

Treeline dynamics with climate change at Central Nepal Himalaya

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Abstract

Global climate change has multidimensional impacts with several biological fingerprints, and treeline shifting in tandem with climate change is a widely observed phenomenon in various parts of the world. In Nepal several impacts of climate change on physical environments have been observed. However, studies on the biological impacts are lacking. This dendrochronological study was carried out at the treeline ecotone (3750–4003 m a.s.l.) in the Kalchuman Lake (Kal Tal) area of the Manaslu Conservation Area in central Nepal Himalaya with the aim to study the dynamic impact of climate change at the treeline. The study provides an insight into regeneration and treeline dynamics over the past 200 yr. Two belt transect plots (size: 20 m wide, > 250 m long) were laid covering forest line, treeline as well as tree species limit. Ecological mapping of all individuals of the dominant tree taxa *Abies spectabilis* and *Betula utilis* was done and their tree-cores were collected. Stand character and age distribution revealed an occurrence of more matured *B. utilis* (max. age 198 yr old) compared to *A. spectabilis* (max. age 160 yr). *A. spectabilis* contained an overwhelmingly high population (89%) of younger plants (< 50 yr) indicating its high recruitment rate. Population age structure along an elevation gradient revealed an upward shifting of *A. spectabilis* at the rate of 2.61 m yr^{-1} since 1850 AD. The upper distribution limit of *B. utilis* was found stagnant in the past few decades. An increment in plant density as well as upward shifting in the studied treeline ecotones was observed. Thus, two species presented species-specific responses to climate change and much wider differences anticipated in their population status as climate continues to change throughout the century. The temporal growth pattern of *A. spectabilis* correlated negatively with the mean monthly temperature of May–August of the current year and with September of the previous year. The regeneration of *A. spectabilis*, on the other hand, was positively related with May–August precipitation and January–April temperature of the current year. The reconstructed average summer temperature (May–August) using tree ring data revealed alternate period of cool and warm period with warming in the 2nd half of the 20th century. Further pa-

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lynological and geochronological studies of sediments of the Kalchuman Lake would advance our understanding of past climatic trends and dynamics of the associated treeline and vegetation in the area.

1 Introduction

During the past 100 yr the global average surface temperature has increased by $0.74^\circ\text{C} \pm 0.2^\circ\text{C}$, and it is projected to rise by $1.4\text{--}5.8^\circ\text{C}$ by 2100 AD (IPCC, 2007), with the most pronounced and rapid changes at high altitudes and latitudes. However, recent studies have shown spatial and temporal heterogeneity in the past long term temperature trend (Marcott et al., 2013; PAGES 2k Consortium, 2013). Rapid climate change has many bio physical impacts (IPCC, 2007) and already left several biological fingerprints including change in species composition of ecological communities, range and distribution shift of species as well as changes in phenology of the organisms (Parmesan and Yohe, 2003; Root et al., 2003; Parolo and Rossi, 2008; Chen et al., 2011; Gottfried et al., 2012; Kirilyanov et al., 2012; Pauli et al., 2012; Webb et al., 2012).

The high altitude limit of forests, commonly known as treeline, timberline or forest line, represents one of the most conspicuous vegetation boundaries (Körner, 1998; Holtmeier, 2009). The position of a treeline is mainly due to strong growth limitation by low-temperature conditions (Körner and Paulsen, 2004; Holtmeier, 2009). Worldwide, high altitude climatic treelines are associated with a seasonal mean ground temperature of $6.7^\circ\text{C} \pm 0.8\text{ SD}$ during the growing period (Körner and Paulsen, 2004). So, natural treeline ecotones are sensitive biomonitors of past and recent climate change and variability (Kullman, 1998), and are well-suited for monitoring climate change impact (Becker et al., 2007). The high elevation treeline is assumed to represent an ideal early-warning feature that responds to climate change positionally, structurally and compositionally (Kullman, 1998, 2001, 2007; Kirilyanov et al., 2012). Many dendroecological studies have documented that trees at the treeline often respond to climatic warming

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with an increase in recruitment or tree-density as well as upward advances in the tree-line position (Bradley and Jones, 1993; Camarero and Gutiérrez, 2004; Kullman, 2002, 2007; Kullman and Öberg, 2009; Kirilyanov et al., 2012). A meta-analysis of a global data set, including 166 sites for which treeline dynamics had been recorded since 1900 AD, showed that the treeline either advanced (52 % of sites) or remained unchanged, while only few treelines (1 %) declined under heavy anthropogenic disturbance (Harsch et al., 2009). Treelines that experienced strong winter warming and treelines with a diffuse form are more likely to advance (Harsch et al., 2009).

Himalayan ecosystems are facing the impacts of climate change. However, uncertainties still exist about our knowledge on the relationships of Hindu Kush–Himalayas (HKH) treelines to other ecological conditions and processes such as carbon balance, freezing and frost, drought, soil temperature, wind, snow cover, soils, regeneration, etc. are yet to be explored (Schickhoff, 2005). Treelines from Tibet and adjacent mountainous regions have shifted very little with climate change (Liang et al., 2011; Gou et al., 2012; Lv and Zhang, 2012). However, a previous study reported an upward movement of the tree species limit due to climate change in the Himalayas (Dubey et al., 2003). High-altitude regions in the interior of Nepal Himalaya are little affected by anthropogenic activities and may therefore provide valuable information to evaluate the isolated consequences of climate change (Cook et al., 2003).

The atmospheric temperature of Nepal has been increasing consistently after the mid-1970s with higher rate than the global average (Shrestha et al., 1999; IPCC, 2007), and the warming has been found to be even more pronounced in the high altitudes of Nepal Himalaya (Shrestha et al., 1999; Shrestha, 2008). However, no specific trend in precipitation has been observed (Shrestha, 2008). The effect of warming temperature in Nepal Himalaya is reflected by shrinking permafrost areas (Fukui et al., 2007), rapidly retreating glaciers (Fujita et al., 1998; Bajaracharya et al., 2007; Bolch et al., 2012; Yao et al., 2012), among other phenomena. Impacts on biological processes including range shifting of species are also expected but scientific studies on these aspects are scarce (Schickhoff, 2005). Past works on tree-rings in Nepal have identified

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several promising species for dendrochronological study, including *Abies spectabilis* and *Betula utilis* (Bhattacharyya et al., 1992; Cook et al., 2003; Sano et al., 2005), which can grow up to the treeline ecotone (Schickhoff, 2005; Ghimire et al., 2008). Recently, researchers from Nepal have initiated dendroecological studies covering various treeline sites of Nepal Himalaya (Bhujju et al., 2010; Suwal, 2010; Gaire et al., 2011). However, concrete results on the treeline shifting due to climate change are yet to be explored.

The present study was carried out to (i) ascertain the present position of upper forest, treeline, and species limits, (ii) characterize the stand structure and dynamics at the forest line and tree line, and (iii) analyze the response of tree growth and regeneration with climate change using both dendroecological and dendroclimatological techniques. For this study, the treeline is defined as the ecotone up to where 2 m tall trees can be found, and the species limit is defined as the highest position to which seedlings or saplings of the tree species are present. Treeline dynamics describes the changes in the regeneration and population dynamics as well as positional change of the tree species in the treeline ecotone.

2 Materials and methods

2.1 Site and species selection

The study was carried out at Manaslu Conservation Area (area: 1663 km²), a high mountain protected site in central Nepal Himalaya, established in 1998 AD. Manaslu Conservation Area has a diverse natural resource base with sparse human population and is relatively inaccessible. The area includes nine bioclimatic zones ranging from the lower sub-tropic to the nival zone with only marginal infrastructure, such as roads. It is the scientifically least explored protected area of the country. Local people depend on local agriculture, animal husbandry and utilization of natural resources for their sustenance. Killing of animals is considered a sin and most of the forest and biodiversity

is protected by these beliefs and guarded by religious Buddhist institutions (Chhetri, 2009).

The study site is a mountain slope adjacent to Kalchuman Lake situated at 3690 m a.s.l. (above mean sea level). With human settlements going up to no more than 2500 m a.s.l., the study site is least disturbed anthropogenically. There is a dense forest in between the settlement and study sites. Soil is rich in humus, dark in color, and the depth of which varies locally with the steepness of the slope. The tree canopy of the treeline ecotone is formed by *A. spectabilis* and *B. utilis* with a *Rhododendron campanulatum* understory and some scattered *Sorbus microphylla*. Above the treeline occur scrubs of *Rhododendron anthopogan* and some herbaceous species. The Himalayan silver fir, *A. spectabilis* is a tall evergreen tree endemic to the Himalaya and found between the lower temperate and lower alpine zone (2400–4400 m) from Afghanistan to Bhutan (Ghimire et al., 2008). Similarly, *B. utilis* is a medium sized deciduous tree which forms monospecific as well as mixed forests at the upper limit of the treeline (Ghimire et al., 2008).

2.2 Field visit and data collection

Field work was carried out in three expeditions: two in 2010 (May–June and September–October) and one in 2012 (October). After careful observation in transect walk at the treeline ecotone, the upper species limits of *A. spectabilis* and *B. utilis* were ascertained. Two altitudinal transect plots (20 m wide and > 250 m long), named Transect 1 (T1) and Transect 2 (T2) were marked at two sites of the treeline ecotone. The plots were oriented with their longer side parallel to the maximum slope and covered the current species limit and treeline ecotone (Fig. 1). T1 was above the continuous forest. However, T2 was situated above the middle part of the lake. This lake might be acting as a barrier for seed dispersal of the species from lower-altitude seed sources further down the slope. So we used two plots with the hope to learn about lateral migration, in addition to vertical migration. Individual plants were categorized and enumerated

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into three height classes: trees (> 2 m), saplings (0.5–2 m) and seedlings (< 0.5 m), following the concepts of Wang et al. (2006) and Kullman (2007).

Census counts were carried out inside each plot for *A. spectabilis* and *B. utilis*. For every *A. spectabilis* individual, their geographic location in the plot (latitude, longitude, and altitude); size (diameter at breast height – DBH, height); growth form and internodes interval of all individuals less than 2 m were recorded. The age of trees was calculated by tree core analysis, while that of seedlings and saplings were estimated by counting the branch whorls and scars left along the main stem (Camarero and Gutiérrez, 2004; Wang et al., 2006; Liang et al., 2011). This age estimation was also validated by comparing it with the age obtained by the number of tree-rings in the basal sections collected from the root collar of saplings and seedlings ($n = 34$). The age estimates by whorl count and ring count correlated positively ($R^2 = 0.91$, $P < 0.0001$), but the internodes or whorl count ages are systematically lower by 1.57 ± 0.33 yr (max. 4 yr) in saplings and 1.27 yr in seedlings. These suggest that the whorl count method can give a fairly accurate indication of the age of saplings and seedlings of conifer species like *A. spectabilis*.

2.3 Tree core and cut-stump collection and analysis

Tree cores were collected using the increment borer (Haglof, Sweden) following the standard technique suggested by Fritts (1976) and Speer (2010). The cores were collected from the base of each and breast (1.3 m) height of some individuals of *A. spectabilis* and *B. utilis* in the plots. Cores were also collected from the larger *A. spectabilis* and *B. utilis* trees outside of these plots for detailed dendrochronological analysis. A total of 249 cores and cut stump samples (172 *A. spectabilis* and 77 *B. utilis*) were collected (Table S1 in the Supplement). Collected core and cut stumps samples were taken to the Dendro-lab of Nepal Academy of Science and Technology for laboratory analysis.

Collected cores were air dried, mounted, sanded and polished using successively finer grades of sand paper (100 to 1000 grits size) until optimal surface resolution al-

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lowed annual rings to be visible under the microscope. Each ring was counted under the stereo zoom microscope and assigned a calendar year. The width of each ring was measured to the nearest 0.01 mm precision with the LINTAB™ measuring system attached to a PC with the TSAP Win software package (Rinn, 1996). All the tree cores were cross-dated by matching patterns of relatively wide and narrow rings to account for the possibility of ring-growth anomalies such as missing or false rings or measurement error. Cross-dating was done using the alignment plotting technique and also looking the math graphs. The quality of cross-dating of each sample was checked using the computer program COFECHA (Holmes, 1983). The cores that were poorly correlated with the mean chronology or had low correlation were re-checked and either corrected or eliminated.

The corrected ring-width data were standardized using the computer program ARSTAN (Cook, 1985). The ring-width series were standardized using conventional detrending methods with appropriate options of a negative exponential, linear or cubic spline curve to each series. Each ring-width-index series was then pre-whitened using autoregressive modeling to remove any autocorrelation effects (Cook, 1987). Finally, three chronologies viz. standard, residual and arstan were prepared using the corrected sample. Various chronology statistics like mean sensitivity, standard deviation, autocorrelation, mean series correlation, signal-to-noise ratio, expressed population signal (EPS) and variance explained were calculated to assess the quality of the site chronologies.

2.4 Population demography, regeneration and treeline dynamics

The age obtained from cross-dated samples was used for demographic analysis after the necessary correction for years to core height and years to center of missed pith. Such correction was made using age-height regression and age-diameter regression combined with the fitting of a circle template to the ring curvature so as to estimate the distance of the core to the center (Camarero and Gutiérrez, 2004; Speer, 2010). For *B. utilis* cores from representative sample trees covering different DBH classes were

collected. Based on the ages of 39 *Betula* trees, a regression analysis model between DBH and age was established (Fig. 2), and the relationship was used to estimate the age of all *B. utilis* trees from which tree cores were not taken.

The regeneration rate was determined by age histogram using the number of seedlings, saplings and trees individuals. The treeline dynamics was analyzed by densities distribution of tree, sapling, and seedling as well as the elevation-wise age distribution of the studied species. The upper species limit expansion was studied by observing the age of each individual in the entire plot following Camarero and Gutiérrez (2004) and Liang et al. (2011). In order to calculate the rate of species limit shift, the maximum elevation of live individuals and the position of the oldest individual within each transect was determined. Then, the species limit shift rate (m yr^{-1}) was calculated by dividing the change in species limit elevation (position) by the time elapsed.

2.5 Climatic influence on radial growth and regeneration

Before proceeding to the response analysis of tree growth and climate, the seasonality of tree growth was defined. From field observation and tree ring data have shown that radial growth of *A. spectabilis* at treeline sites ceases in September–October (Sano et al., 2005). Because climate in the preceding growing season often influences tree growth in the following year (Fritts, 1976), we analyzed the influence of temperature and precipitation since September of the previous growth year until October of the current growth year. Simple Pearson correlation coefficients were used to quantify relationships between tree-ring chronologies and two climate variables, i.e. mean monthly temperature and total monthly precipitation. Thirty years (1980–2009) of climatic data of the nearest stations at Chame ($28^{\circ}33' \text{ N}$, $84^{\circ}14' \text{ E}$ and 2680 m.a.s.l.) of Manang and Larke Samdo ($28^{\circ}40' \text{ N}$, $84^{\circ}37' \text{ E}$ and 3650 m.a.s.l.) of Gorkha were used. Missing values were replaced by mean value of the same month's data.

To investigate the relationship between regeneration and climate change, recruitment or age data was summed across five-year intervals as the finest resolution to take into account uncertainties in age estimates and compared with monthly climate

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records compiled into five-year averages over the same time period (Camarero and Gutiérrez, 1999; Wang et al., 2006). To describe the climate–recruitment relationships, monthly climatic data (mean temperatures, total precipitation) from Chame and Larke stations were used. Climatic factors limiting regeneration were identified from linear correlation analysis between regeneration and climatic data.

3 Results

3.1 Treeline position and structural parameters

The species limit of *A. spectabilis* was recorded at 3984 m (GPS e-Trex) in Transect 1 (T1) and 3955 m in Transect 2 (T2) and its treeline at 3907 m in T1 and 3830 m in T2. In case of *B. utilis* the treeline and species limit were recorded at the same elevation in both transects, i.e. at 3996 m in T1 and 4003 m in T2.

Structural parameters (age, DBH and basal area) revealed that both of the species were more matured in T1 than that of T2 (Table S2 in the Supplement). The maximum age of *A. spectabilis* and *B. utilis* was higher in T1 than that of in the T2. *A. spectabilis* tree density ranged from 50 to 280 trees/ha. The total basal area of *B. utilis* in both plots was higher than *A. spectabilis*. The DBH distribution of *A. spectabilis* showed bimodal distribution in T1 with peaks at 0–10 and 35–40 cm DBH class (Fig. S1 in the Supplement). In T2, the DBH distribution of the same species had an inverse-J shaped distribution indicating continuous regeneration in the area. DBH distribution of *B. utilis* in T1 is unimodally bell-shaped, indicating poor regeneration in the recent years. However, DBH distribution of the same species in T2 indicates better recruitment of individuals. Similar trends were observed in height distribution. Age class distribution of the species was heterogeneous with an inverse-J shaped and unimodal to multimodal bell-shaped distribution (Fig. S2 in the Supplement).

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3.2 Age structure, regeneration and treeline dynamics

The demographic distribution of *A. spectabilis* and *B. utilis* revealed the recruitment and mortality pattern over time (Figs. S2 (Supplement) and 3). The age distribution of *A. spectabilis* indicated that trees could be dated back to the early 1850s in T1 (Fig. 3a) and they migrated laterally and established in T2 in the 1950s (Fig. 3b). *A. spectabilis* population was dominated by young individuals (< 50 yr) comprising 89% of the population and only 2% were older than 100 yr. The recruitment of *A. spectabilis* was slow in the 1850s and accelerated after 1950, and again after 1980. This could be related to increased temperatures in the area. The recruitment of *B. utilis* started from the 1820s in T1, then, gradually migrated laterally and reached to T2 in the 1840s (Fig. 3a and b). The proportion of young population of *B. utilis* was low (13% of the population < 50 yr old) as compared to middle aged trees (42% being 50–100 yr old) and older ones (45% over 100 yr old). Recruitment of *B. utilis* was lower at the beginning in both transects, but increased slowly to peak in the 1880s in T1 and the 1930s in T2. Regeneration oscillated between the 1880s and 1940s and declined steadily since then.

The comparative age of two tree species shows that the regeneration of the *B. utilis* was higher before the recruitment of *A. spectabilis* in the treeline community. Spatial-temporal assessment of upper species limit distribution of *A. spectabilis* and *B. utilis* revealed that the position of *B. utilis* was higher than the position of *A. spectabilis* in both transects (Fig. 3a and b). Similarly, *B. utilis* colonized the area earlier than *A. spectabilis*. Seedlings of the *A. spectabilis* species were found about 80 m higher than trees (Fig. 3c). Matured trees and young seedlings were mostly dominant at lower elevation indicating stand densification. T2 had a lower number of seedlings than T1. Seedlings of *B. utilis* were not recorded in both transects, but some were observed just outside the plots. On the basis of the temporal and spatial distribution of the ages of *B. utilis* at an elevation gradient, we calculated that the seedlings of the species were established at 3860 m between 1810s and 1820s and at 3990 m during the 1890s (Fig. 3a). *A. spectabilis* on the other hand made a treeline community

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around 1850 at 3765 m and reached 3907 m (present *A. spectabilis* treeline) during the 1950s. Seedlings of this species are now established at 3984 m, which is close to the upper limit of *B. utilis*. The average upward movement of the upper distribution limit of *A. spectabilis* at the study sites was calculated to be 2.61 myr^{-1} (1.56 to 3.66 myr^{-1}).

5 The upward shifting of *A. spectabilis* was more pronounced in T2 with migration rate of 3.66 myr^{-1} , while it was 1.56 myr^{-1} in T1. This showed that there was clear upward migration tendency of *A. spectabilis* with some spatial variation in the migration rate.

Observing total numbers of trees, saplings and seedlings (Table S3 in the Supplement) it is seen that recent regeneration of *A. spectabilis* was found to be higher in T1 than in T2 and also higher than for *B. utilis* in both transects. Since there were no seedlings of *B. utilis*, with the presence of a large number of saplings and seedlings of *A. spectabilis* in the site, it is anticipated that the composition of this treeline community will change in the future.

3.3 Local climate scenario

15 The mean annual rainfall at Chame meteorological station was 967 mm (SD = 280). The monthly average temperature was found to be highest in July and lowest in November (Fig. 4a). The highest recorded temperatures were 23.4°C during June 1998, the lowest -4.5°C during January of 1999 and 2000. During the past 30 yr (1980–2009), Chame station experienced a decreasing trend in rainfall by 3.9 mm yr^{-1} ($n = 30$, $R^2 = 0.014$, $p < 0.52$) (Fig. 4b) and an increasing trend in mean annual temperature by $0.017^\circ\text{C yr}^{-1}$ (Fig. 4c). In recent years, particularly after 2000, monthly mean minimum temperatures were decreasing while monthly mean maximum temperature was increasing significantly. Similarly, mean annual rainfall at Larke, Gorkha, was 1252 mm (SD = 535). In Larke, during the past 30 yr (1980–2009) there was a significant ($n = 30$, $R^2 = 0.26$, $p < 0.003$) decreasing trend of rainfall by 28 mm yr^{-1} (Fig. 4b). This decreasing trend is more pronounced and significant ($p < 0.0003$, $R^2 = 0.46$, $n = 23$) after 1987 with a decrease in annual rainfall by 55 mm yr^{-1} between 1987 and 2009.

3.4 Tree-ring chronology

A 229 yr long (1782 to 2010 AD) standard tree ring chronology of *A. spectabilis* was prepared using 46 cores from 29 trees (Fig. 5). The chronology revealed that there was no constant increment in the growth of trees but it oscillated through time. The years 1818, 1819, 1974 and 1999 were characterized by particularly poor growth, whereas the years 1789, 1814, and 2009 resulted in particularly wide rings. Several statistics that were calculated for the time span of 1782–2010 AD and for the period of overlap (1920–2005 AD) of all tree-ring series indicated a high dendrochronological potential (Table S4 in the Supplement). The value of mean sensitivity and standard deviation is 0.136 and 0.18, respectively. The mean series correlation within tree was high (0.467) as compared to the mean correlation between tree (0.192) and among all radii (0.196). The EPS, an indication of how well the site chronology estimates the population chronology, was above (0.918) the threshold limit of 0.85 (Wigley et al., 1984). The signal to noise ratio was 11.23 and the percentage of variance explained by the first eigenvector was 24.4 %.

3.5 Response of tree growth and regeneration to climate change

Temporal patterns of growth in *A. spectabilis* correlated negatively with the mean monthly temperature of July–August ($r = -0.54$, $P < 0.002$) of the current year and September ($r = -0.53$, $P < 0.002$) of the previous year (Fig. 6a). Although statistically insignificant, a tendency for a positive relationship of growth with previous November through current March temperatures was noticed. Similarly, radial growth was negatively but insignificantly correlated with monthly precipitation of most months of the current year (Fig. 6a). There was a negative but significant relationship between tree growth and the average of May–August temperature of the current year ($r = -0.554$, $p = 0.001$). The relationship between ring width and precipitation of February of the current year was negative and significant ($r = -0.34$, $P < 0.05$). However, the relationship between regeneration and temperature of January to April ($r > 0.7$ with each

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month) and October to December of the current year was positive while the relationship was negative with the temperature of May to September of the current year ($r > -0.7$) (Fig. 6b). The relation between regeneration and temperature in March ($r = 0.84$, $P < 0.05$) and June ($r = -0.84$, $P < 0.05$) of the current year and precipitation in August ($r = 0.96$, $P < 0.01$) was positive and statistically significant (Fig. 6b). Similarly, no significant relation was observed between available precipitation data of Larke station and ring width.

3.6 Climate reconstruction

In accordance with the discussion in the preceding section, May–August temperature can be theoretically reconstructed. The transfer function explained by Fritts (1976) was applied for the climate reconstruction of May–August month. Thus, the transfer function was in the form:

$$T_{MJJ\text{A}} = a \text{ RW} + c \quad (1)$$

where, $T_{MJJ\text{A}}$ is the mean May–August temperature, RW is the ring-width index, a and c are the regression coefficients. This model was subjected to the F test of significance using the entire climate records available, i.e., of 1980–2009. It was found that the temperature transfer function was highly significant at 1 % (Table S5 in the Supplement).

Finally, mean May–August temperature for 229 yr long period from 2010 AD extending back to 1782 AD was reconstructed. The reconstructed May–August temperature shows several warm and cool periods. This also shows the slight warming at the end of 20th century (Fig. S3 in the Supplement).

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4.1 Position, structure and dynamics of treeline

The position and dynamics of the treeline are the result of the interaction of several factors including topoclimate (radiation, temperature, precipitation, length of growing season and snow cover), topography (slope inclination, relief forms), ecology of tree species (regeneration, seed dispersal, successional stage), site history (climate oscillations, fire, human impact, insect attacks), current biotic (browsing, trampling, diseases and insect pests) and anthropogenic influences (burning, logging, grazing, recreation and tourism) (Holtmeier, 2009). The position of the treeline, species line and species composition varies across the globe as well as at sites within the region (Miehe et al., 2007). In Nepal, the position of the treeline varies between the eastern, central and western region (Schickhoff, 2005).

Regardless of the sites, the *A. spectabilis* treeline in the present study was found at 3907 m a.s.l. and the *B. utilis* treeline at 4003 m a.s.l., which is comparable to the other studies (Körner and Paulsen, 2004; Bhujju et al., 2010). It was diffuse in nature. However, along the western slope of Mt Annapurna, the upper timberline (*B. utilis*, *R. campanulatum*) at north-facing slopes ascends to 4000–4100 m a.s.l. and to even 4400 m a.s.l. on the Nilgiri northern slope (Schickhoff, 2005). Bhujju et al. (2010) found the treeline at 4050 m a.s.l. in Pangboche of Sagarmatha (Everest) region in eastern Nepal, while at the Lauribina of Langtang in central Nepal it was observed at about 3900 m a.s.l. (Gaire et al., 2011). Generally, the upper treeline elevations in the HKH region increases along two gradients: a NW–SE gradient (corresponding to higher temperature sums at the same elevations along the mountain arc) and a peripheral–central gradient from the Himalayan southern slope to the Great Himalayan range and the Tibetan highlands (related to the combined effects of continentality and mass-elevation both leading to higher temperature sums) (Schickhoff, 2005).

The size class distribution of the tree species reflects its regeneration status (Lv and Zhang, 2012). In this study, the structural parameters of the studied species varies be-

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tween the two transects T1 and T2. The DBH class distribution of *A. spectabilis* shows a bimodal distribution in the T1 with peaks in lower and intermediate DBH classes. The peak in low DBH class indicates that regeneration in recent years is good. The DBH distribution of *B. utilis* is slightly bell-shaped, indicating poor regeneration during the recent years. An inverse J-shaped and unimodal to multimodal bell-shaped DBH and Age class distribution of *A. spectabilis* and *B. utilis* observed in present study have also been reported in the other treeline ecotones of Nepal (Shrestha et al., 2007; Bhuju et al., 2010; Suwal, 2010; Gaire et al., 2011), indicating site specific regeneration condition. Similarly at the *A. spectabilis* treeline near the same region on the Tibetan side, Lv and Zhang (2012) observed a multimodal age distribution with peaks during 1840–1860 and in recent years. Similar bimodal distributions of both DBH and height of *Pinus uncinata* was observed at the southwestern limit of the species' distribution in Iberia, NE Spain (Camarero and Gutiérrez, 2007). We observed a decrease of tree density with altitude, which is also observed in other treeline sites of Nepal (Shrestha et al., 2007; Bhuju et al., 2010; Suwal, 2010).

Upward shifting of tree species at high elevations with global warming is a widely observed phenomenon, although the rate and magnitude varies across the region (Harsch et al., 2009) and even at different slopes within a single mountain range (Holtmeier, 2009). Recruitment, critical determinants of the rate of forest or treeline shift (Camarero and Gutiérrez, 2007), has been found to be more sensitive to climate than adult mortality in harsh environments where competition is low, because recruitment has lower climatic thresholds than adult mortality (Lloyd, 1997). Recently, two agents of change, accelerating socio-economic transformation processes and climate change have been emerging that might exert a comparatively strong influence on treeline dynamics in the HKH mountain system (Schickhoff, 2005). Studies revealed that the tree-lines which experienced strong winter warming and with a diffuse form are more likely to have advanced than other form (Harsch et al., 2009). Our study site has a diffuse type of treeline and also experiencing winter warming in recent years. Hence much dynamics is anticipated in response to the environmental changes in the Himalayas.

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The recruitment of *A. spectabilis* was high during the 1940–1950s and after 1980s which might have been facilitated by the observed increased temperature in the area and in the country (Cook et al., 2003; Sano et al., 2005). In the present study, the establishment of *A. spectabilis* was high in recent decades as compared to the previous decades, which is consistent to the findings of other studies (e.g. Gaire et al., 2011; Liang et al., 2011; Lv and Zhang, 2012). Lv and Zhang (2012) found a significant tree recruitment in the recent three decades and sporadic recruitment in earlier periods from 1760 to 1960 AD in the treeline of Tibetan side of the Everest region. Liang et al. (2011) also found an increased recruitment of Smith fir (*Abies georgei*) after the 1950s with an abrupt increase in the 1970s in Tibetan mountain.

Patchy distribution of *A. spectabilis* in this study treeline ecotone with gaps in some diameter and age class resulting into multimodal distribution were observed, which indicates anthropogenic disturbance or episodic regeneration of the species during some favorable climate in the past. However, no single cut stump was recorded in the plots indicating episodic regeneration. The regeneration at the treeline can be sporadic or episodic (Cuevas, 2002; Lv and Zhang, 2012). The dominance of multimodal age distributions also observed in other alpine or forest-tundra ecotones (Szeicz and MacDonald, 1995; Cuevas, 2002; Batllori and Gutiérrez, 2008; Lv and Zhang, 2012) indicate that recruitment in tree line forest ecosystems is episodic rather than gradual.

In this study, establishment of *B. utilis* in recent decades has been very poor as compared to previous decades. A similar trend was reported from other treeline sites (e.g. Bhujju et al., 2010). The regeneration of the *B. utilis* trees at the study site of Kalchuman Lake started from the beginning of the 18th century as revealed from the cores collected from below the plots while trees from the studied plots dated back only to the early 19th century. Recruitment of the species was slow in the beginning in both transects and increased gradually to reach at peak in the 1880s in T1 and the 1930s in T2 with a slight oscillation between 1880s and 1940s. Stand age distribution showed both vertical as well as horizontal migration of the species in this study area in the past. Similarly, the regeneration of *B. utilis* before the arrival of *A. spectabilis* was high. The

maximum age of *B. utilis* was higher than *R. campanulatum* (Prabina Rana, personal communication, 2013) and the maximum age of *R. campanulatum* was higher than that of *A. spectabilis*. Hence, this area might have been colonized by shade intolerant *B. utilis* trees followed by shade tolerant *R. campanulatum* and was later invaded by *A. spectabilis* trees.

At and above the treeline in the study site in the Kalchuman Lake area, we observed neither long-living Krummholz nor sub-fossil wood of *A. spectabilis* and *B. utilis*. Matured as well as young seedlings were mostly dominated in the lower elevation. However, some seedlings, probably due to global warming, have been thriving at much higher elevation than tree individuals. This indicates both stand densification and upward migration as recorded in many other areas (Harsch et al., 2009). Average upward shifting of the upper distribution limit of *A. spectabilis* at the treeline ecotone was about 2.61 myr⁻¹ with site-specific variation in rate i.e. in T2 upward shifting of *A. spectabilis* was more prominent as compared to T1. This migration trend is consistent with the migration trend in other treeline ecotones of the Himalayas (Dubey et al., 2003; Suwal, 2010; Gaire et al., 2011) and other regions of the world (Camarero and Gutiérrez, 2004; Harsch et al., 2009; Chauchard et al., 2010; Kirdeyanov et al., 2012). From the study at Samagaun region of Manaslu area, Suwal (2010) reported an upward expansion of *A. spectabilis* by an average of 34 m decade⁻¹ which is higher than the average upward migration in the present study. In another study at the upper elevation limit of Himalayan pine (*Pinus wallichiana*) in the western Himalayas, Dubey et al. (2003) estimated an upward shift of 19 and 14 m decade⁻¹ on south and north facing slopes, respectively. However, Liang et al. (2011) found no significant upward movement in fir treelines in the Tibetan plateau despite the warming in the region in the past 200 yr. Kullman and Öberg (2009) presented a regional-scale treeline rise of *Betula pubescens* ssp. *czerepanovii*, *Picea abies* and *Pinus sylvestris* in the southern Swedish Scandes by 70–90 m on average with maximum up-shifts by about 200 m since around 1915 AD. So, treeline shifting with environmental change is spatially heterogeneous.

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We observed a stagnant upper distribution limit or treeline of *B. utilis* in the recent decade along with poor regeneration. Presence of a large number of fecal pellets of deer species in the studied plots indicated that besides climate change, grazing and browsing might be affecting the regeneration and dynamics of palatable species *B. utilis*. In spite of the high regeneration in the Trans-Himalayan treeline forming pure *B. utilis* forest, Shrestha et al. (2007) also did not find any upward shifting of the *B. utilis* treeline as that treeline had sharp boundary along with matured trees at upper part. They concluded that herbivory pressure in that region shaped the treeline and limited the upward migration of *B. utilis*. Similarly, recent landscape-scale experimental evidence in Europe has demonstrated that, even at relatively low densities, livestock can limit the recruitment and dynamics of mountain birch (*Betula pubescens tortuosa*) tree-line (Speed et al., 2010). Herbivores may also hamper the development of a treeline from recruiting individuals by repeatedly browsing shoots and preventing trees from growing above browse-height (Speed et al., 2011). From these analyses it may be anticipated that *A. spectabilis* in the treeline of the Manaslu region of Nepal Himalaya is benefitting from global warming and the facilitative role of grazing and browsing of associated competent *B. utilis* trees by wild animals.

4.2 Response of tree growth and regeneration to climate change

Growth of a tree is associated with several factors including climate. Studies from Nepal Himalaya revealed that tree-ring width of *A. spectabilis* is controlled by pre-monsoon (March–May) climate with negative correlation with temperature and positive correlation with precipitation indicating that moisture availability in this season limits tree growth (Cook et al., 2003; Sano et al., 2005; Chhetri and Thapa, 2010; Gaire et al., 2011). The negative relationship with the pre-monsoon temperature indicates that increase in pre-monsoon temperature without rainfall in the season increases the evapotranspiration which leads to a soil-moisture deficit and limits tree-growth. However, in this study, ring width was negatively correlated with precipitation of current July–August and with September of the previous year, and positive with winter temperature. This

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suggests that temperature before the growing season has a main influence on the radial growth because it was positively correlated with temperature of previous year October to current year March. High winter temperature may induce early melting of snow with the easy availability of melt water for growth in the growing season. Similarly, Borgaonkar et al. (2011) found a strong positive relationship between the mean annual and winter (December–February) temperatures of the concurrent year and growth of western Himalayan conifers. Above-average moisture during late summer and early autumn may promote storage of carbohydrates and bud formation, thus enhancing growth during the following year (D'Arrigo et al., 2001).

Relationship between regeneration of *A. spectabilis* and temperature of January to April and October to December of the current year was positive while the relation was negative with the temperature of May to September of the current year. This implies that a warm winter season may help plants to survive by reducing the amount of energy required to maintain body heat in the cold environment and for early initiation of growth. The regeneration of *A. spectabilis* was positively correlated with the precipitation of May to August. The positive relation with precipitation of these months implies that as temperature already crossed the minimum threshold values required for growth, high rainfall helps survival and growth of seedlings or saplings. During warmer summers the recruitment of *A. spectabilis* was positive with precipitation because at that time temperature is very high in the area and low rainfall may create a desiccation situation and small seedling and sapling may die. Therefore, increased rainfall favors the growth and survival of seedlings. While during the winter season low temperature may limit growth by delaying the initiation of the growth as it is positively related with the temperature of the cold season.

Due to the lack of young seedlings and saplings as well as long climatic data, the climatic variables limiting growth and regeneration of *B. utilis* could not be identified for the present study site. However, in a study from central Nepal Himalaya, Dawadi et al. (2013) found a significant positive relationship between tree-ring width chronologies of timberline *B. utilis* and precipitation in May and the pre-monsoon season, and

inverse relationships with temperature in May and precipitation in August of the current year. That study indicated that cool and wet conditions during the pre-monsoon season favor the growth of Himalayan birch in central Nepal.

From a similar study at the timberline in the Everest region, Lv and Zhang (2012) found that fir recruitments in 5 yr classes were positively correlated to their corresponding monthly mean air temperatures in June and September and with PDSI in June. Consistent with Lv and Zhang (2012), in this study, regeneration was correlated positively with precipitation of most of the months of the current year recorded at Larke station. The relationship was an inverse for regeneration and ring width. Wang et al. (2006) found significant and positive correlations between recruitment of *Picea schrenkiana* and total precipitation for June and spring, and significant and positive correlations between recruitment and mean summer minimum temperature. As there is wide variation in topography even in the small area of the high Himalayas, the difference in the response function with climatic data of different stations of the study area might be associated with this.

In this study, we did not observe a complete synchronization between high regeneration and high radial growth time. Sometimes, it matched, for example during last decade there is both high regeneration and high radial growth. However in some cases it lags behind. At a global scale, treelines are considered to be constrained primarily by growing season temperature (Körner and Paulsen, 2004). However, in this study the tree recruitment was found to be associated positively with winter temperature. Climate conditions that facilitated *A. spectabilis* establishment were different from those that enhanced radial growth as has been found in other tree species (Wang et al., 2006; Camarero and Gutiérrez, 2007). In some month climatic influence on regeneration was similar to radial growth which is similar to the findings of other studies (Szeicz and MacDonald, 1995; Camarero and Gutiérrez, 1999). Hence, tree establishment at the treeline ecotone may be controlled by local micro-environmental factors and episodic climatic events (Wang et al., 2006).

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4.3 Over 200 yr climate history using tree ring data

The *A. spectabilis* is identified as a dendrochronological potential species as it meets the criteria of a low autocorrelation, a high mean sensitivity and a high standard deviation that are considered to have a good potential for dendroclimatological studies (Fritts, 1976). Although our calibration is based on short (30 yr) climate data record, our 229 yr long average May–August temperature (1782–2010 AD) reconstruction showed the warming trend in the second half of the 20th century. The March–September temperature reconstruction (1752–2000 AD) done by Sano et al. (2005) for western Nepal has shown a warming trend from 1750s until approximately 1790, followed by cooling until 1810, then by a gradual warming trend extending to 1950, and a notable cold period continuing up to the present. Similarly, the October–February month’s temperature reconstruction (1605–1991 AD) for Nepal Himalaya is exhibiting the strongest increase in temperature over the past ~ 400 yr (Cook et al., 2003). Yadav et al. (2011) also reported different cool and warm periods since 940 AD in mean summer (May–August) temperature in the western Himalaya and an increase in the temperature since the late 19th century. Similarly, the tree-ring based summer temperature (July–August) reconstruction for temperate East Asia has also revealed a Little Ice Age cold period and 20th century warming up to the present time (Cook et al., 2012).

5 Conclusions

Our study provided a recruitment and dynamics history of Himalayan fir and mountain birch at the high altitude treeline of central Nepal Himalaya. Although regeneration patterns varied between the species, increasing trends of stand densification as well as upward shifting of the studied treeline is evident. The upward shift of *A. spectabilis* at MCA was estimated to be 2.61 m yr^{-1} . However, the upper distribution limit of *B. utilis* was stagnant in recent years. The regeneration of *A. spectabilis* was positively related with precipitation in May–August and temperature in January–April during the current

year. Spatial and temporal variations in age structure and regeneration of these two species and their species-specific response to climate indicated that the plant communities at the treeline ecotone in the Nepal Himalaya were sensitive to environmental change. Reconstructed summer temperature shows oscillations of warm and cool periods. Studies incorporating multiple species and covering other proxy evidence like pollen from lake sediments could enhance our understanding on spatio-temporal tree-line and vegetation dynamics in association with climate change.

Supplementary material related to this article is available online at <http://www.clim-past-discuss.net/9/5941/2013/cpd-9-5941-2013-supplement.pdf>.

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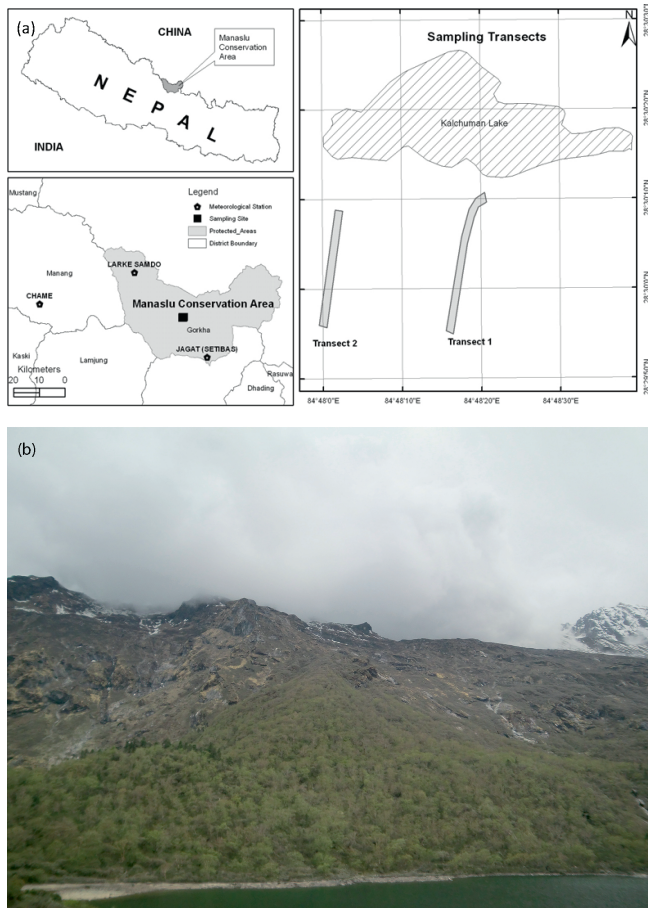


Fig. 1. Location map of the study area showing the position of the study plots and local meteorological stations **(a)**, and a photo of the study site showing treeline, species limit and some portion of Kalchuman Lake **(b)**.

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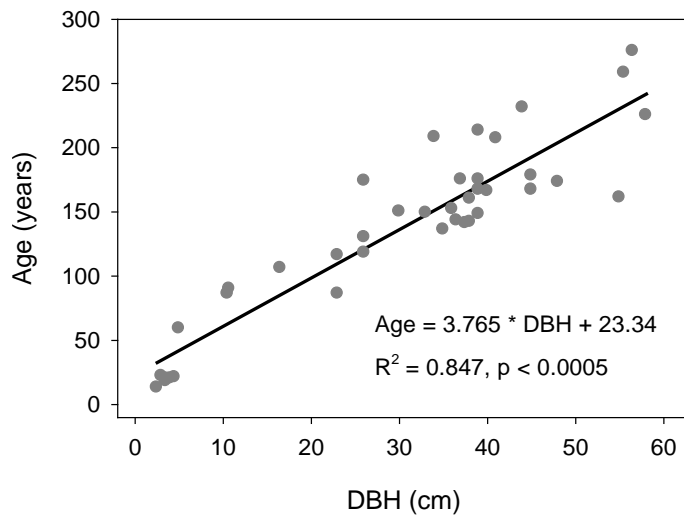


Fig. 2. Diameter at breast height (DBH)-Age relationships of *Betula utilis* from the Kalchuman Lake area, Manaslu Conservation Area.

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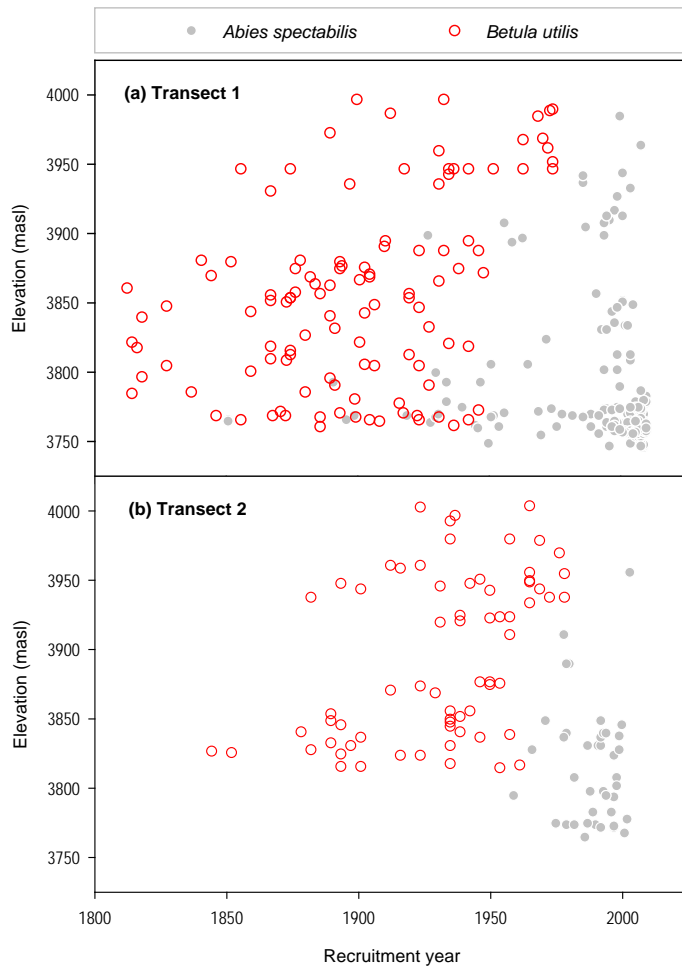


Fig. 3. (a and b) Spatial and temporal variation in the recruitment of tree species in T1 and T2.

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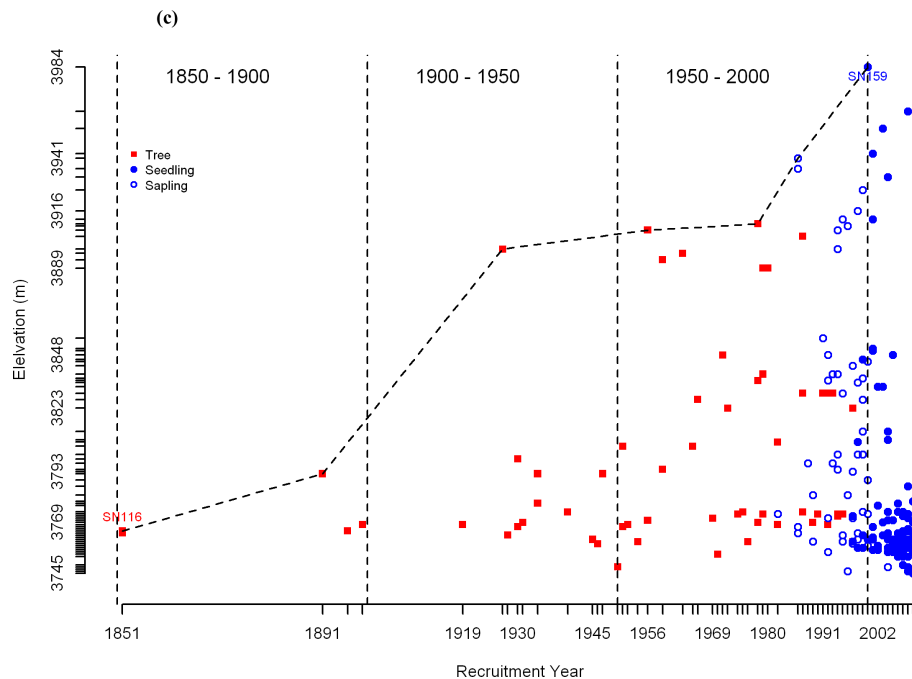


Fig. 3. (c) Temporal upward shifting of *Abies spectabilis* along an elevation gradient in the study site.

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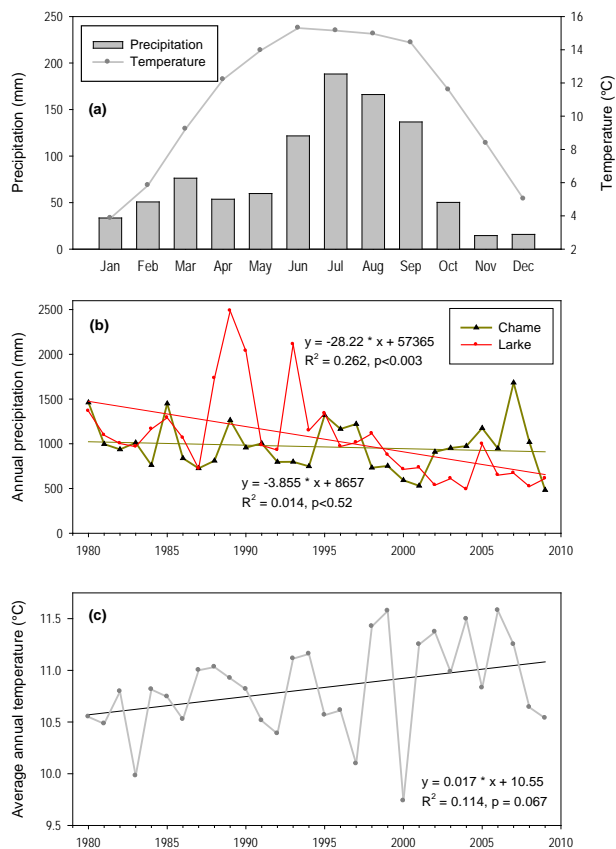


Fig. 4. Climatic trend in the local stations: mean monthly (1980–2009) precipitation and temperature at Chame, Manang station **(a)**; annual trend of precipitation at Larke, Gorkha and Chame **(b)**, and trend of mean annual temperature at Chame **(c)**.

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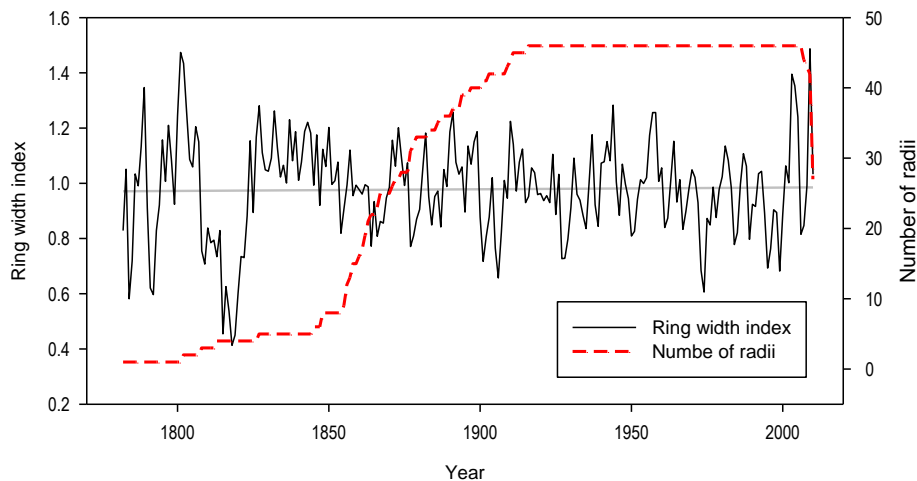


Fig. 5. Tree ring standard chronology of *Abies spectabilis* from the Kalchuman Lake area of Manaslu, Central Nepal.

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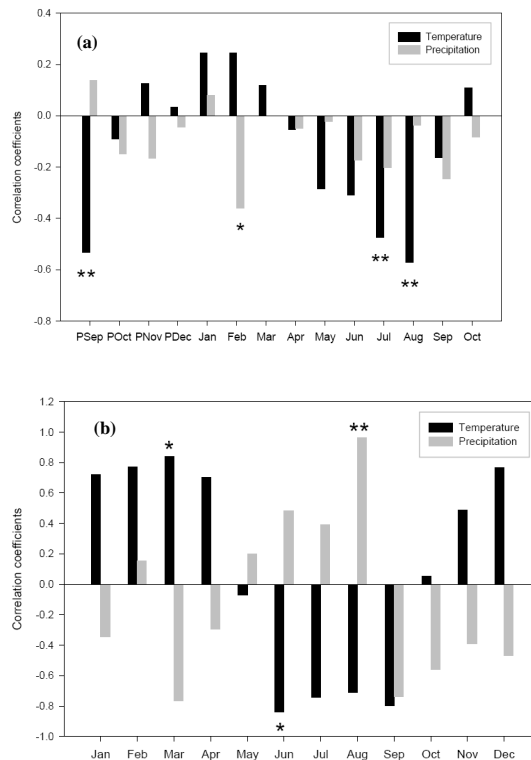


Fig. 6. Relationship between the *A. spectabilis* radial growth with monthly climate data **(a)**, and relationship between regeneration *A. spectabilis* with monthly climate **(b)**; symbols over the bar indicate the level of significance of the correlation coefficient at 5% (*) and 1% (**) significance level. **(a)** shows the response of radial growth to the monthly climate of September in the previous year to October of the current year. For climatic influence on the regeneration of the *A. spectabilis* climatic window of 12 months of current years are used.