Botanica Orientalis – Journal of Plant Science (2020) **14**: 29–38 ISSN 1726-6858

Research article

Temperature sensitivity of alpine larch treeline in the southeast of Tibetan Plateau

Achyut Tiwari[1*], Huasheng Huang[2], Zhekun Zhou[3]

[1]Central Department of Botany, Tribhuvan University, Kirtipur, Kathmandu, Nepal

[2]Institute for Biodiversity and Ecosystem Dynamics (IBED), University of Amsterdam, Amsterdam, The Netherlands

[3]Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences Yunnan, PRC China

Abstract

Tree-rings from upper forest boundary including treelines provide reliable indications of climatic changes as tree growth at treelines is highly sensitive to climate (temperature and moisture). Tibetan Plateau (TP) includes the highest elevation treeline in the world, and they show both temperature as well as moisture as a critical climatic factor for tree radial growth. Tree cores were collected from alpine larch (*Larix potaninii*) treeline ecotone from south east fringe of TP in Hengduan Mountains of China, and analyzed growth-climate relationship by using tree-ring width chronology. Our results identified the early growing season (May) mean temperature sensitivity to radial growth in larch tree population. We have also found difference in growth sensitivity at treeline and timberline even with the low elevation difference; treeline to be more sensitive to temperature. It is emphasized that tree growth could be improved in treelines with significant warming at high mountains until there is moisture limitation. However, microhabitat conditions, disturbance factors, and biotic interaction among species are also important drivers of tree growth at upper treelines.

Key-words: Growing season, Hengduan Mountains, *Larix*, precipitation, radial growth, tree-ring.

Introduction

High elevation treelines are the transition zone between timberline and treeless alpine vegetation (Körner 2003). The association of the upper distributional limit of the tree life (treeline), which is formed on thermal balance (Körner 1998, 2003, 2012; Holtmeier and Broll 2007; Harsch *et al.* 2009) emphasizes that climate warming is expected to promote forest growth at their elevation range edge, generate densification of ecotone, and advance treelines upward (Grace *et al.* 2002; Dullinger *et al.* 2004; Smith *et al.* 2009). However, such expectations are true until moisture is not a limiting factor at treelines (Qi *et al.* 2015; Sigdel *et al.* 2018). In case of comparatively dry and semiarid treeline, tree growth is frequently limited by drought stress (Lloyd and Fastie 2002; Wilmking *et al.* 2004; Qi *et al.* 2015; Tiwari *et al.* 2017a). In such regions, current warming may exacerbate moisture stress and growth performance of trees.

The Himalaya, Tibet and Hengduan Mountains are rapidly warming regions of the northern hemisphere, substantially exceeding the global average trend of warming (IPCC 2013). The boundary between northwest Yunnan and Sichuan Plateau, located in the southeastern fringe of the Tibetan Plateau, belongs to a region highly sensitive to global climate change (Liu and Chen

*Corresponding author. Email: achyut.tiwari@cdb.tu.edu.com

2000). There are several studies from this region that have used tree-rings to reconstruct the climate, to analyze growth climate relationship, and to explore the spatiotemporal dynamics of treeline (Fan *et al.* 2009, 2010; Bi *et al.* 2015; Tiwari *et al.* 2017a, b; Panthi *et al.* 2018). Observed trends in Hengduan Mountains show increasing temperature of the warmest and coldest nights by 0.016 m/yr and 0.055 m/yr, respectively, decrease in the number of frost and ice days, and increase in the length of the growing season during the past half-century (Ning *et al.* 2012). However, the widespread increase of air temperature and variation in precipitation trends associated with strong topographic gradients and rain shadow effects are largely responsible for the complex climate system in Hengduan Mountains (Ning *et al.* 2012) raising significant questions about how tree growth of the region might respond to climate change.

Dendroclimatology is a traditional method of analyzing tree growth pattern in association with climatic conditions, which helps to understand the impact of changing climate on tree establishment, survival, growth and reproduction (Fritts 1976). Growth-climate response of trees at climatically sensitive ecosystem such as treeline is the key to understand limiting climatic factors influencing tree growth (Zhang *et al.* 2003; Liang *et al.* 2006; Shao *et al.* 2010). Both temperature as well as moisture sensitive treelines have been reported from Hengduan Mountain and Tibet (Shi *et al.* 1994; Qi *et al.* 2015). We hypothesize that tree growth is limited by temperature in high elevation treeline in Hengduan Mountain region. Hence we sought to explore growth climate response of larch (*Larix potaninii*) of upper treeline and timberline at Maan Mountain of Sichuan Province, China. Specifically, we aimed to (1) explore the climatic trend at high mountain treelines, and (2) identify limiting climatic factors for tree radial growth at treeline ecotone.

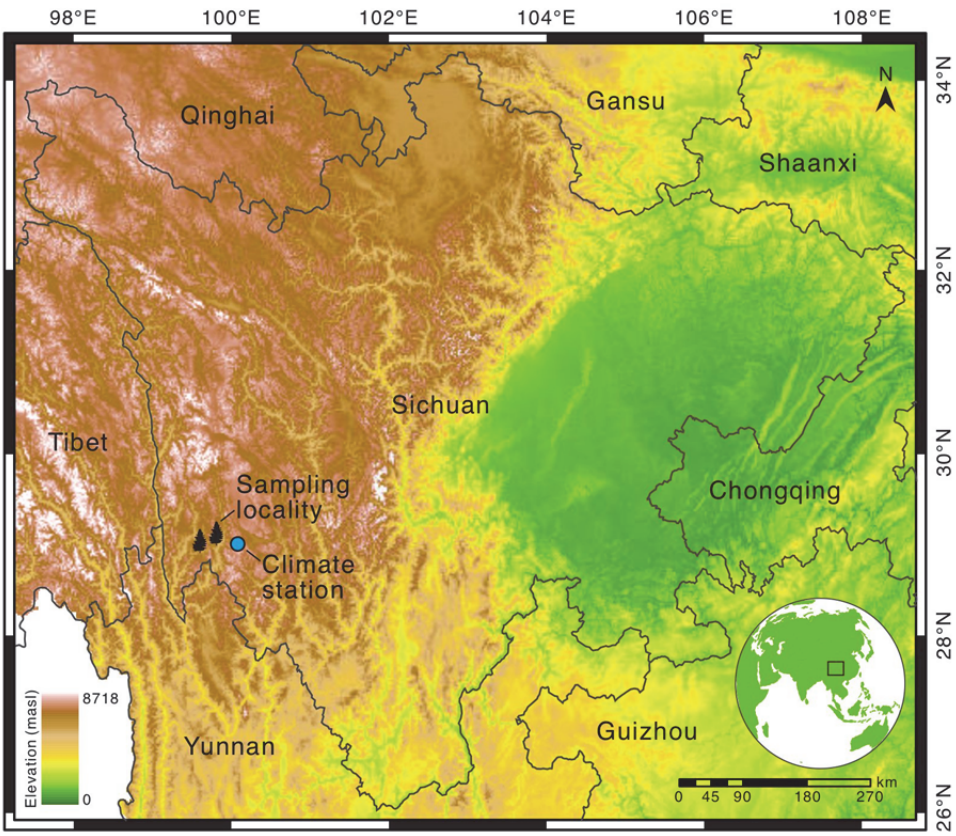

Figure 1. Geographic Information System map showing the sampling locality (with *Larix* tree symbols) and Daocheng climate station (blue dot) in the vicinity of Xiangcheng, Sichuan Province, southwest China, made with ArcGIS 10.5 (Environmental Systems Research Institute, Inc.). The range of the map is indicated by a square in the bottom-right spherical map.

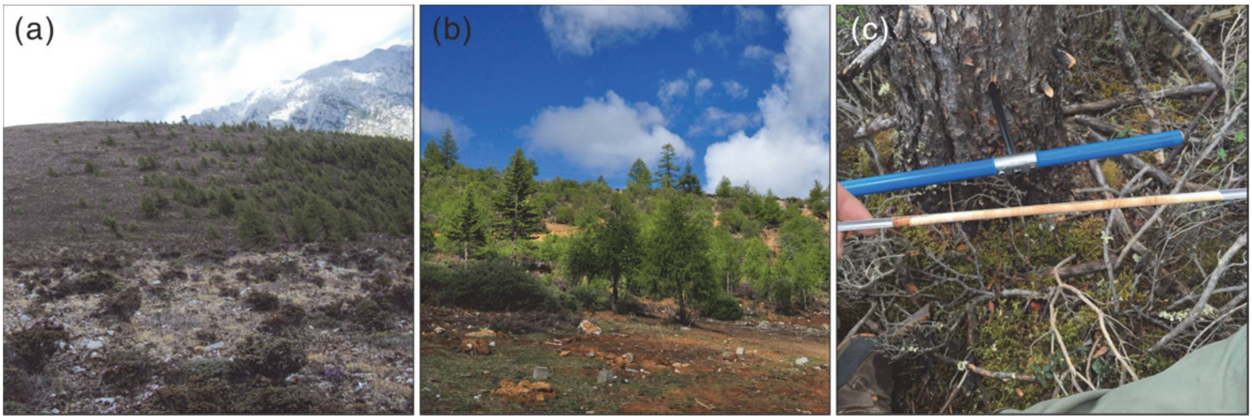

Figure 2. Photographs showing the landscape of the sampling locality (a); some *Larix potaninii* trees in the sampling locality (b); and increment borer with a collected tree-ring sample (c).

Materials and Methods

STUDY AREA

The treeline site at Xiangcheng (Maan Shan-Mountain) is located in the northern part of Hengduan Mountains (28.59° N, 99.44° E and 4400 m above sea level, m.a.s.l.) in Sichuan Province, China. The climate station is located at Daocheng airport (29.03° N, 100.18° E and 3727 m.a.s.l.) (Figure 1). Climatic data were collected and analyzed for the period of 1958-2012 from the Climatic Data Center (CDC) of the National Meteorological Information Center of China (NMIC). The climate in Daocheng is cold and temperate. The summers are much rainier than the winters in Daocheng. The average temperature in Daocheng is 4.8 °C and precipitation here is about 646 mm per year. About half of the Hengduan region within Sichuan was originally forested; the other half is part of what in China is called the Chuan-Zang-Gaoyuan (Sichuan-Xizang Plateau) (Sichuan Vegetation Research Group 1980; Wu 1988). Above 3,500 meters from sea level, are a rich mixture of alpine meadows, scree slopes, cliff-faces, marshes surrounding glacial lakes, and other vegetation types generally dominated by a highly diverse flora of herbaceous plants and shrubs (Zhang *et al.* 2008).

TREE-RING-WIDTH SERIES

An increment borer was used to take the core from trees; one, two or multiple cores were extracted from each tree within the plot. The tree cores were collected from the base of trees (<30 cm from the base of tree) at alpine treeline ecotone (ATE), and from DBH height (1.3 m at breast height) in case of closed timberline forest (CTF) trees. At ATE each tree was cored from sampling transect (20 m × 120 m), and at CTF the selected matured trees were only cored for tree ring sample collection. The sampling sites were chosen without the prior knowledge of stand characteristics other than that the respective species is dominant with enough growing area above treelines, and with little influence by livestock grazing and other human impacts such as fire (near natural forest). Forests with not known fire incidents and or heavy loggings and with no signs of landslide and erosion were chosen for establishing sample plot.

The samples were stored in plastic straw and the cores were air dried and mounted on sample holders with vertical alignment of tracheids. The wood surfaces were sanded using progressively finer sandpaper until the rings boundary is clearly visible (Fritts 1976). Ring widths were measured at a resolution of 0.01 mm with a LINTAB II measuring system (Rinntech, Germany). Tree cores were cross-dated by visual inspection (Stokes and Smiley 1996) and by statistical tests (sign-test and t-test) using the software package TSAP-Win (Rinn 2003). Ring-width measurements were detrended with a negative exponential or a linear regression function, with the help of ARSTAN software (Cook and Holmes 1986). All detrended series were averaged to chronologies by computing the biweight robust mean in order to reduce the influence of outliers (Cook and Kairiūkštis 1990). The quality of site chronology was indicated by signal-to-noise ratio and expressed population signal (EPS). A level of 0.85 for EPS was considered to indicate a satisfactory quality of a chronology (Wigley *et al.* 1984).

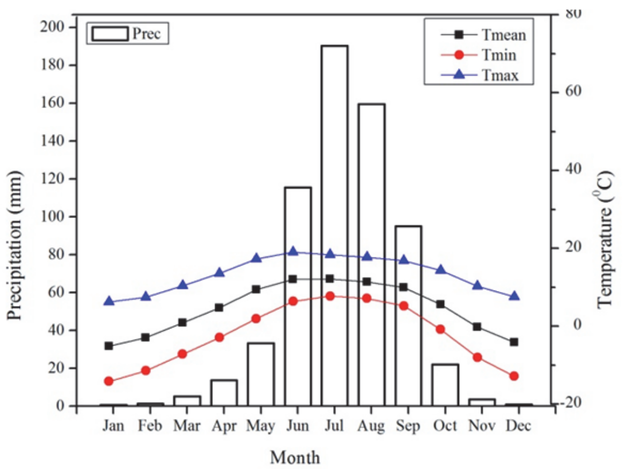

Figure 3. Climate summary of Daocheng (Hengduan Mountains), showing the mean trend (1958-2012 AD) for total precipitation, maximum temperature (T*max*), minimum temperature (T*min*) and mean temperature (T*mean*).

Growth-climate analysis was performed in order to establish the relationships between climate and the growth response of by using annual ring width index standard chronologies and climate data. Climate in the preceding growing season has a strong influence to tree growth in the following year (Fritts 1976). Monthly climate data were used, comprising a 17-month period from June of the year prior to ring formation, up until October of the year of ring formation. This period includes the growing season of previous year, intervening winter/spring and the growing season during the year of ring formation (Cook and Kairiūkštis 1990; Biondi and Waikul 2004). We applied simple linear regression model for climatic trend analysis. The temporal trend of annual average maximum temperature (T*max*), average minimum temperature (T*min*) and average mean temperature (T*mean*) were analyzed (Figures 3 and 4). The total mean rainfall trends were analyzed annually as well as seasonally, especially for early growth season (March-May). Pearson's correlation coefficients were calculated by comparing 68 climate variables, that is each of 17 months for both temperature and precipitation (Blasing *et al.* 1984). Significance was tested using 1000 bootstrap replicates and with 95% confidence intervals in R with the R package bootRes (Zang and Biondi 2013; R Core Team 2019).

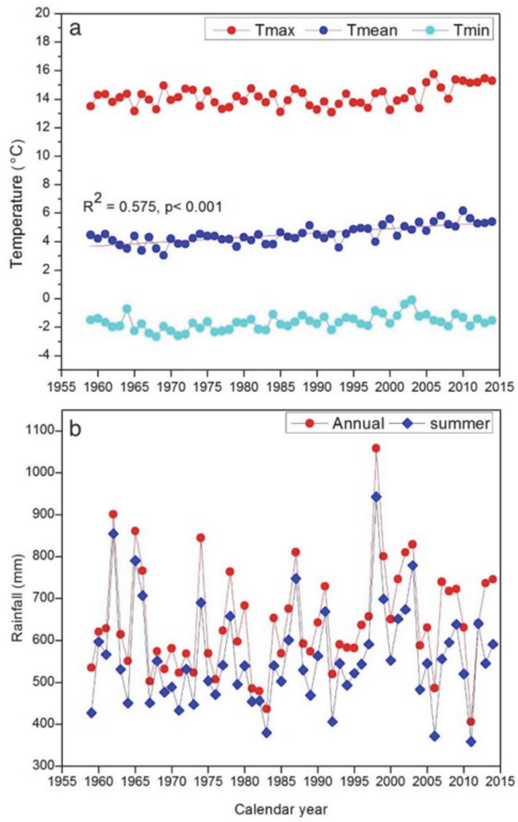

Figure 4. Climate trend of Daocheng (1958-2012 AD), showing the mean trend for total precipitation, summer precipitation, maximum temperature (T*max*), minimum temperature (T*min*) and mean temperature (T*mean*); the stronger trend is seen for mean temperature (T*mean*).

Results

CLIMATIC TREND

Hengduan Mountains of China showed various local climatic zones within the region due to its extensive land area, north-south orientation and strong topographic gradients. Hengduan Mountain region is mainly influenced by Indian monsoon and partly by East Asian monsoon in some regions. The meteorological data showed mean annual rainfall of 633 mm with mean summer rainfall (June-September) accounting for about 84% of annual rainfall at Daocheng (northern Hengduan region). The Annual mean maximum temperature (T*max*) is 14°C; however mean minimum temperature (T*min*) is -1.64°C. The warming trend is different in different sites of Hengduan Mountains; Daocheng showed annual warming rate of 0.014°C (T*max*) and 0.011°C (T*min*) during 1958-2014 AD as shown by the climate station data (Figure 4).

GROWTH-CLIMATE RELATIONSHIP

We produced two well-replicated standard tree-ring chronologies from *Larix potaninii*, from ATE and CTF (below treeline with more than 30 coverage of larch tress). We produced a composite ring-width standard chronologies by combining site chronology from two treeline transects, as the number of trees in each site were relatively low. The ring width chronology from treeline is of 111 years (1904-2014 AD) and that of timberline is of 131 years (1884-2014 AD) (Figure 5). The summary statistics of tree ring-width chronologies are presented in Table 1. The growth climate response was examined with the tree-ring width chronology of both ATE and CTF form the same study site.

The growth climate response showed positive contribution of temperature both at treeline and timberline, the strengths of correlation is different although the elevation did not show greater difference. Larch radial growth at Maan Mountain showed remarkable influence of mean temperature of May (T*mean*) of current year (r = 0.34, *P*< 0.005) both at timberline and treeline. T*max* of September of previous year also showed highest correlation to the radial growth both at timberline (r = 0.37, *P*< 0.005) and treeline (r = 0.30, *P*< 0.005). Further T*mean* of September of previous year also showed significant positive correlation with ring-width series of treeline (r = 0.30, *P*< 0.005) and timberline (r = 0.29, *P*< 0.005). Interestingly, the correlation between radial growth and annual T*mean* is significantly positive (r = 0.34, *P*< 0.005) for timberline and the correlation becomes weaker for timberline (r = 0.19, *P*< 0.005) (Figure 6).

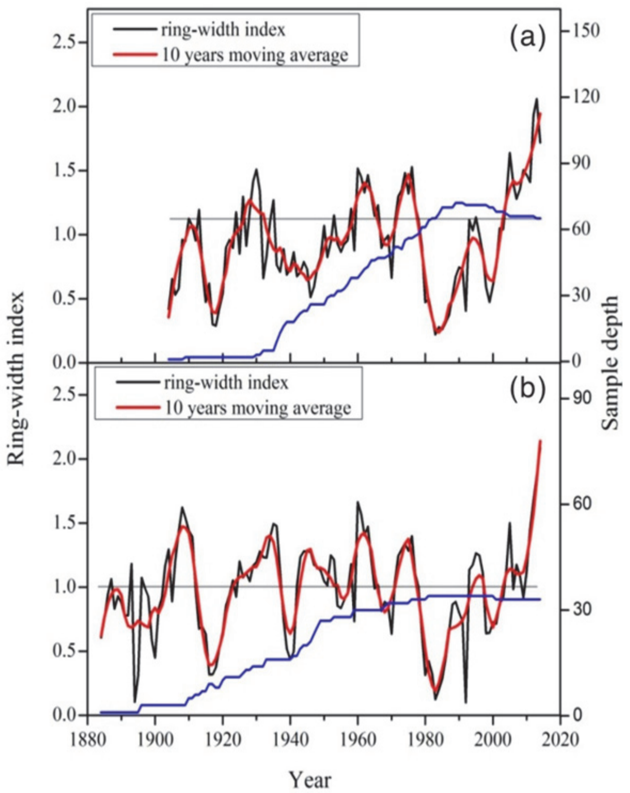

Figure 5. Tree-ring-width standard chronologies of *Larix potaninii*; Xinagcheng treeline composite chronology at upper treeline (a) and closed timberline forest (b). Horizontal axis showing calendar year, left vertical axis showing the ring width indices and right vertical axis showing the number of tree cores measured. Blue lines indicate the number of tree cores and red line is the 10-years moving average for ring width indices.

Table 1. Tree-ring chronology summary statistics of *Larix potaninii* in sampled locations at treeline and timberline. EPS = expressed population signal, AC = auto-correlation, ATE = at upper treeline, CTF = closed timberline forest.

Site	Elevation (m.a.s.l.)	Chronology (years)	Trees (cores)	Mean sensitivity	EPS	All series Rbar	1st order AC
ATE	4360-4444	111	54 (76)	0.235	0.875	0.514	0.539
CTF	4100-4300	131	20 (35)	0.230	0.969	0.463	0.789

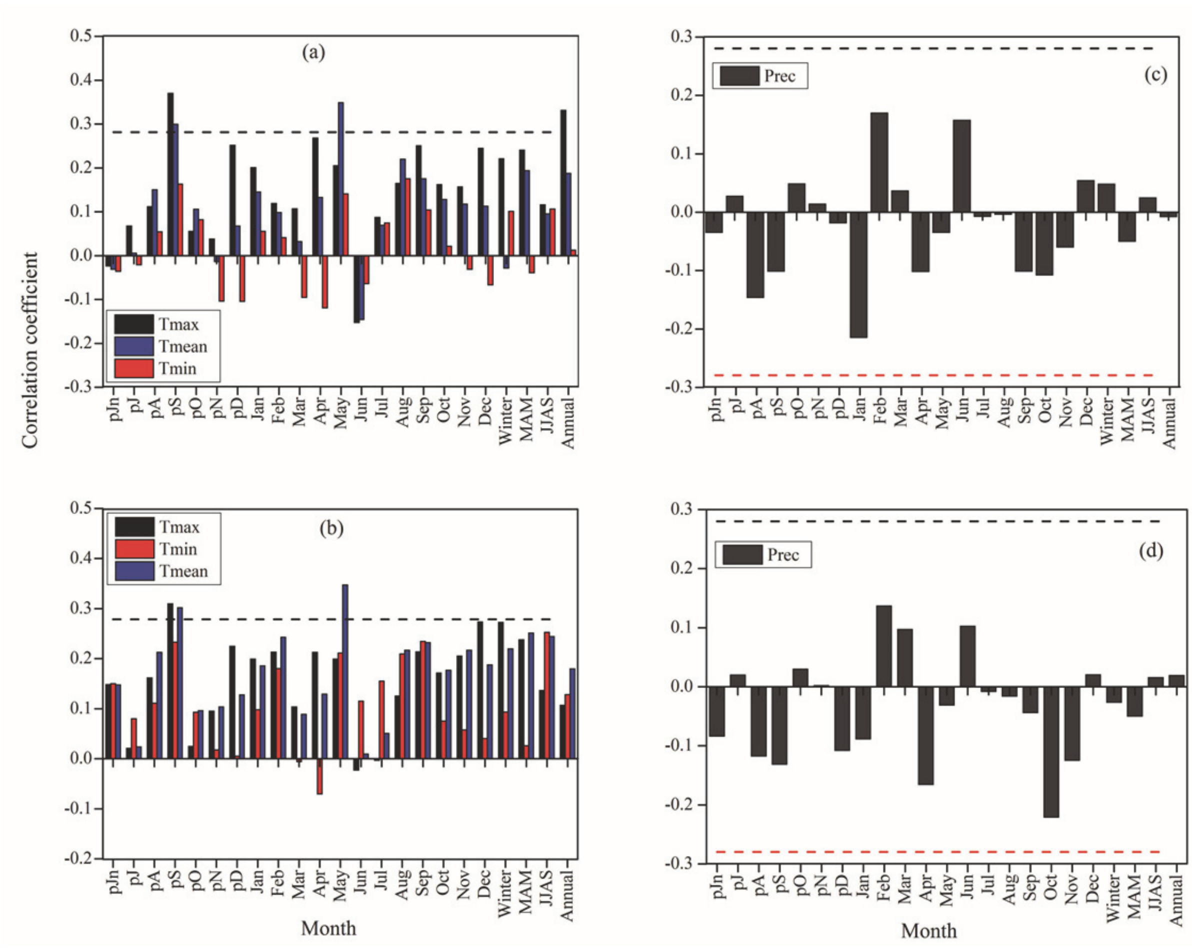

Figure 6. Climate growth analysis of *Larix potaninii* at Xiangcheng; correlation coefficients of tree-ring width indices, with total monthly maimum (T*max*), mean (T*mean*) and minimum temperature (T*min*) and total monthly rainfall; treeline (a, c), timberline (b, d) of June in the previous year to October of the current year, spring season and annual climate, dashed horizontal lines indicate significant correlation at 95% confidence limit for a two-tailed test.

Discussion

CLIMATIC TREND

The climatic trend in the study area demonstrated that there has been steady increase in the average mean temperature (T*mean*). However, the southern and central parts of Hengduan Mountains are experiencing rapid warming in comparison to the northern part, with decreasing number of frost and ice days, and with the increasing length of the growing season during the past half-century in the whole region (Ning *et al.* 2012). It is very likely that the number of cold days and nights will decrease and the number of warm days and nights will increase on the global scale, which will enhance the frequency of heat waves in large parts of Asia (IPCC 2013). This leads to increasing possibility of co-occurring of warm-day conditions and widespread drought in the northern hemisphere either by decreasing precipitation or increasing transpiration or by both (Dai 2011, 2013; McCabe and Wolock 2015). The warming trend (mainly winter warming) is clearly different from Himalayan highlands as they show a strong positive trend in annual maximum temperatures across South (Tarai) to North (Himalayan region) (DHM 2017). This clearly showed the elevation dependent warming in Himalaya as mentioned by Pepin *et al.* (2015).

Studies indicated that the annual and seasonal precipitation trends showed positive correlations with elevation in the Hengduan Mountain region, where precipitation was found to be increased by 7.8 mm decade^{-1} per 1000 m for altitudes ranging from 500–4000 m, showing an increasing trend with an increase in elevation during 1961–2011 (Xu *et al.* 2018). Although precipitation in China increased by 2% the frequency of precipitation events decreased by 10% from 1960–2000 (Liu *et al.* 2005) and there has been great uncertainties about future trend in rainfall as indicated by IPCC (2013).

GROWTH-CLIMATE RELATIONSHIP

Our results indicated that both maximum and mean temperature (T*max* and T*mean*) were found to have more pronounced influence at larch tree growth, although the significant correlation was only observed between radial growth and mean temperature (T*mean*) of May. Similar growth climate response was found for larch in many parts of China (Sun *et al.* 2010). These findings corroborate the positive contribution of May temperature to early cambial differentiation, cell enlargement and emergence of new needle in larch (Ou and Qian 2006). However, the winter temperature sensitivity of ring width of several treeline conifers was also reported from southeast Tibet and northwest Yunnan (Bräuning and Mantwill 2004; Bräuning and Griebinger 2006; Fan *et al.* 2009). In such cases, it was hypothesized that warmer conditions during winter may improve the storage of higher levels of carbohydrates to regulate root system activity, and improve plant productivity (He *et al.* 2013).

The high elevation treeline and timberline are more sensitive to temperature than rainfall in Hengduan region as the East Asian Monsoon causes rainfall in the summer season, with same periods of high temperature (Shi *et al.* 1994). The higher correlation with Spring season temperature (May) indicated that the early growing season temperature enhances annual radial growth of tracheids and photosynthetic accumulation due to higher rate of cambium differentiation, cell enlargement thereby contribute for development of new needles (Creber and Chaloner 1984; Chen *et al.* 2009). The moisture availability was not seen as the critical factor for larch growth in these regions due to abundant rainfall in monsoon, hence there is no corresponding relationship between growth and rainfall as indicated by correlation analysis (Figure 6). This supplies additional evidence that tree growth at the upper treeline of high mountains is controlled by temperature rather than moisture (Fritts 1976; Körner 2003; Holtmeier and Broll 2007; Harsch *et al.* 2009).

Larch tree growth at Xiangcheng sites is steadily increasing as indicated by increasing tree-ring width indices (although the series is detrended) in the recent decade (Figure 6), along with increasing average mean temperature of the region (Figure 4). Many studies indicated that tree growth at upper treeline in the dry regions of the Himalaya was also found to be moisture sensitive (Liang *et al.* 2014; Tiwari *et al.* 2017b; Sigdel *et al.* 2018). However the low elevation areas in central Himalaya are experiencing higher fluctuations in precipitation (moisture availability) and consistent warming temperature, hence enhanced warming-induced drought stress (moisture demand) is affecting tree growth in such areas (Liang *et al.* 2016; Tiwari *et al.* 2017b). It has been found that the temperature sensitivity increased even in low elevation difference as indicated by the correlation strength between radial growth and mean temperature at treeline and timberline (Figure 6), and we have similar results for *Abies spectabilis* from Trans-Himalayan zone of central Nepal (Tiwari *et al.* 2017a).

Conclusions

The northern part of Hengduan Mountains in the southeast fringe of Tibetan Plateau is experiencing the rapid warming temperature following the global trend. And the warming is mainly related to steady rise in average mean temperature. The growth-climate relationship of larch showed that the radial growth is significantly positively correlated with the average mean temperature of May (early growing season), and is not influenced by rainfall in the region. Further the temperature sensitivity is higher at upper treeline (ATE), which decreased at closed timberline forest (CTF) just below treeline even at low elevation difference. Further investigations with multiple species from different sites would improve our understanding on growth-climate relationship of high mountain forest, particularly their growth performance corresponding to climate warming in the future.

Acknowledgements

The authors would like to thank Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences for providing research opportunity. Dr. Jian Huang and Dr. Shufeng Li are acknowledged for their great help in sample collection.

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