 2019). The negative relationship observed in MCA and KCA in the present study, with the pre-monsoon and monsoon season temperatures, might hold the answer to establishing some thresholds of temperature or moisture stress.

Larix species from these two study sites have good potential for temperature reconstruction to observe warm and cool episodes along with a recent warming trend. This reconstruction can be similar to February–June (Cook et al. 2003), an *A. spectabilis* ring-based reconstruction of March–September (Sano et al. 2005), and a *Picea smithiana* tree-ring based reconstruction of March–May (Thapa et al. 2015), and from outside of Nepal, such as a *P. spinulosa* temperature reconstruction from the Bhutanese Himalayas (Krusic et al. 2015), and others from East Asia (Cook et al. 2013; Shi et al. 2015). From the reconstruction, some potential common signals can be captured, including a recent warming trend.

Conclusions

In the present study, we investigated the tree-ring climate response of *Larix* species from the Nepal Himalayas and developed two ring-width site chronologies for *Laryx himalaica* from Langtang Valley, Rasuwa and *L. griffithii* from Tsum Valley, Gorkha, Nepal. This is one of the few first studies of this sort for these tree species. The most extended site chronology for the Manaslu Conservation Area spanned 1771–2015 AD with good dendroclimatic potential showing high mean sensitivity, and low to moderate autocorrelation. A pointer year analysis showed an increase in both the frequency and the intensity of drought events. These chronologies have the potential for climate reconstruction. It is expected that the information obtained from this study, under lack of local hydro-meteorological information, can be used for the effective management of these forests.

Acknowledgements We would like to thank GoldenGate International College, Nepal Academy of Science and Technology (NAST), Department of National Parks and Wildlife Conservation (DNPWC), Government of Nepal; and Department of Hydrology and Meteorology (DHM), Government of Nepal for support. This paper is based on research financed under the Climate Change Research Grants Program implemented by the Nepal Academy of Science and Technology. The Program is part of the Mainstreaming Climate Change Risk Management in Development project. This project is a component of Nepal's Pilot Program for Climate Resilience and is executed by the Ministry of Population and Environment (Nepal), financed by the Climate Investment Funds, administered by the Asian Development Bank with technical assistance from ICEM, METCON and APTEC.

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